Open Access

Journal of Energy and Power Technology

LIDSEN Publishing Inc.

Original Research

Advancing Marine Renewable Energy for Island Nations: Design and Development of a 20 kW Floating Kuroshio Turbine (FKT)

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Academic Editor: Andrés Elías Feijóo Lorenzo

Collection: Optimal Energy Management and Control of Renewable Energy Systems

Journal of Energy and Power Technology
2025, volume 7, issue 4
doi:10.21926/jept.2504017

Received: September 15, 2025
Accepted: December 07, 2025
Published: December 10, 2025

Abstract

Taiwan relies heavily on imported fossil fuels, with over 98% of its energy demand supplied by foreign sources, posing significant challenges to national energy security. To explore alternatives, this study investigates the potential of marine renewable energy by developing a 20 kW floating hydrokinetic turbine prototype designed for deployment in the Kuroshio Current. The research encompasses system design, model validation, and both tank and at-sea testing to evaluate hydrodynamic performance and power generation efficiency. A parametric design approach, combined with controlled tank experiments and in-situ monitoring, was employed to assess turbine behavior under various flow conditions. During sea trials, the turbine achieved blade rotational speeds of approximately 30 rpm at 2.5 knots and nearly 40 rpm at 3 knots of vessel-relative water velocity. Power generation reached 10 kW at 40 rpm under a 5 kW load, and 12 kW at 32 rpm under a 10 kW load, demonstrating a proportional relationship between rotational speed and electrical output. These experimental results confirm the technical feasibility of energy conversion from the Kuroshio Current and provide valuable reference data for the future design and optimization of commercial-scale hydrokinetic energy systems.

Keywords
Kuroshio current energy; marine renewable energy; floating Kuroshio turbine; open-sea testing; commercial-scale ocean energy

1. Introduction

The excessive use of fossil fuels has accelerated global warming and depleted non-renewable energy resources, prompting an urgent global pursuit of clean, renewable alternatives. Among renewable energy sources, ocean energy has emerged as a promising candidate due to its higher energy density compared to wind. Ocean energy can be categorized into four types: ocean current energy, ocean thermal energy conversion (OTEC), tidal energy, and wave energy. Of these, ocean current energy offers substantial potential through the direct conversion of the kinetic energy of marine currents into electricity. A notable example is the Kuroshio Current, which flows with relatively stable velocity.

The Kuroshio Current, the most significant ocean current in the North Pacific, passes along the eastern coast of Taiwan with a width of 120-170 km. As it flows between Taiwan's east coast and Green Island, the current maintains a velocity of approximately 1.0 to 1.5 m/s, with a transport volume of 20.7 to 22.1 Sv (10^6 m^3/s) [1]. Green Island is a small volcanic island located roughly 33 km off Taiwan's eastern shore. Previous estimations have suggested that the exploitable energy potential in this region could reach at least 30 GW [2-4]. Despite the considerable energy potential of the Kuroshio Current, harsh marine conditions and the technical challenges associated with the construction and operation of ocean energy systems have significantly constrained development in this region. Although several types of marine current turbines have been successfully developed in recent years [5-8], most of these designs are optimized for flow velocities above 2.0 m/s—conditions typical of tidal channels—thus limiting their effectiveness in the moderate flow regime of the Kuroshio Current, where the average velocity generally remains below 1.5 m/s. To address these challenges, many countries have intensified research and development efforts in ocean energy technology. Among these initiatives, the Ocean Current Turbine (OCT) has been developed in Europe and has been suggested to achieve stable operation at depths of up to 90 m and within a current velocity range of 0.5-2.5 m/s [9-11].

IHI Corporation has successfully developed a 100 kW Kairyu turbine based on a floating-type ocean-current turbine concept and has performed comprehensive experimental assessments. The turbine's power generation capability was validated through towing and mooring trials in open water environments [12, 13]. Alongside the two-rotor design, a single-rotor ocean current turbine was also engineered and tested in Japan. This configuration features a float positioned at the top and a counterweight at the bottom, which work together to mitigate rotor torque during operation. Towing tests confirmed the system's stability and demonstrated effective blade performance [14, 15].

