DEVELOPMENT OF A GRAVITY-BASED TIDAL CURRENT POWER PLANT
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ABSTRACT
Adapting to the actual conditions of the tidal current energy resources in Northern China, which has the features of relatively low velocity and shallow water, a kind of gravity-based tidal current energy converters was developed. Two full-scale 50kW horizontal axis tidal current turbines were produced. Tower typed gravity-based supporting structure of the turbine was adopted in order to fit for the real situations of the sea area where the power plant would build. To ensure the stability of the supporting structure, numerical simulation was carried out by using the wave theory and CFD method. Then combined effect of wave load and current load on the device was discussed. Moreover, offshore construction plan of the device including towing, deployment, recovery and maintenance was presented, reliability and the ability of anti sliding or overturning during the operation period was assessed to ensure safety of deployment and running. A tidal current power plant has been constructed based on technology presented in this paper.

KEY WORDS
Tidal current energy, power coefficient, ocean energy, horizontal axis turbine

1. Introduction
Ocean energy is one of the sustainable energy sources that could be relied on in the future to solve the issue of energy crisis. China has a quite long coastline and a vast ocean territory. So there is a great potential of ocean energy resources to be exploited. [1] So developing ocean energy bears enormous strategic significance for China’s sustainable development. Tidal current energy technology is a promising way to harness the ocean energy. In recent years, technology of tidal current energy development has been largely improved. Especially since the National Special Funds Program for Marine Renewable Energy in China has been launched July, 2010, several demonstration projects were approved and several hundred kilowatts level tidal current energy pilot power stations were being constructed.[2] It heralds that China is now stepping into pre-commercial stage of ocean energy development.

There are considerable rich reserves of tidal current energy, especially in Zhejiang and Fujian provinces. However, although the total amount of the tidal current energy reserves is rather big, quality of most of the tidal current energy resources in China is not as good as the tidal current energy resources in Atlantic coast. In Northern China, there are tidal current energy sources areas with available resources, but the tidal current velocity is relatively low and the depth of water is relatively shallow.[3] So developing tidal current energy technology suitable for exploiting such energy resources has significance for tidal current energy technology spreading.

In this paper, development of a tidal current power plant which is representative in ocean energy exploiting in Northern China would be introduced.

2. Background of the project
The pilot tidal current power plant we discussed is a part of a project sponsored by National Special Funds Program for Marine Renewable Energy. The project is a multi-energy complement independent power supply system for an island. The system is made up of ocean current power, wind power and solar photovoltaic power. This tidal current power plant is a section of tidal current power system. The total installed capacity of the plant is100kW. It has two 50kW tidal current turbine units, which were named “Haiyuan I” and “Haiyuan II” respectively.

The pilot tidal current power plant is located in sea area to the southeast of Zhaitang Island, Jiaonan. The site is close to Qingdao city, which gives more convenience in transport and installation of the turbine units.

Fig.1 Tidal current energy resources of the site
According to historical measured data, the maximum tidal range of the site is 4.64m, mean tidal range is 2.81m, and the maximum flow velocity of the sea area can reach 2m/s, with NE-SW tidal flow direction (shown as Fig.1). The tidal current energy resources condition of the sea area is typical in Northern China. Technology suite for this site is likely can be applied in other similar sea area in Northern China.

As shown in Fig.2, the deployment site of the power plant is 200m away for the island. The water depth of the locations is about 35 meters, geology of the seabed is sand waves area with a slightly incline, as Fig.3 showed.

3. Scheme of the power plant

3.1 Layout of the turbine units

The tidal current turbine units, “Haiyuan I” and “Haiyuan II” were designed to meet the demand of the project in the condition of sea area near the Zhai Tang Island. Basic performance parameters of the turbine set could be listed as following.

- Rated flow speed: 1.5m/s;
- Cut-in speed: 0.8m/s;
- Rated power: 50kW
- Coefficient of power: 0.35;
- Diameter of the turbine: 10.5m

As shown in Fig.4, the turbine units were composed of the tidal current turbine set and supporting structure. The turbine set consist of blades, hub, power take off system, generator and electrical components cabin. As the key component of the tidal current power plant, the function of the turbine determines performance of the whole system. In “Haiyuan I” and “Haiyuan II”, horizontal axis tidal current turbines were adopted for relatively maturity of technology and high efficiency of the device.

