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Hydrodynamic consideration in ocean current turbine design*

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Abstract: Ocean currents are one of important resources of ocean energy. Although it is not widely harnessed at present, ocean current power has a vital potential for future electricity generation. In fact, several turbine systems have been proposed in the world. In the present, we consider what factors should be considered in designing the system from the perspective of hydrodynamics. As an example, a floating Kuroshio turbine system which is under development in Taiwan is employed to serve as the case study. The system consists of five major parts; i.e. a foil float which can be employed to adjust the system submergence depth, a twin contra-rotating turbine system for taking off the current energy, two nacelles housing power generators, a cross beam to connect two nacelle-and-turbine systems, and two vertical support to connect the foil float and the rest of the system.

Key words: ocean current energy, renewable energy, system dynamics, rotor design, floating turbine

Introduction

Ocean currents represent an uninterrupted flow of green energy. Their power in the form of kinetic energy has an important potential for electricity supply in the future. It is known that they are more predictable than wind and solar power. In addition, they are stable and steady when compared to other types of ocean energy. With the advancement of technology, several prototypes of ocean energy devices have been developed. Some representative systems are shown in Fig.1.

The Aquantis Current Plane (“C-Plane”) technology[7] was developed for power generation in the Gulf Stream off of Florida, USA. The passive depth stability of the system makes the turbines to operate at a specific incoming flow speed, therefore, the power output is more stable. Hence, it could be used to produce reliable base load power. However, due to its depth stability, the position of the turbine varies with the time-varying flow speed profile. This could make it more difficult to build an energy harvesting farm. In addition, The Center for Ocean Energy Technology of Florida Atlantic University developed a single-turbine system. It is tethered to a buoy which is permanently moored. Cribbs[8] developed a numerical model for the mooring system and conducted the system optimization. He pointed out that for deep water moorings, vortex-induced vibrations are of great concern in lock-in condition which might create harmful effect to the system, especially at connection points. The Gulf stream turbine system developed by Robson for the Gulf Stream Current is a more complicated one, compared to the former two[9-11]. A self-supporting structure was design that allowed the turbines to be positioned at depths for which the current could generate electricity at about the design capacities of the turbine.

A floating type ocean current turbine system is also under development in Japan[12-14]. The system has a pair of contra-rotating turbines which are connected by a cross beam. To avoid destruction due to extreme weather caused by typhoons, the device is moored by a single mooring line to have a weathervane function. It is normally installed approximately 100 m deep to avoid the influence of surface waves. In Taiwan, Wanchi Steel Industrial Company proposed an ocean current energy converter[15]. For power generation, it

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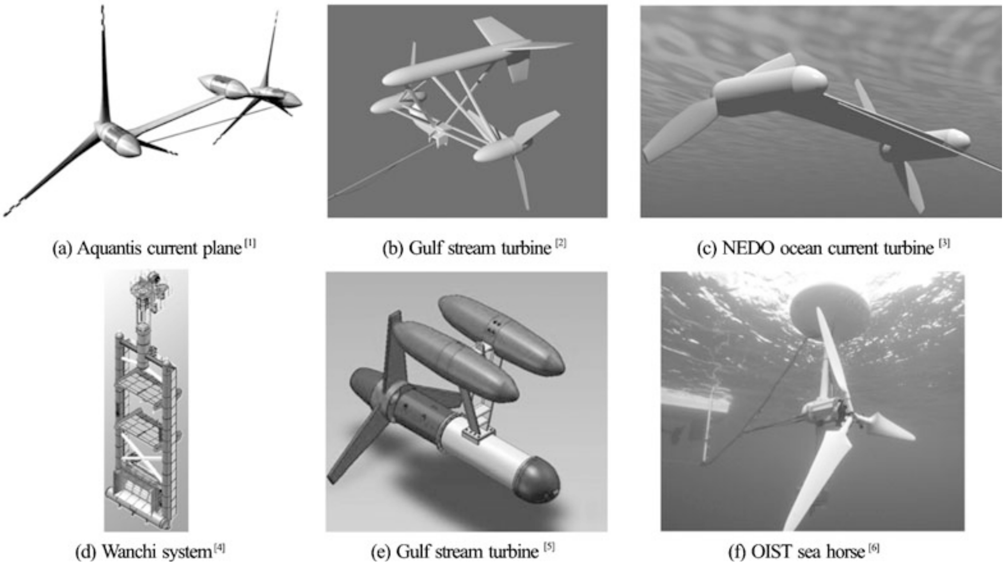