This study introduces the design, fabrication, and performance testing of a novel Floating Kuroshio Turbine (FKT) system in Taiwan. The research encompasses two stages: (1) scaled model testing of a 1/25 small-scale prototype in a controlled flume environment, and (2) full-system development and sea-trial validation of a 1/5-scale, 20 kW-class prototype through towed testing in open water. These efforts aim to verify both the technical feasibility and economic viability of the system, providing critical data to guide the development of commercial-scale demonstration units for long-term field deployment. Through the development of the 20 kW-class floating Kuroshio turbine system, this project has established a collaborative academic-industry research team capable of designing and analyzing marine current turbine and mooring systems. The work validates the feasibility of the proposed innovative floating turbine design, generates key intellectual property, and contributes to the strategic technology roadmap for Taiwan’s emerging marine current energy sector. The outcomes of this project are expected to facilitate industry engagement, promote localized manufacturing of core components, and accelerate the development of integrated ocean energy systems.

2. Materials and Methods

During the NEPII project, CFD simulations were performed to analyze the hydrodynamic behavior of the turbine rotor and flow interaction with the supporting structure. The CFD results were used to establish the preliminary performance estimates and to provide the basis for subsequent development of the prototype. In addition, an 800 W scaled turbine was fabricated and tested in a circulation water tank, and its hydrodynamic characteristics were experimentally validated as reported in [16]. In the present study, therefore, no additional CFD simulations were conducted. The design of the 20 kW turbine was instead refined based on the previously validated CFD results and the 800 W tank test data. Its performance was further evaluated through new tank experiments and verified in sea trials, which confirmed that the turbine meets the intended power production targets.

2.1 Development of Floating Kuroshio Turbine (FKT)

The development of the Floating Kuroshio Turbine (FKT) system was initiated under the National Energy Program–Phase II (NEP-II), funded by the Ministry of Science and Technology, Taiwan, from 2015 to 2017. This program supported a collaborative research effort involving National Taiwan University, National Taiwan Ocean University, the Taiwan Institute of Economic Research, and the Taiwan International Shipbuilding Corporation. The primary objective of the program was to design and develop a prototype floating Kuroshio current turbine system. In 2018, the research team completed towing tank validation tests of an 800 W FKT prototype (Figure 1). The experimental results showed good agreement with the computational predictions, confirming the validity of the hydrodynamic design [16]. Based on these results, the team proceeded to develop a 20 kW FKT system.

Figure 1 800 W FKT prototype.

2.2 Progress in Marine Current Turbine Design and Full-Scale Sea Trials in Taiwan

Following the establishment of the Ocean Affairs Council in 2019, the "Marine Current Energy Key Technology Development Program" was launched to promote marine energy technologies further. During this phase, three critical technologies were developed: (1) the design and fabrication of a 10 kW direct-drive permanent magnet synchronous generator, (2) the hydrodynamic design and manufacturing of fiber-reinforced plastic (FRP) turbine blades, and (3) the development of a passive hydraulic compensator-based watertight shaft seal system. the National Academy of Marine Research (NAMR) continued the four-year development plan from 2020, In collaboration with National Taiwan University, leading to the construction of a 10 kW FKT prototype (Figure 2) [17, 18], Towing test of real sea were conducted off the coast of Anping, Taiwan, including towing-based power generation tests and submersion tests at a depth of 60 meters, confirming both power generation efficiency and operational depth capacity. In 2021, the team completed development of a 20 kW FKT system (Figure 3) [18, 19], including a critical buoyancy-control system that enables autonomous submergence and resurfacing to avoid Extreme Climate (typhoon) damage. Full-scale sea trials off Kaohsiung verified both the generator performance and its storm-avoidance capabilities.