Blades of the turbines have great influence on efficiency of the turbine. So foil profile of the blades should be optimized. According to results of numerical simulation, NACA63-8XX series foil is suitable for the turbine units working in the conditions. Fig.5 shows the blades foils used in the turbine. According to the extreme loads, combining the actual tidal current and the type of the support structure, a laminate-theory-based structural design was used to determine the optimal layout specification of composite laminas along the blade and the number of shear webs. Following the blade structure design, the distributed structural properties were verified. Using ANSYS, hydro-elastic analysis of tidal current turbine blades was made and perform mode, stability, loads and response of the blades were also analyzed.

The blades were made by glass fibre reinforced plastics with steel framework. Before they were assembled into the turbine, loading tests were needed to be conducted to ensure enough strength and stiffness of the blades to bear the load when the turbines running in harsh marine environment. Fig.6 shows the test bench and a vision of loading test. The tests proved the reliability of the blade structure.
In order to extract energy from tidal current with high efficiency and easy to start running, the turbine adopted pitch-adjusting technology to solve the problem of relatively low tidal current velocity. Pitch angle of the turbine blades can be adjusted by gear rack mechanism encapsulated in the hub according to the current velocity and rotating speed of the turbine rotor. Rotation movement of the rotor transmitted to the shaft of the generator through a half direct drive PTO system. The PTO system is made up of a gear train with speed ratio of 1:15. PTO system and the generator were encapsulated in a sealed nacelle, as well as the electrical components cabin. The electrical elements of leakage detection, temperature and humidity sensor and pressure transducer are all integrated in the cabin.

Supporting structure is important for tidal current device. In scheme of the power plant, tower typed gravity-based supporting structure was adopted in order to fit for the real situations of the sea area near Zhaitang Island, where the power plant would be built.

### Table.1 Specifications of the turbine units

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>50 kilowatt (kW)</td>
</tr>
<tr>
<td>Number of rotors</td>
<td>1</td>
</tr>
<tr>
<td>Number of rotor blades</td>
<td>3</td>
</tr>
<tr>
<td>Control type</td>
<td>Variable speed, Variable pitch (VSVP)</td>
</tr>
<tr>
<td>Maximum rotor speed</td>
<td>22.4 rpm</td>
</tr>
<tr>
<td>Normal flow speed range</td>
<td>0.6~2.0 m/s</td>
</tr>
<tr>
<td>Hub height</td>
<td>11 m</td>
</tr>
<tr>
<td>Blade foil</td>
<td>NACA63-8XX</td>
</tr>
<tr>
<td>Water depth</td>
<td>35 m</td>
</tr>
</tbody>
</table>

Since water depth of the sea area where the turbine units located in is not great, gravity based supporting structure is practicable in such conditions. Three big cylinders with concreting cast in provided necessary gravity to ensure the stability of the whole structure. The bottoms of the cylinders were thorn bumped to increase the anti slide coefficient of the foundations in sand wave areas. The turbines have a bevel join in bottoms, which can be planted in to the socket of the foundations. It could provide easy access for maintenance of the rotor components and sub-components, and easy transportation and installation. [5]

Table.1 listed main specifications of the two turbine units. Detailed design of the turbine units would follow them.

### 3.2 Power Conversion and Control System

Power generated by the two tidal current turbine units, “Haiyuan I” and “Haiyuan II” would send to the onshore power conversion and control center 200m away on the island through underwater cables. System condition monitoring and control signals transmitted through CAN bus. Running status and data of tidal stream are acquired by monitor of operational state of the turbine unit, transmitted to power conversion management apparatus through the cable, then transmitted to horizontal axis tidal current energy management system, and finally delivered to the top level energy management system of the multi-energy complement independent power supply system.

### 4. Stability Analysis of the Supporting Structure

Stability is of most important for gravity-based supporting structure of tidal current turbine. For long-term safe operation of the tidal current power plant, the turbine units must not be overturned or slide during the period of operation.

The supporting structure seated to the seafloor is subject to a system of forces including fluid loading, mass, buoyancy and torque. Environmental load on horizontal axis the tidal turbine unit s can be calculated as [6] mentioned.

#### 4.1 Verification Calculation of anti-overturning of the Supporting Structure

The volume of the whole tidal current converter device is 15.6m$^3$ and the volume of the supporting structure including three cylindrical concrete foundations is 52m$^3$. So the buoyancy $F_F$ can be derived, which is 691.74667kN. The gravity force of a whole tidal current turbine unit, including the turbine set and the gravity-based supporting structure is 1754.24kN.

The center of gravity of the supporting structure can be got by what showed in Fig.7.
Referring to standard literatures of seabed seated ocean platform\[7\], the anti-overturning ability of the platform is indicated by factor of safety against overturning, which can be expressed as

$$K_{zi}=M_{zi}/M_{zf}$$  \hspace{1cm} (1)

Where $M_{zi}$ is the anti-overturning moment of seabed seated platform; $M_{zf}$ is the overturning moment of seabed seated platform. The max thrust force appears in the direction perpendicular to the rotary plane of the turbine, so overturning would likely to be occurred in the direction. And because the distance between the gravity center of the device and the front end is smaller than the distance between the gravity center and the rear end of the foundation, so it is simply needed to ensure that the device not be overturned forward.