(a) Aquantis current plane[1] (b) Gulf stream turbine[2] (c) NEDO ocean current turbine[3]

(d) Wanchi system[4] (e) Gulf stream turbine[5] (f) OIST sea horse[6]

Fig.1 Some representative ocean current turbine systems

employs water turbines. The design of turbine blades incorporates the mechanism of planetary gear to increase the efficiency of energy harvesting. Chen[16] proposed a feasibility study to explore the power of the Kuroshio and to construct a 30 MW pilot plant. Recently, Chang et al.[17] have addressed the analysis of the interaction between turbine and current. Several additional ocean current energy conversion systems are under development. The reader may be referred to [18].

Fig.2 Schematic of the FKT system

1. The floating kuroshio turbine system

More recently, a new ocean current turbine has been being developed in Taiwan to harness the kinetic energy of Kuroshio which meanders offshore the East Taiwan Channel. For a feasibility study, a 1/5 model with a rated power of 20 kW at the current speed of 1.5 m/s is being designed and will be constructed for real sea tests in the future. Shown in Fig.2, the system consists of five major components, the foil float on the top, two vertical supports connecting the foil float and the ocean current turbine generator system, the cross beam connecting the twin turbines, the rotors to harness the kinetic energy of ocean current, and the power generators inside the nacelles to transform the mechanical energy into electricity.

In the following, we discuss the hydrodynamic features which were considered in the system design. For further specification of the system in our study, the major dimensions of the 1/5 model system are shown in Table 1.

Table 1 Description of the principal dimensions

Main parts	Values
Chord of the foil float	4.0 m
Span of the foil float	8.0 m
Shape of the foil float	NACA0018
Length of nacelle	3.0 m
Radius of nacelle	1.2 m
Length of vertical support	3.0 m
Length of cross beam	6.3 m
Diameter of turbine	5.0 m
Distance between two nacelle centerlines	7.5 m

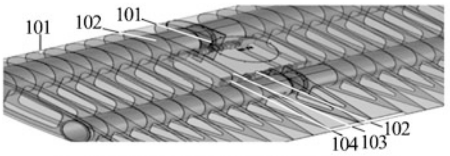
2. The hydrodynamic considerations

2.1 *Diving control*

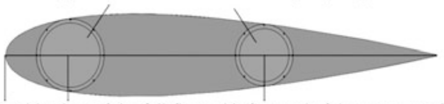
From the perspective of unpredictability of the ocean state due to extreme weather conditions, the control of diving depth is very important and vital. For the

Gulf Stream and the Kuroshio which are often the target currents to deploy ocean current turbine systems, extreme weather is not unusual. It is well known that they are on the paths of hurricanes and typhoons. Therefore, direct effects due to extreme waves and indirect effects due to long waves must be taken into consideration for the long-term deployment of the system. To increase the system survivability and reduce the impact on the system dynamics, we must consider the controllability of system diving depth. Unfortunately, the how to control the system's diving depth is seldom considered in the design of ocean current turbine systems.

To control the diving depth of the system, we proposed in the present design the new concept of foil float which is not available in other ocean current turbine systems. The foil float is on the top of the system and connected to the turbine generator system by two vertical supports. Figure 3 shows the schematic of the foil float. Inside the foil float are installed four buoyancy engines with their openings on both of its sides. Water can flood in by opening the baffles or pumped out by the engines.