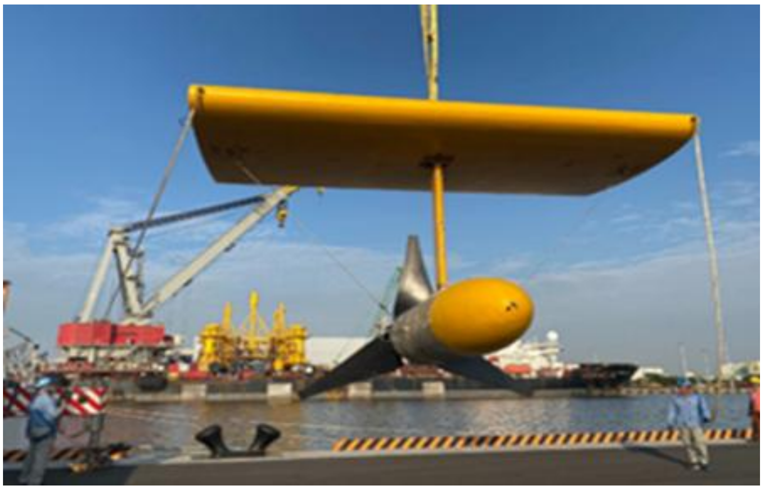
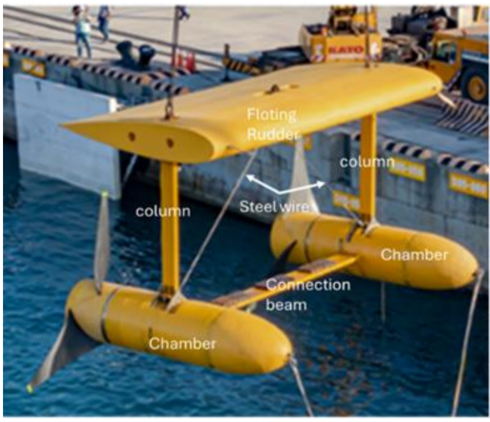


Figure 2 10 kW FKT.

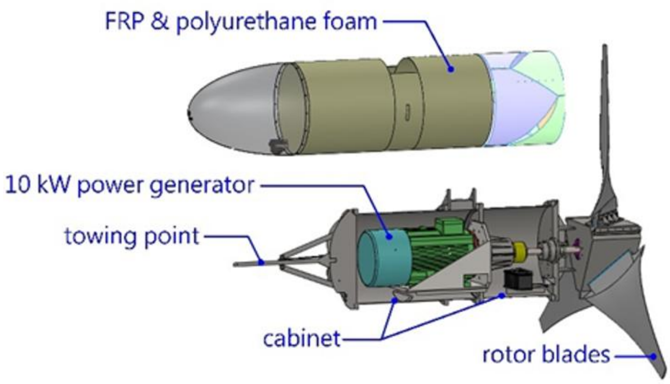


Part	Dimension
Chord line of floating rudder/Length	4m/8m
Profile of floating rudder	NACA0018
Diameter of Chamber	1.5m
Dimension between two Chamber	7.5m
Diameter of Rotor	5m
Profile of Rotor	NACA66

Figure 3 20 kW FKT.

The 20 kW Floating Kinetic Turbine (FKT) module developed in this study (Figure 3) features a modular architecture consisting of two generator chambers, a central connection beam, two vertical support columns, and a wing-shaped floating rudder. The two chambers are connected by the connection beam and vertically mounted to the floating rudder through the twin support columns. To ensure structural integrity during underwater operation and towing, each support column is fabricated using a pair of parallel H-beams. Additionally, 16 mm stainless steel wire ropes are installed on both sides of the nacelles as reinforcement elements. Both the top and bottom ends of the columns are structurally reinforced to enhance the system's resistance to hydrodynamic and mechanical forces.

Each chamber is constructed from SUS 304 stainless steel with a sealed bolted cover (Figure 4A). Considering the 1:5 scale model's intended operational depth range of 10 to 50 meters, the chamber and its cover are designed to withstand external hydrostatic pressure of at least 6 bar. Finite element analysis (FEA) and pressure resistance simulations confirmed that the chamber body and cover can endure up to 11 bar and 9 bar, respectively. The outer surface of the chamber is coated with fiber-reinforced plastic (FRP) and is affixed with high-buoyancy foam, which adds approximately 400 kg of positive buoyancy. This design improves hydrodynamic shaping and minimizes flow disturbances, thus enhancing overall energy conversion efficiency. The fully assembled chamber is shown in Figure 4B.



A

B

Figure 4 A. Design of 10 kW chamber. B. Assembly of 10 kW chamber.

Internally, each chamber houses a 10 kW permanent magnet synchronous generator, a drivetrain system, a torque sensor, associated control and sensing units, and a set of FRP turbine blades. The blade geometry is optimized to achieve a rated generator speed of 30 rpm under a 1.5 m/s inflow velocity, yielding 10 kW of electrical power. Based on the calculated blade swept area and axial force coefficient, the peak thrust exerted on the blades is estimated at 2,027 kg. To accommodate this load, the drivetrain incorporates two tapered roller bearings, each rated for dynamic loads up to 17,600 kg, ensuring robust support for both axial and radial loads on the main shaft.

