Hydrodynamic Performance of a Towed Floating Kuroshio Current Turbine

Jing-Fa Tsai*[1], Yi-Hsiang Liao*[2], Forng-Chen Chiu*[3]

*Department of Engineering Science and Ocean Engineering, National Taiwan University
No. 1, Sec.4, Roosevelt Road, Taipei, Taiwan

[1]jftsai@ntu.edu.tw

[2]r05525015@ntu.edu.tw

[3]fcchiu@ntu.edu.tw

Abstract— **A 20 kW floating current turbine prototype was designed for operation in the Kuroshio Current, which passes along the eastern coast of Taiwan. The location and speed of the Kuroshio Current are generally consistent, which offers Taiwan a stable and secure energy source. A test apparatus, including a 1/5 scale model of the proposed turbine with a direct drive permanent magnet generator, was used to measure the rotation, torque and thrust. The test was conducted in a towing tank at four loads of 728, 364, 242, and 182 ohm. The tension force of the towing rope was measured using a tension meter. The pitch and roll angles of the floating current turbine were measured with angle meters. The power coefficient, torque coefficient, thrust coefficient and total efficiency were calculated from the measured data. The measured power coefficient and torque coefficient agreed with the calculated results. However, the measured thrust coefficient was higher than the calculated values. The hydrodynamic efficiency of the turbine was approximately 0.45, which meets the design requirements.**

***Keywords*— Kuroshio Current, Current Turbine, Hydrodynamic Performance, Power Coefficient, Thrust Coefficient**

I. INTRODUCTION

According to the Global Climate Report of NOAA, the annual average global temperature increased by 0.99℃ in 2016 [1]. The earth is suffering the impacts of global warming, such as melting of ice at the poles, rise in sea levels, and strong hurricanes and typhoons. Global warming is caused by the emission of greenhouse gases, which are generated by the burning of fossil fuels. To address the critical issue of global warming, the United Nations Framework Convention on Climate Change established Kyoto Protocol [2], Copenhagen Accord [3] and COP21 [4] to curb climate change and limit the emission of greenhouse gases. To reduce greenhouse gas emissions, eco-friendly renewable energy is required. Numerous types of renewable energy can be obtained from the ocean, such as wind, wave, tidal, current and ocean thermal energy. Wind power is a mature technology that is well established on land. Offshore wind farming is under development, and has the potential to become a major contributor to the electrical energy market [5]. However, technologies to harvest other forms of ocean energy, such as tidal, wave and current energy, are still in their infancy. Stability is often a major challenge with regard to renewable energy. Tidal current occurs once or twice a day and persist for inconsistent periods of time, and wave depends on the weather. By contrast, ocean currents, which are continuous directed movements of seawater, are a stable and dependable form of ocean energy. Currents flow for considerable distances and play a dominant role in determining the climate of many regions.

The Kuroshio Current is a north-flowing ocean current on the west side of the North Pacific Ocean. It begins off the east coast of Luzon, Philippines, and passes along the eastern coast of Taiwan and Japan as it flows northeast, where it merges with the easterly drift of the North Pacific Current. The Kuroshio Current is the most important current in the seas east of Taiwan. The Current is stable and carries a large amount of ocean energy. Hydrographic surveys [6] have revealed that the distance of the high velocity core from the coast of Taiwan at 23.75° N is 30-120 km with maximum current speeds of 0.6-1.2 m/s. In a study performed in 1990, the transport speed varied between 15 and 26 Sv (1 Sv = 10^6 m^3/s) [6]. The total average power (P) of the Kuroshio Current can be estimated using the following formula:

$$P = \frac{1}{2}\rho A V^3 = \frac{1}{2}\rho S V^2 \qquad (1)$$

In equation (1), ρ is the average density of seawater, V is the average flow velocity, A is the cross-sectional area of fluid passage, and S is the average volumetric flow rate. According to the survey of Chen [7], the total energy approaches 5.5 GW when the flow velocity is higher than 1 m/s.

Floating current turbine generator sets are a new technology for the development of ocean current energy. Deep Green, is a floating current generator developed by the Swedish company Minesto. Currents are used in the wings to generate dynamic lift to allow the crew to produce ∞-shaped trajectory movements. The turbine is accelerated to increase the power generation efficiency. The estimated power generation of the turbine is 500 kW. The turbine is currently in the commercialization stage [8]. The Aquantis Current Plane ("C-Plane") [9] was developed to operate in the Gulf Stream off the coast of Florida, United States. A floating type ocean current turbine system is under development in Japan [10]-[12]. The system has a pair of counter-rotating rotors that are connected by a cross beam. To avoid destruction due to extreme weather caused by typhoons, the device is moored using a mooring line to enable a weathervane function. The device is installed approximately 100 m deep to avoid the influence of surface waves. Wan-Chi Steel Industrial Company in Taiwan has also proposed an ocean current energy converter for operation in Kuroshio Current [13].