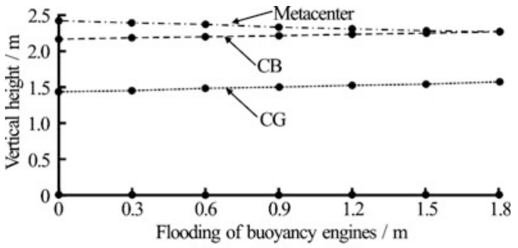


(a) Foil float structures and buoyancy engines

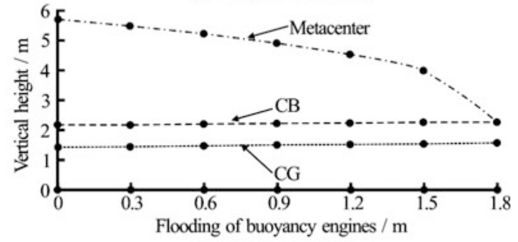


(b) Side view of the foil float with four and aft buoyancy engines

Fig.3 The foil float



(a) Longitudinal stability



(b) Transverse stability

Fig.4 Variation of CB and CG with flooding of buoyancy engines

With these four buoyancy engines, the net buoyancy of the system can be adjusted. There are several functions which can be performed through the foil float with these buoyancy engines. The distance between the center of buoyancy and the center of gravity can be increased so that the system stability can be raised. In contrast, the system proposed by NEDO, for example, can suffer from more serious stability problems. When the buoyancy engines are flooding for the system to submerge into the water, the variations of transverse and longitudinal centers of buoyancy and gravity are shown in Fig.4.

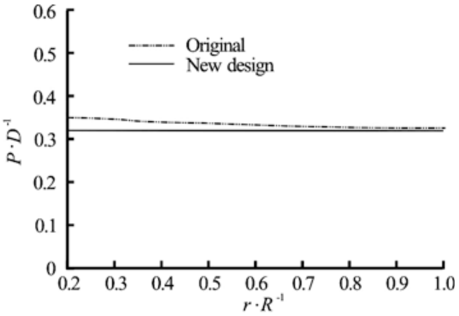
In addition, the system can be easily dive for operation by flooding water into the buoyancy engines or surface for retrieval/maintenance by pumping water out of them. Furthermore, by properly flooding water into the aft and fore buoyancy engines, we can adjust the relative angle of attack of incoming flow to the foil float so that it can produce dynamic lift to push the system dive even further or to surface even faster, depending on the sign of the relative angle of attack. Therefore, it provides a simple mechanism to enhance deep diving for survival in extreme weather conditions such as typhoons and surfacing.

2.2 *Turbine system*

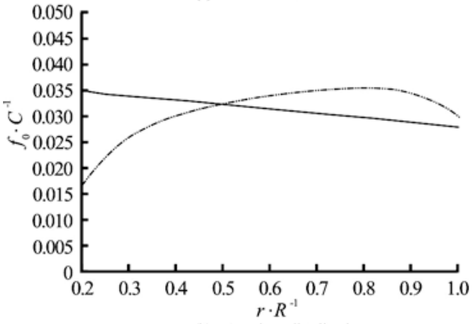
To maintain proper system stability during deployment, operation, and retrieval, the concept of a downwind turbine system is usually adopted. For a downwind turbine configuration, the nacelle naturally aligns itself with the wind direction even during blackout conditions. Furthermore, because the rotor orientation always aligns with updrafts, this provides high efficiency.

To generate significant amount of electric power in an ocean current flow at a relatively low speed of approximately 1.5 m/s, we need to develop a highly efficient underwater turbine. Furthermore, the system must be of floating tethered type due to great water depth at the possible operation site. A horizontal-axis turbine with a rated output of 20 kW for the 1/5 model turbine is then designed.