The rotor and three-blade assembly have a combined mass of approximately 520 kg. The main shaft is fabricated from grade 630 stainless steel, heat-treated to H1150, and finished with hard chromium plating to enhance its mechanical strength and wear resistance. After the nacelle was fully assembled, harbor measurements indicated that the total submerged weight of the nacelle and its internal components was approximately 6,854 kg. Accordingly, the wing-shaped floating rudder was designed to provide a buoyant force of at least 7,539 kg, corresponding to approximately 10% greater than the measured submerged weight. This buoyancy margin ensures that the aerodynamic wing surface remains above the water surface under static conditions.

The floating rudder structure comprises an FRP shell and cover plate filled with high-pressure flotation material capable of withstanding hydrostatic pressure at depths of up to 50 meters. This material maintains stable buoyancy and resists performance degradation due to volumetric compression. To enhance structural stiffness, a central H-beam steel spine is integrated into the rudder. This spine not only reinforces rigidity but also serves as the primary load-bearing member for system lifting and column attachment. To enable automatic depth control, the fore and aft sections of the H-beam spine are equipped with buoyancy regulation module compartments, enclosed with FRP panels. These ensure the continuity of the streamlined airfoil profile and help preserve optimal hydrodynamic performance during deployment and operation.

3. Innovation and Advantages of the Floating Kuroshio Turbine (FKT) System

To address the specific energy resource potential of the Kuroshio Current, this study presents a novel configuration of a floating marine current turbine. It establishes a comprehensive system integration framework and design flowchart (Figure 5), including design and performance validation. The proposed turbine system consists of five principal components (dimensions shown in Figure 3): a wing-shaped floating body with ballast water control capability, vertical support columns, a transverse connection beam, nacelles housing direct-drive permanent magnet synchronous generators, and a pair of contra-rotating horizontal-axis rotors mounted on the main shaft. In addition to providing buoyancy and depth control, the wing-shaped float leverages hydrodynamic lift generated by ocean current inflow to actively regulate operational depth, forming a hybrid system with both buoyancy- and flow-induced stability. This innovative architecture is distinct from existing international marine current power technologies, offering potential advantages in depth control, structural robustness, and modularity. The specific research contributions are outlined as follows:

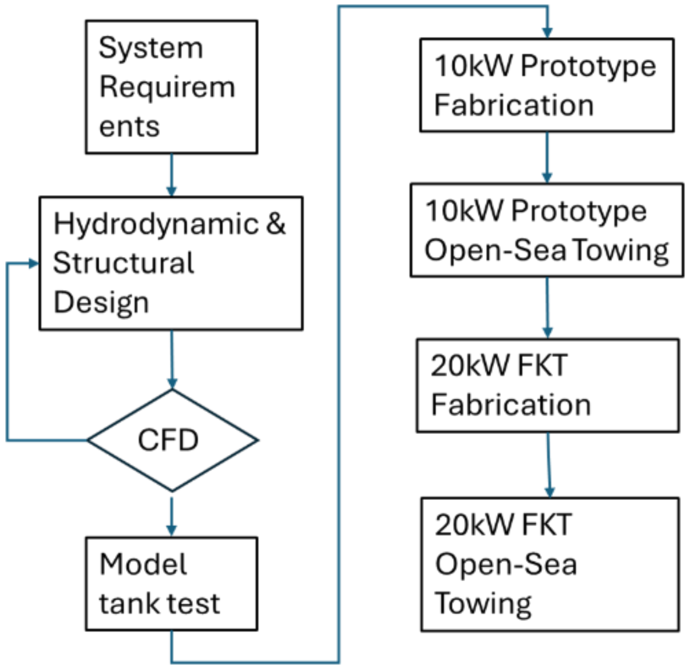


Figure 5 Design flowchart.