In this study, a 20kw floating current turbine prototype was proposed to operate in the Kuroshio Current flowing along the coast of Taiwan. A 1/5 model was constructed for conducting the hydrodynamic performance test in a towing tank to validate the design requirements. Tsai and Zeng [14] performed the hydrodynamic performance test for a single turbine using a torque simulator. In this study, a floating current turbine model set, which includes two counter-rotating blades, two direct drive permanent magnet generators inside two nacelles, and a foil type floater, was towed using a mooring line fixed in the support at the towing carriage to conduct the hydrodynamic performance test. The hydrodynamic performance of the floating current turbine was determined in the test.

II. Proposed Kuroshio Current Turbine

The 20 kW current turbine comprises five components, namely the foil floater, vertical support, cross beam, nacelle of a direct drive permanent magnet synchronous generator and downwind counter-rotating rotors (Figure. 1).

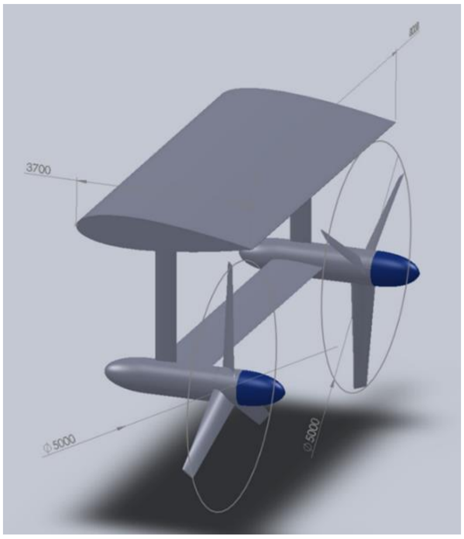

Fig.1 Proposed 20 kw Kuroshio current turbine

The principal dimensions of the 20 kW Kuroshio Current turbine are provided in Table I. The diameter of the rotor was 5 m and the blade was made of the NACA 66 foil section. The chord length of the foil floater was 4 m with the NACA0018 section and the span was 8 m. The length of the nacelle was 6 m. The distance between two nacelles was 7.5 m. The designed rotation speed of the rotor was 30 RPM. The corresponding principal dimensions of the 1/5 scale model turbine are also provided in the Table I. The power of the 1/5 scale model was 800 W and the rotation speed was 150 RPM.

Table I
Principal Dimensions of the Kuroshio Current Turbine

Item	**Prototype (20kw)**	**Model Scale (1/5 800w)**
Foil Floater	Chord 4m, Span 8m	Chord 0.8m, Span 1.6m
Foil Section	NACA0018	NACA0018
Diameter of Nacelle	1.2m	0.24m
Length of Nacelle	6m	1.2m
Length Between Nacelles	7.5m	1.5m
Length of Crossbeam	6.3m	1.26m
Diameter of Rotor	5m	1m
Section of Blade	NACA66	NACA66

III. Hydrodynamic Performance Parameters

The hydrodynamic performance of the current turbine can be assessed by examining the relationships of the power, torque and thrust coefficients with the tip speed ratio of the turbine using the axial momentum theory. The power coefficient is defined as follows:

$$C_p = \frac{P}{\frac{1}{2}\rho U_0^3 A} \quad (1)$$

where P is the power generated by the turbine, U_0 is the inflow velocity, and A is the section area of the turbine. The torque coefficient is defined as follows:

$$C_Q = \frac{Q}{\frac{1}{2}\rho U_0^2 A} \quad (2)$$

where Q is the torque generated by the turbine. The thrust coefficient is defined as follows:

$$C_A = \frac{A}{\frac{1}{2}\rho U_0^2 A} \quad (3)$$

where A is the axial force which includes the thrust and drag force produced by the turbine. The tip speed ratio is defined as follows:

$$\lambda = \frac{\omega R}{U_0} \quad (4)$$

where ω is the rotation speed and R is the radius of the rotor. The power coefficient is the product of the torque coefficient and tip speed ratio.

$$C_P = C_Q * \lambda \quad (5)$$

The hydrodynamic performance coefficients of the current turbine can be calculated using numerical methods or a model test. The numerical method RANS was used to calculate the hydrodynamic performance coefficients [15]. The calculated results are displayed in Fig.2. The maximum power coefficient was 0.445 when TSR was 5.236. The maximum torque coefficient of 0.094 occurred when the TSR was 4.620. The maximum thrust coefficient of 0.759 occurred when the TSR was 5.236. The total efficiency is the product of the power coefficient and electrical generator efficiency.

$$\eta_T = C_P * \eta_G \qquad (6)$$

where η_G is the efficiency of the electrical generator.