The turbine should be able to operate with high efficiency in power generation at various different operation states ranging from a low-current-speed state in which the turbine starts to operate to the maximum-current-speed state. Therefore, to design a proper turbine blade to fit the local current state is very important to harness the kinetic energy in a low-speed flow. For this purpose, we design the turbine blade and verify its performance by a series of numerical methods and towing-tank experiments. For the first step, two procedures are employed to design the turbine blade. The first one is similar to the propeller design method. Combining the Lagrange multiplier technique, we use the lifting line method for the design of the loading distribution and find the optimum circulation distribution. Then, we adopt the lifting surface method for the blade geometry design and find the pitch and camber distributions. Additionally, an alternative design procedure, the genetic algorithm method, is also employed to design the turbine blade geometry. The two design methods results in different pitch and camber distributions, as shown in Fig.5. Nevertheless, the differences of the two pressure coefficient distributions at different blade sections are usually not significant. Finally, hydrodynamic performances of the marine current turbine, such as the axial force, torque, and power, are then computed by both the potential flow boundary element method and the viscous flow RANS method. The two designs lead to almost the same power performance but somewhat different axial forces. In more details, the power is minutely bigger for the turbine blade designed by the genetic algorithm method but, oppositely, the axial force is bigger for the one by the propeller design method. Nevertheless, the design results show the geometries designed by the presented procedures satisfy the design goal. It is believed that both methods are applicable for the current turbine blade designs.



(a) Pitch distributions

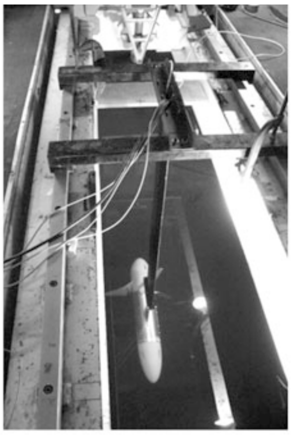


(b) Camber distributions

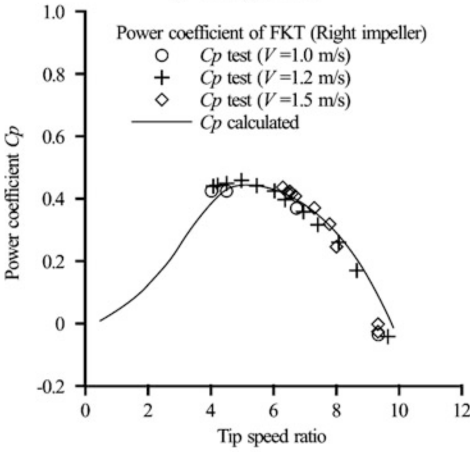
Fig.5 Pitch distributions (a) and camber distributions (b) of the two designs

We also study the effects of different number of blades. The numerical results by both the BEM and RANS methods show that three-bladed turbine has the best power performance.

Experiments are also conducted to verify the design. Shown in Fig.6, they are carried out in the towing tank with a 1/25 model turbine at National Taiwan University. The results show that the numerical prediction is consistent and agrees very well with the experimental data.



(a) Towing-tank test



(b) Power distributions

Fig.6 Experimental tests of the turbine

2.3 *System dynamics*

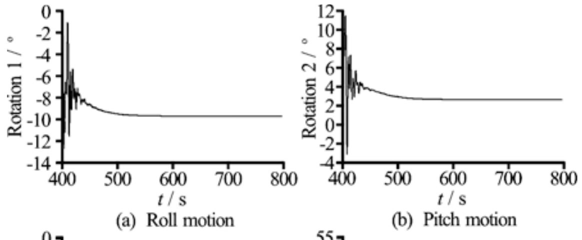
Due to the fact that ocean currents usually meander in the deep sea regions, one of the common features in harnessing the ocean current energy is the employment of floating tethered turbine system concept. For example, it is known that over 50% of the kinetic energy of Kuroshio is concentrated in its central core and within a depth of about 100m from the sea surface[16]. To harness the energy as much as possible, the system must submerge under the sea surface to reduce the impact of wave load and float at a proper depth in the deep ocean to take advantage of the strong Kuroshio.