3.1 System Integration Design and Performance Evaluation

Based on the proposed novel configuration, this section establishes a full-system design methodology for the floating Kuroshio current turbine. It includes hydrodynamic form design and hydrostatic analysis, structural pressure resistance and fatigue life assessment, direct-drive generator design and power transmission planning, electromechanical control integration, and comprehensive system dynamics and control strategy development. The integration further incorporates rotor blade hydrodynamic design, mooring-tension analysis, experimental data from scale-model tank tests, and open-sea towing tests, culminating in a validated performance evaluation framework for the overall system.

3.2 System Dynamic Simulation Analysis

To focus on assessing the dynamic behavior of the turbine system under various sea conditions. Computational Fluid Dynamics (CFD) simulations are conducted to analyze hydrodynamic responses of the float, columns, and nacelles, and a multi-body dynamics model is developed for system-level simulations. Scenarios considered include normal operational conditions and extreme weather events (e.g., typhoons), enabling the design and verification of the mooring system, structural connections, and buoyancy regulation modules for reliability and performance.

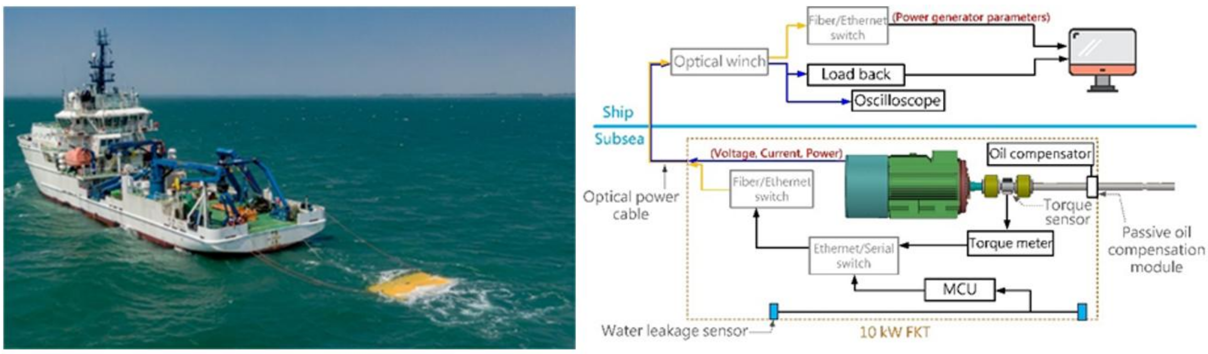
3.3 Rotor Blade Design and Hydrodynamic Analysis

CFD-based tools were employed to develop the three-dimensional rotor blade geometry and predict performance characteristics. A 1:5-scale, 20 kW-class prototype blade system was designed, incorporating near-field flow interactions among the blade, nacelle, and float. A rotor performance evaluation framework was established that accounts for dynamic inflow and underwater motion coupling. The prototype blades were fabricated in collaboration with domestic FRP manufacturers, with an accompanying quality control and manufacturing protocol to ensure scalability for future full-scale production.

3.4 Tank Testing and Open-Sea Towing Experiments

To validate the design performance and critical technologies, a 1:25-scale model was first tested in a towing tank. Key experimental focuses included blade hydrodynamic characteristics, system motion responses, and variations in mooring line tension. Subsequently, 10 kW and 20 kW prototype units at 1:5 scale were constructed for open-sea towing tests. These tests assessed real-world power generation performance under varying current speeds and operating depths, verifying the accuracy of numerical simulations and design parameters.

Open-sea towing tests were conducted to evaluate the operational performance of the 10 kW Floating Kinetic Turbine (FKT), including the FRP rotor, generator unit, and submerged stability. Because no national or international standards currently exist for assessing the power performance of Kuroshio current turbines, the test plan was developed using established engineering practices and the characteristics of the custom generator. The generator was manufactured in accordance with the Taiwanese CNS 2901 standards, and factory tests were performed to establish its rotational-speed–power and rotational-speed–torque curves. These curves were used as baseline references for evaluating turbine performance during the towing experiments. The towing tests were performed approximately 7 miles offshore of Anping Port, Tainan, Taiwan, in October 2020 (Figure 6A). The FKT was connected to the support vessel via a composite-fiber towing rope, and the vessel speed was adjusted to provide controlled inflow velocities. A 20 kW resistive load bank and oscilloscope were used to measure voltage, current, and waveform, and integer loads from 1 to 20 kW were applied to assess performance under different operating conditions. A torque sensor installed on the rotor shaft recorded torque and rotational speed. Generated electrical power was transmitted to the vessel through power cables, while sensor data—including torque, RPM, and nacelle pressure—were transmitted via a fiber-optic communication system. The overall measurement configuration is shown in Figure 6B.