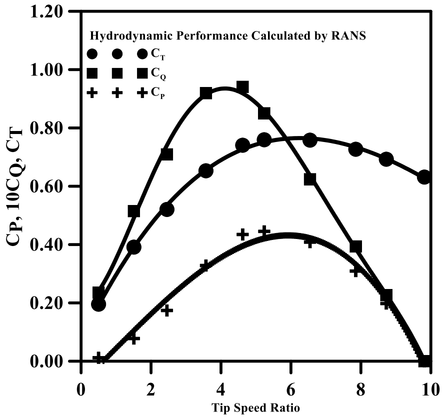

Fig.2 Hydrodynamic performance Calculated using RANS

IV. Test -Apparatus

The test apparatus is displayed in Fig.3. The Kuroshio Current turbine was towed using a towline fixed at the foil support which was 2 m below the free surface. A tension meter was used to measure the tension force at the towline.

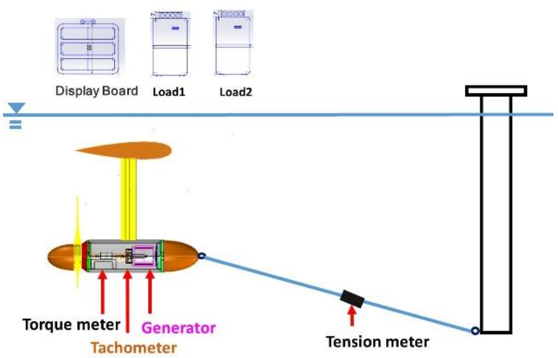

Fig.3 Schematic diagram of the test apparatus

Inside of the nacelle featured a torque meter, tachometer and direct drive permanent magnet generator. The torque meter was used to measure the torque generated by the rotor. The tachometer was used to measure the rotation speed of the rotor. Two loads were used for the two direct drive permanent magnet generators. Each load consisted of four 728 ohm resistors in parallel that could generate four loads (ie., 728, 364, 262 and 182 ohm) for each direct drive permanent magnet generator. A display board was used to measure and display the power generated by the direct drive permanent magnet generator. The display board displayed the powers generated by each generator and the total power generated by the two generators (Fig.4). A two-dimensional angle meter located at the middle of the cross beam (Fig.5) was used to measure the pitch and roll angles of the turbine. All of the sensors were calibrated before the test was conducted. Table II provides the calibrated slope and 95% confidence interval for all sensors.

Fig.4 Power display board


Fig.5 Test model with a two-dimensional angle meter

Table II
Calibration results of the sensors

	Slope	95% Confidence interval
Tension meter	0.020(V/kg)	1.96(Kg)
Torque meter(Clockwise)	0.009(V/kg-cm)	2.83(Kg-cm)
Torque meter(Counter-Clockwise)	0.008(V/kg-cm)	4.46(Kg-cm)
Pitch meter	0.233(V/Deg.)	0.50 Degree
Roll meter	0.235(V/Deg.)	0.34 Degree

V. TEST RESULTS

The performance tests were conducted by applying four loads (728, 364, 262 and 182 ohm) to the generator. The towing speeds were varied for each load to generate different rotation speeds for the rotor and different tip speed ratios. The tip speed ratio ranged between 4 and 9 for the combination of the applied loads and towed speeds. The torque, tension force, pitch and roll were measured for each test. The power was calculated using equation (5). The power coefficient, torque coefficient, thrust coefficient, and total efficiency were calculated using the measured parameters. Figures 6 and 7 display the power coefficient of the clockwise and counter-clockwise rotors, respectively. The measured power coefficients agreed with the calculated power coefficients by RANS. Figures 8 and 9 display the torque coefficients of the clockwise and counter-clockwise two rotors, respectively. The torque coefficients also agreed the calculated results. However, the peak values were higher than the calculated values when the tip speed ratio was approximately 4.5. Figures 10 and 11 display the measured axial forces of the two rotors. The measured axial forces were larger than the calculated values.