For the current 1/5 model, the design operating depth is 10 m-40 m in the water of 50 m in depth from the water surface to the bottom. A mooring system is provided. Two mooring lines are connected to the foremost points of nacelles to the incoming current and join together with a connector to another mooring line which is then connected to the anchor on the bottom. Therefore, the mooring system consists of mooring lines of Y shape. The length of the main mooring line is 40 m long and each of the two auxiliary lines connecting the turbine system and the main line is 5 m long.

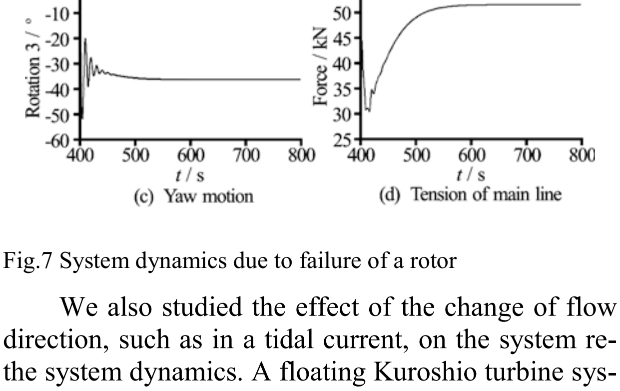
The FKT system is acted by several forces, including buoyancy, weight, drag force, dynamic lift force of the foil float, tension force from the mooring system, and force due to the motion of turbine. The dynamic motion of the system derives from the balance of these forces. It is important to evaluate the system dynamics subject to these varying forces.

To capture the system dynamic motion, we integrate several commercial and in-house packages. The system buoyancy and weight and their centers were estimated using the Rhino software. The system hydrodynamic coefficients were obtained through WAMIT, system drag coefficient through FLUENT, turbine propulsive force through lifting surface code, and system dynamics through OrcaFlex. Several scenarios in association with the deployment, effects of ever-changing ocean environments, and unexpected system failures were studied.

As some examples, Fig.7 shows the system response due to a sudden failure of a turbine. The turbine is not functioning and stops its operation in a moment. These results show that, after violent process of motion, the system finally reaches a stable and askew state which is neither horizontal nor normal to the incident current. For the final stable state, the system tilts in all three directions. It rotates about 9°, 2.7° and 37° about x-, y- and z-axis, respectively. The new balanced state is highly askew to the incoming incident current. Furthermore, the abrupt stop of the turbine induces a stronger oscillation of system motion.



(a) Roll motion (b) Pitch motion



(c) Yaw motion (d) Tension of main line

Fig.7 System dynamics due to failure of a rotor

We also studied the effect of the change of flow direction, such as in a tidal current, on the system responses. Figure 8 shows the current speed variation in time. Figure 9 shows the system dynamics. It is found that the transient pitching and rolling motions can be very significant. However, the system finally reverses its direction to align with the current direction and settles down. In the transient motion, the tension force of the mooring line reaches its maximum of about 120 kN which is much larger than the one in the normal operation. In fact, the present simulation shows an abrupt change of yaw angle after the current fully reverses. This is due to the fact that the simulation is conducted with a perfectly symmetric flow condition. This is physically implausible and not realistic. In the real world, the flow condition is not symmetric and, therefore, such an abrupt change could not possibly happen. Nevertheless, the present study shows that even suffered from a violent change, the system can finally reach its new stable position. This somehow shows the system robustness in the changing ocean.

the system dynamics. A floating Kuroshio turbine sys-

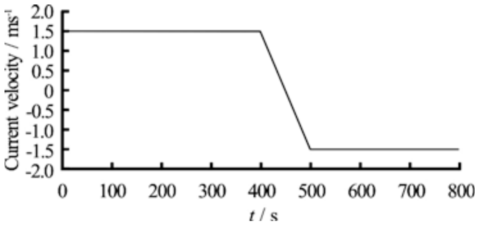
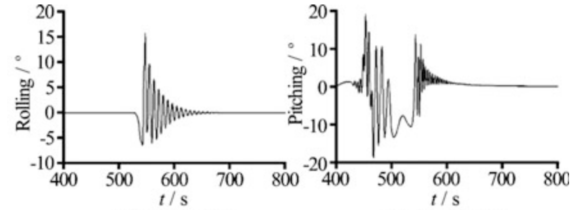
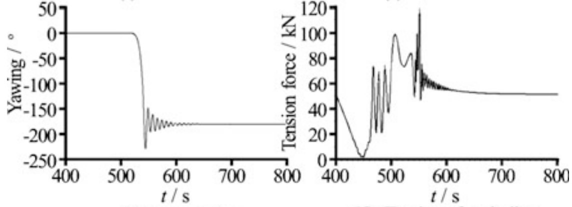