A B

Figure 6 A. Towing of 10 kW FKT. B. Towing of 20 kW FKT.

3.5 Economic Feasibility and Supply Chain Analysis

This section presents a preliminary economic and techno-industrial feasibility assessment for the deployment of marine current power systems. The evaluation includes the current status of the global marine and tidal energy industries, the cost structure of turbine systems, levelized cost of electricity (LCOE) estimates, and an inventory of domestic and international supply-chain capabilities. Preliminary results indicate that the LCOE for a small-scale demonstration turbine ranges from 18.65 to 37.12 NTD/kWh [16]. For medium-scale demonstration arrays, economies of scale reduce the estimated LCOE to 4.86–11.17 NTD/kWh [16]. At full commercial deployment, the high capacity factor of Kuroshio power generation is expected to further reduce the LCOE to approximately 3.46–8.09 NTD/kWh [16]. These findings provide an initial assessment of the technical maturity and cost-effectiveness of the floating turbine system and offer guidance for future industrialization and commercialization strategies.

Through these five research tasks, this study successfully establishes an innovative design methodology, modeling framework, and validation process for the floating Kuroshio current turbine. The development and open-sea demonstration of pilot-scale units confirm the system's high stability, operational flexibility, and technical viability. These results position the proposed configuration as a promising foundational platform for future practical marine current power applications.

4. Results

4.1 Towing Tests of the Kuroshio Turbine System

20 kW towing tests were conducted in October 2021 in safe waters between Kaohsiung Port and Xiaoliuqiu Island. This test utilized a submerged ballast mass for depth control and evaluated the performance of a 20 kW floating marine current turbine. The 2021 tests specifically verified the system's autonomous depth regulation capability, as well as the turbine system's stability and the integrity of cable routing and mooring configuration. Compared to the 2020 trials (Figures 7A, 7B), sea conditions were notably calmer, wave surfaces were smooth and free of whitecaps, yielding more consistent and realistic measurements of generator voltage, current, and power output.

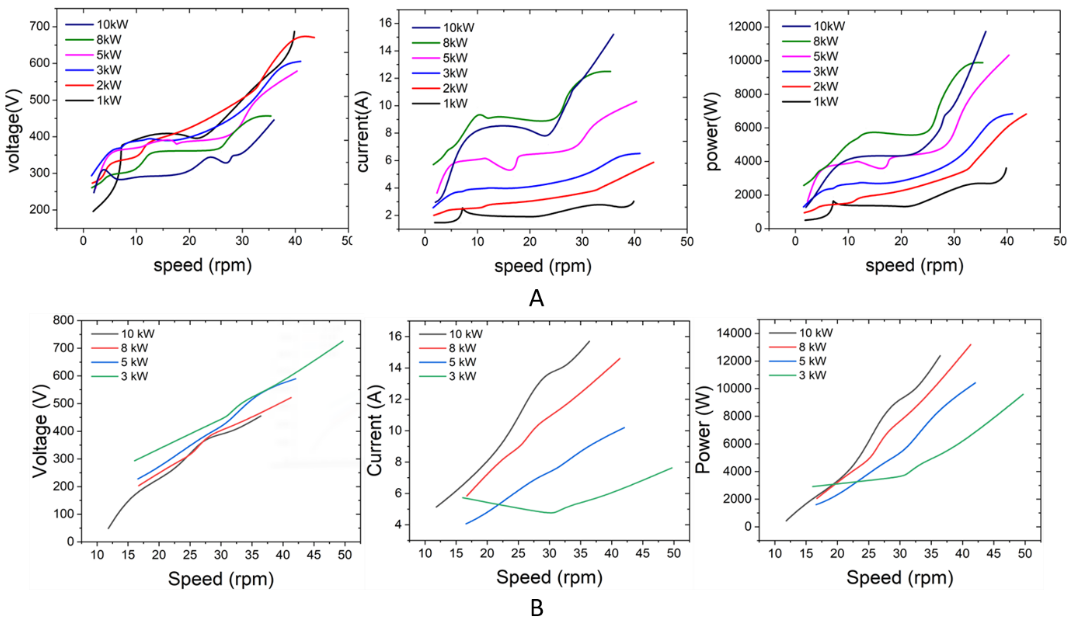


Figure 7 A. 20 kW FKT Towing Test Results (2020). B. 20 kW FKT Towing Test Results (2021).