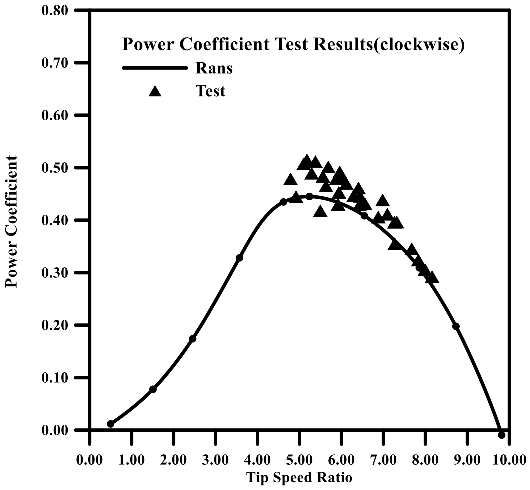

Fig.6 Measured power coefficients of the clockwise rotor

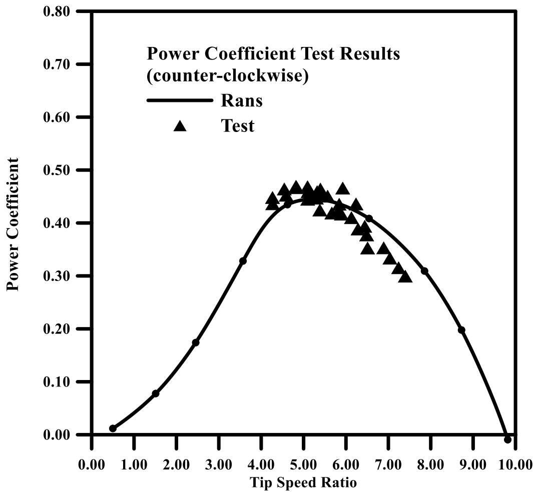

Fig.7 Measured power coefficients of the counter-clockwise rotor

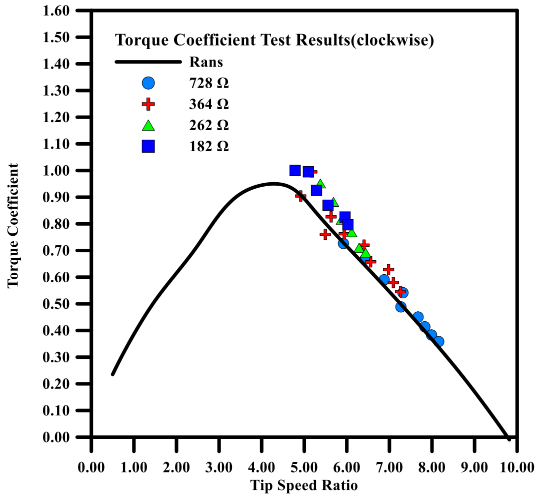

Fig.8 Measured torque coefficients of the clockwise rotor

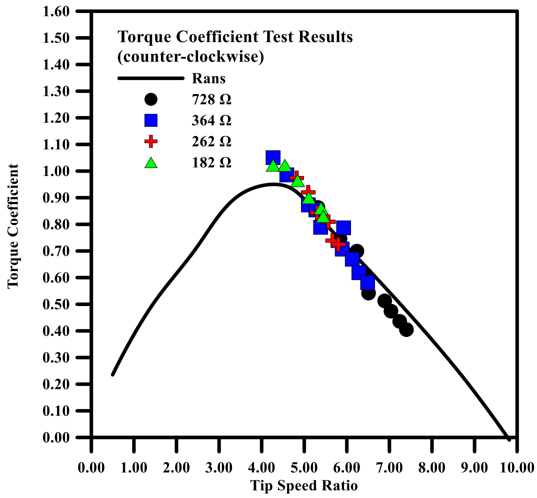

Fig. 9 Measured torque coefficients of the counter-clockwise rotor

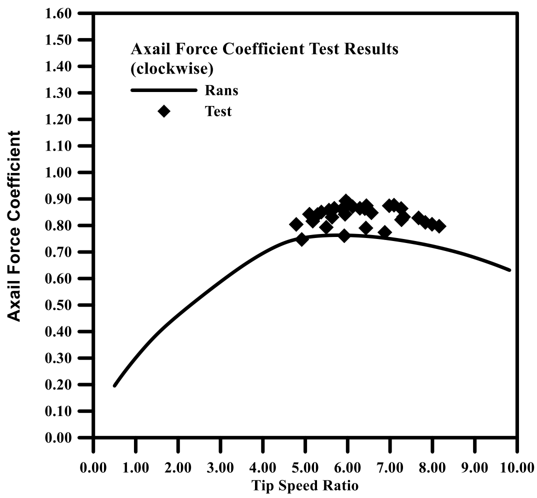

Fig.10 Measured axial forces coefficients of the clockwise rotor

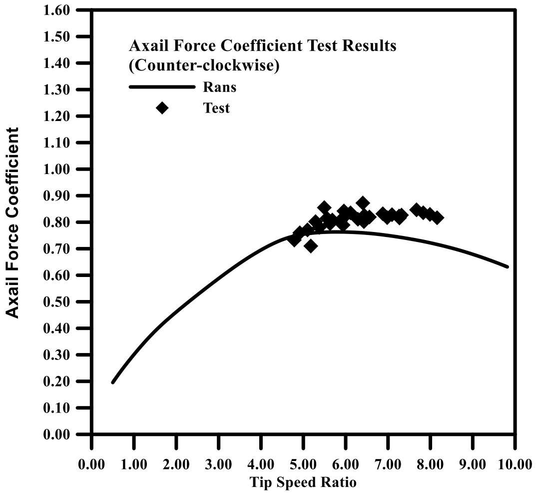

Fig.11 Measured axial force coefficients of the counter-clockwise rotor

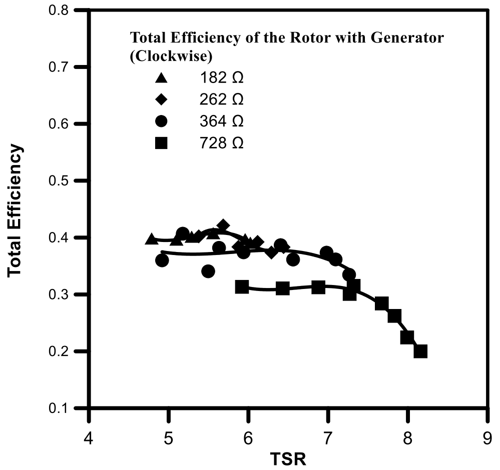

Fig.12 Measure total efficiency of the clockwise rotor with a generator