According to design of the turbine, the force transmitted from the swept surface to the supporting structure is supposed to be 200kN, and the resultant force of wave and tidal current act on the supporting structure is 143.13kN. The anti-overturning moment and the overturning moment can be calculated by

$$M_{zi}=F_{a} \cdot H$$  \hspace{1cm} (2)

$$M_{zf}=(G-F_{p}) \cdot l$$ \hspace{1cm} (3)

Where $M_{zi}$ is the overturning moment; $M_{zf}$ is anti-overturning moment; $F_{a}$ is the thrust force in horizontal direction; $F_{p}$ is the buoyancy; $G$ is the gravity of the whole device; $H$ is the height of the hub; and $l$ is the distance between the gravity center of the whole device and the most front end of the supporting structure. Put the data into, and the result is $M_{zi}=7834.826kN.m$ and $M_{zf}=2854.514kN.m$. Obviously $(G-F_{p}) \cdot l>F_{a} \cdot H$, so the overturning criteria is not be satisfied. $K_{zi}$ is about 2.6, so stability is ensured in the assumed condition.

According literature of design and study of mobile jack-up platform, the platform’s anti-sliding safety factor is

$$K_{H}=R_{H}/F_{H}$$ \hspace{1cm} (4)

Where $R_{H}$ is the sliding resistant force on the platform; $F_{H}$ is the sliding force of the platform. In full load case, $K_{H}$ must be not less than 1.4.

Considering the gravity force, buoyancy and tidal current thrust force exert on the turbine unit with supporting structure and the foundation, to ensure no sliding on the contact surface, it can be calculated by

$$R_{H}=F_{H}+F_{N}=\mu(G-F_{p})$$ \hspace{1cm} (5)

$$F_{H}=F_{a}$$ \hspace{1cm} (6)

Where $F_{H}$ is the sliding force, including the indirect tidal thrust force 200kN; the direct resultant force that wave and tidal current act on the supporting structure, 140.13kN; $R_{H}$ is sliding resistant force; $F_{T}$ is the static friction between bottom of the foundation and the seabed; $F_{N}$ is the support force on bottom of the foundation; and $\mu$ is static friction coefficient. According to the design feature of the foundation and the installing form, the static friction coefficient is assigned to be 0.55.

Put the gravity, buoyancy etc. into anti-sliding formula, result of $R_{H}>F_{H}$ can be obtained, and $K_{H}$, the anti-sliding safety factor is about 1.77. In the case, anti-sliding stability of the tidal current energy device can be assured.

5. Installation of the Turbine Units

After being manufactured, assembled and testing in land, the tidal current turbine units would be deployed in the specific sites. As shown in Fig.8, The turbine units, “Haiyuan I” and “Haiyuan II” were waiting for installation in a dock of a port about 3.5km from the sea site where the tidal power plant would be built.

![Fig.8 “Haiyuan I” and “Haiyuan II” in dock](image)

Installation of the turbine units should be performed in appropriate time window. For safety of operation, the installation process often takes the opportune one hour time of slack water period between ebb and flood when the speed of the tidal current is the minimum, and the weather conditions should be fine, no significant wind and wave.

“Haiyuan I” and “Haiyuan II” were respectively installed on two separate days in August 2013. Two working vessels and one transporting ship were used. Firstly, a working vessel lifted the turbine units up from the dock and put it down on the deck of the transporting ship with cable capstan lifting cooperation of a hoist on the vessel left and another working vessel unmoored and lay the cable to the seafloor until it reached the shoreline of the island.

As shown in Fig.9, after the transporting ship left, the turbine would be lowered and laid down into the seabed, ensuring the orientation of the turbine was align with the major direction of the tidal current. Then the working vessel left and another working vessel unmoored and lay the cable to the seafloor until it reached the shoreline of the island.
6. Conclusion and Future Works

A 100kW gravity-based tidal current power plant was developed. Technologies of adjusting-pitch turbine blades and tower typed gravity-based supporting structure used in the plant are suitable for the actual conditions of the tidal current energy resources in Northern China. Stability of anti sliding and overturning during the operation period was verified. Two full-scale 50kW horizontal axis tidal current turbines have been installed and the power plant is finishing. The pilot tidal current power plant is planned to demonstrate operating for a long time.

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References