Moreover, by adjusting the water intake and discharge of the left and right ballast chambers located within the wing-shaped float, the submerged posture of the FKT could be modified to a certain extent. These tests confirmed the system's controllability and adaptability under real oceanic conditions, providing critical data for further optimization of the turbine's hydrodynamic performance and structural configuration.

5. Discussion

During the 2020 towing tests, electrical load conditions of 5 kW, 8 kW, and 10 kW were applied to evaluate the power generation performance of the system. The measurements showed that the turbine produced an output power of 10 kW at a rotor speed of 40 rpm under a 5 kW load and at 33 rpm under an 8 kW load. Notably, under a 10 kW load at 32 rpm, the turbine generated nearly 12 kW of electrical power. Two primary factors were identified as possible causes for this discrepancy. First, the rotor blades were conservatively designed with performance margins, enabling higher-than-expected rotor speeds under equivalent flow conditions. Second, the inflow velocity at the rotor may have been enhanced by the wake effects generated by the support vessel's propeller, resulting in an effective inflow velocity greater than the measured value. A comparison of the data indicated that at a vessel water-relative speed of 2.5 knots, the rotor speed reached approximately 30 rpm, while at 3 knots, the speed approached 40 rpm. These results confirm the effective coupling between the rotor and the generator under real-sea conditions. Both voltage and current increased with rotor speed, consistent with the inherent characteristics of a synchronous generator. The measured rotor speeds during the towing tests exceeded the original design specifications. However, owing to the rotor's superior hydrodynamic performance relative to the generator's rated operating range, future tests will incorporate stricter control of inflow velocity to ensure stable power output and to prevent generator overloading.

In the 2021 tests, the voltage, current, and power output curves were found to be more consistent and reliable than those from 2020, attributable in part to more favorable sea conditions and system refinements. Additionally, the buoyancy control modules demonstrated stable operation throughout the sea trials. By varying the intake and discharge of water in the port and starboard buoyancy engines within the floating rudder, it was possible to adjust the roll angle of the FKT while submerged moderately. However, attempts to control the pitch angle using these modules were notably limited. Effective pitch control was achieved by making significant adjustments in the overall buoyancy of the system—specifically, by entirely flooding the buoyancy chambers during descent and fully expelling water during ascent. This approach proved more effective for achieving the desired vertical positioning and orientation control of the FKT.

6. Conclusions

This study presents a comprehensive approach to the design, simulation, and performance validation of a floating Kuroshio current power generation system. The key findings and contributions are summarized as follows:

6.1 Stable and Reliable Operation

The 20 kW-class floating kinetic turbine (FKT) demonstrated robust performance under real marine conditions, including autonomous depth regulation and structural integrity. System monitoring included rotor torque sensors, voltage and current measurements via a resistive load bank, and fiber-optic data transmission, which together confirmed system stability and controllability during towing and sea trials.

6.2 Hydrodynamically Optimized Rotor Design

A novel rotor blade design framework tailored for ocean current conditions enabled efficient power extraction under moderate flow velocities characteristic of the Kuroshio Current. Scaled-model tank tests and full-scale trials validated the design and confirmed alignment with numerical predictions.

6.3 Strategic and Industrial Impact

The project establishes a technical foundation for Taiwan’s marine energy sector, supporting technology localization, academic-industry collaboration, and pathways toward commercial-scale ocean current turbine systems. The hybrid buoyancy- and flow-induced stabilization approach, validated through both modeling and experiments, provides a feasible framework for future deployment.

Author Contributions

The author led the arrangement of the floating Kuroshio Current turbine system's sea trials in Taiwan's marine and was responsible for analyzing the sea trial data and validating the results. This study introduces an innovative design for ocean current energy conversion in offshore environments, overcoming the deployment limitations of existing technologies. A technical roadmap is proposed and validated, offering a practical reference for the future commercialization of marine current energy in Taiwan.

Competing Interests

The author has declared that no competing interests exist.

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