Fig.8 Current speed variation in time



(a) Roll motion (b) Pitch motion



(c) Yaw motion (d) Tension of main line

Fig.9 System response due to the current direction change

3. Conclusion

Some important hydrodynamic features in the design of an ocean current turbine system have been discussed in the present paper. They include the diving control, the turbine blade design of high efficiency, and

tem which is being under development in Taiwan is adopted as a study case to address these hydrodynamic issues. To cope with these issues, we may integrate various existing computational tools for design and analysis purposes.

Acknowledgement

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References

[1] http://www.independent.com/news/2010/sep/20/carpinteria-business-obtains-grant-develop-clean-o/. [EB/OL].

[2] http://wdstudio.net/gulfstreamturbine/index.htm. [EB/OL].

[3] http://www.businesswire.com/news/home/20141224005313/en/IHI-Toshiba-Launch-Demonstration-Research-Ocean-Current. [EB/OL].

[4] Bai J.-Y. Ocean current power generation project [C]. *Workshop on Development of Marine Mechanical Energy Industry in Taiwan*. Keelung, 2012(in Chinese).

[5] http://public.eng.fau.edu/design/news-archive/archive/2010-2009/1008_coet.php. [EB/OL].

[6] https://groups.oist.jp/qwmu/research. [EB/OL].

[7] Fleming A. Aquantis ocean current turbine development: Innovative power generation technology [R]. Dehlsen Associates, LLC, Santa Barbara, Washington DC, USA: CA and US Department of Energy, 2014.

[8] Cribbs A. R. Model analysis of a mooring system for an ocean current turbine testing platform [D]. Master Thesis, Boca Raton, USA: Florida Atlantic University, 2010.

[9] Driscoll F. R., Alsenas G. M., Beaujean P. P. et al. A 20 kW open ocean current test turbine [C]. *IEEE Oceans 2008*. Quebec City, Canada, 2008.

[10] Robson J. H. Submersible electrical power generating plant [P]. US Patent, No. 6531788, 2003.

[11] Robson J. H. Submersible electrical power generating plant [P]. US Patent, No. 7691936, 2007.

[12] Takagi K., Waseda T., Nagaya S. et al. Development of a floating current turbine [C] *IEEE Oceans 2012*. Hampton Roads, VA, USA, 2012.

[13] Kubo K., Nakamura K., Ueno T. et al. Development of blade for floating type current turbine system [C] *IEEE Oceans 2014*. St. John's, Canada, 2014.

[14] Shirasawa K., Tokunaga K., Iwashita H. et al. Experimental verification of a floating ocean current turbine with a single rotor for use in Kuroshio currents [J]. *Renewable Energy*, 2016, 91: 189-195.

[15] Chen Y.-Y., Bai J.-Y., Chen C.-Y. et al. Efficiency verification for the ocean current power system [C]. *2014 Taiwan Wind Energy Conference*. Taipei, 2014 (in Chinese).

[16] Chen F. The Kuroshio Power Plant [M]. Berlin, Germany: Springer, 2013.

[17] Chang L.-Y., Chen F., Tseng K.-T. Dynamics of a marine turbine for deep ocean currents [J]. *Journal of Marine Science and Engineering*, 2016, 4(4): 59.

[18] Tzelepis V. Electromechanics of an ocean current turbines [D]. Master Thesis, New Orleans, LA, USA: University of New Orleans, 2015.