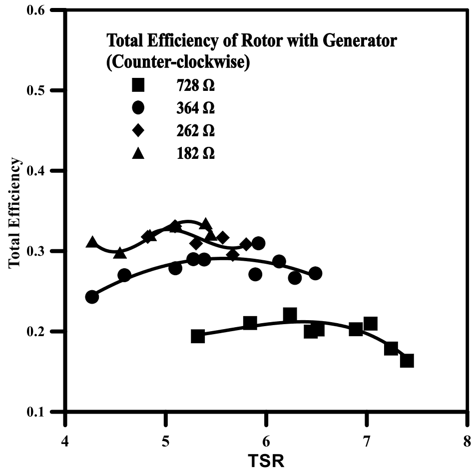

Fig.13 Measured total efficiency of the Counter-clockwise rotor with a generator

Figures 12 and 13 illustrate the total efficiency of the rotors with a generator. The total efficiency of the clockwise rotor with a generator was higher than that of the counter-clockwise rotor with a generator. The power coefficients of the two rotors were approximately the same (Figs.6 and 7). However, the efficiency of the clockwise generator was higher than that of the counter-clockwise generator (Figs.14 and 15). This may be due to imperfections in the manufacture of the direct drive permanent magnet generator. The maximum electrical efficiencies of the clockwise and counter-clockwise generators were approximately 0.88 and 0.73, respectively.

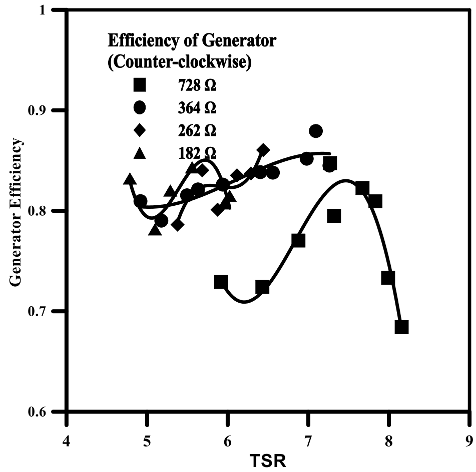

Fig.14 Efficiency of the clockwise generator

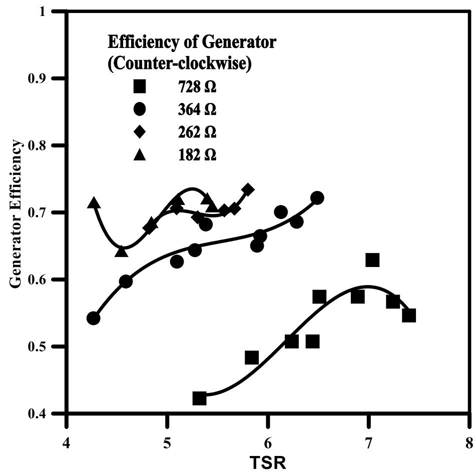

Fig.15 Efficiency of the Counter-clockwise generator

VI. Conclusions

An 800 W floating Kuroshio Current turbine model was used to conduct the performance test of the rotor with a direct drive permanent magnet generator in towing tank. The performance tests were conducted by applying four loads (728,384,262 and 182 ohm) to both the generators. The following conclusions can be drawn from the test results and analysis.

1. The measured power and torque coefficients agreed with the values calculated using RANS.
2. The measured axial force coefficients were higher than values calculated using RANS. Further studies are required to explain this phenomenon.
3. The electrical efficiency of the clockwise generator is higher than that of the counter-clockwise rotor. This may be due to imperfections in the manufacturing of the generator.

ACKNOWLEDGMENT

This research funded by the Ministry of the Science and Technology, Taiwan, under the grant MOST 106-3113-E-002-020-CC2.

REFERENCES

[1] NOAA National Center for Environmental Information, State of the Climate: Global Climate Report for Annual 2017, published online Jan., 2018, https://www.ncdc.noaa.gov/sotc/global/201713.
[2] United Nations. 1998 Kyoto Protocol to the United Nations Framework Convention on Climate Change, unfccc.int/kyoto_protocol/
[3] United Nations. 2009, Copenhagen Accord Framework Convention on Climate Change, unfccc.int/resource/docs/2009/cop15/
[4] United Nations, 2015 UNFCCC COP 21 Paris France - 2015 Paris Climate Conference, www.cop21paris.org/
[5] A. Smith, T. Stehly, and W. Musial, 2015 2014–2015 Offshore Wind Technologies Market Report, Technical Report, NREL/TP-5000-64283, September.
[6] Y.C. Hsin, C.R. Wu, and P.T. Shaw, 2008, "Spatial and Temporal Variations of the Kuroshio East of Taiwan,1982–2005: A Numerical Study," Journal of Geophysical Research, Vol. 113.
[7] F. Chen, 2010," Kuroshio Power Plant Development Plan," Renewable and Sustainable Energy Review, 14, pp.2655-2668.
[8] Minesto, Deep Green Technology. [cited 2017; Available from: http://www.minesto.com.
[9] A. Fleming, Aquantis Ocean Current Turbine Development: Innovative Power Generation Technology, Dehlsen Associates, LLC, Santa Barbara, CA and US Department of Energy, Washington, DC 2014.
[10] K. Takagi, K. Waseda, T. Nagaya, S. Niizeki, and Y. Oda," Development of a Floating Current Turbine," IEEE Oceans 2012, Hampton Roads, VA, USA, 2012.
[11] K. Kubo, K. Nakamura, T. Ueno, Y. Kabat, and S. Nagaya, "Development of Blade for Floating Type Current Turbine System," IEEE Oceans 2014, St. John's, Canada, 2014.
[12] K. Shirasawa, K. Tokunaga, H. Iwashita, and T. Shintake," Experimental Verification of a Floating Ocean Current Turbine with a Single Rotor for use in Kuroshio Currents," Renewable Energy, 2016, 91, 189-195.
[13] Y.-Y. Chen, J.-Y. Bai, C.-Y. Chen, R.-Y. Yang, H.-C. Hsu, K.-C. Yang, C.-W. Su, S.-H. Chen, and Y.-C. Yang, "Efficiency Verification for the Ocean Current Power System," 2014 Taiwan Wind Energy Conf., Taipei, Taiwan, 2014 (in Chinese).
[14] J. F. Tsai and Y.X. Zeng, "Experimental Study on the Performance of a Floating Kuroshio Current Turbine," Ocean and Underwater Technology Quarterly, 2017, Vol. 27, No.1, pp50-56.
[15] C.Y. Hsin, S.Y. Wang, J.H Chen and F.C. Chiu, "Design of Floating Kuroshio Turbine Blade Geometries," Journal of Taiwan NSAME, 2016, Vol.35, No.3, PP.145~153.