Development and demonstration test for floating type ocean current turbine system conducted in Kuroshio Current

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***Abstract*— Ocean current known as Kuroshio Current flows in the vicinity of Japanese coastal area is the one of strongest ocean current all over the world. In order to realize power generation utilizing the Kuroshio ocean current, IHI has been developing the floating type ocean current turbine system. In this study, we have carried out technical development of the floating type ocean current turbine system, engineering, and construction of design rated output 100kW turbine demonstration prototype named 'Kairyu' in IHI. With using this Kairyu, the world first demonstration test in Kuroshio Current area located off Kuchinoshima Island of Kagoshima prefecture was conducted and completed on August-2017. As a result, we achieved installation procedure feasibility, submergence height and attitude stability in operating condition with control, and power generation output, and so on.**

Keywords*— power generation, ocean current, Kuroshio, floating type ocean current turbine, experiment in sea, renewable energy, turbine, Kairyu, IHI, demonstration test.

I. Introduction

Japanese Exclusive Economic Zone (EEZ) extending outside Japanese territorial waters is the world's sixth largest EEZ. Proceeding development of utilizing ocean renewable energy in the EEZ actively is required in terms of the reduction in greenhouse gas emissions and energy security. Ocean current known as Kuroshio Current shown in the Fig.1 flows stably almost all year in the vicinity of Japanese coastal area. Accordingly, by using this Japanese own natural enormous energy, it is strongly expected to establish new clean and stable source of electric power. Additionally, ocean current has potential to enable stable power generation compared to another clean energy, such as wind, solar, and tidal power generation. In order to realize power generation utilizing the Kuroshio Current, Floating type ocean current turbine system is developed [1], [2]. In this study, we have carried out technical development of the floating type ocean current turbine system, engineering, construction, integration, and preliminary check of designed rated output 100kW turbine demonstration prototype named Kairyu in IHI Yokohama works. And with using this Kairyu, the world first demonstration test in Kuroshio current area located off Kuchinoshima Island of Kagoshima prefecture was conducted and completed on August-2017. We achieved installation procedure feasibility, submergence height and attitude stability in operating condition with control, and power generation output, and so on.

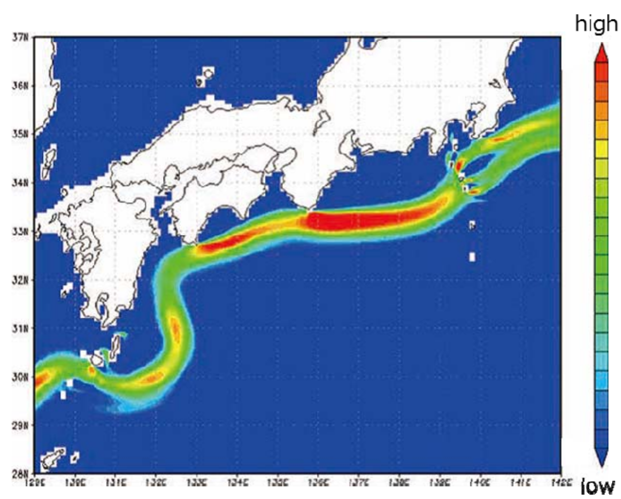

Fig. 1. Current path of Kuroshio Current

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II. CONCEPT AND DEVELOPMENT OF FLOATING TYPE OCEAN CURRENT TURBEINE SYSTEM

Ocean current turbine shown in Fig.2 has two major features.

- Counter-rotating Twin Turbines: Rotary torque generated by turbine rotation can be canceled by coupling two counter-rotating underwater turbines. This will allow the turbines to maintain a stable position under the sea to achieve efficient power generation.
- Single line mooring: In this system, the floating turbines are moored to the seabed so that they remain suspended in the ocean. Installation work is easy since the mooring system consists of single line. Additionally, they can even be installed in deep water, which means that a wide ocean area is available for power generation using this system. Therefore, it allows us to construct a large-scale energy farm consisting of a number of power generators.

In addition to these two features, ocean current turbines will be used in the middle layer of the sea, which makes influence on the motion caused by waves much smaller. Also, due to the downwind type, this system can be applied in any current direction without active control.

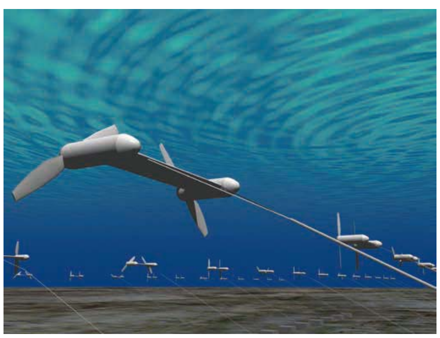

Fig. 2. Floating type ocean current turbine system

Studies we have implemented so far are as follows.

- 1/25 scale model test in towing tank/sea for confirming the behavior of floating type ocean current turbine system in water (shown in Fig.3)
- Static strength test and dynamic fatigue test of 5m scale turbine blades (shown in Fig.4)
- Pressure test for the hull and hatch with using mock-up model at the 100m deep (shown in Fig.5)

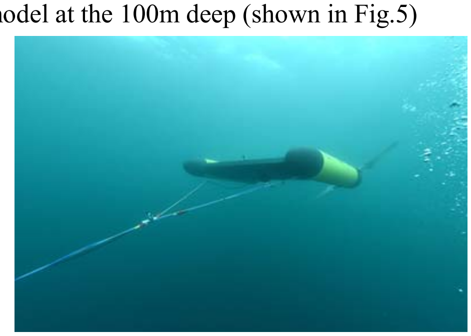

Fig. 3. Sea trial of 1/25 scale test model of floating turbine system

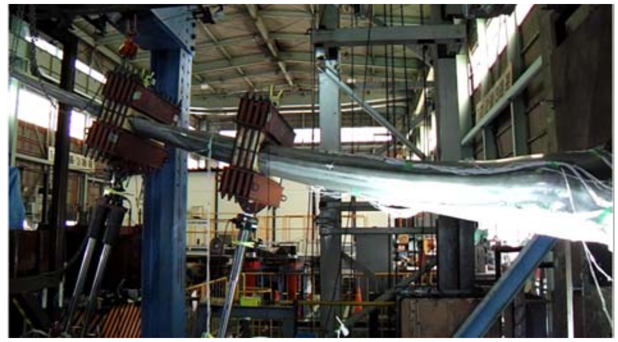

Fig. 4. Static strength test for 5m scale turbine blade

Fig. 5. Pressure test with using mock-up model

We have obtained technical knowledge from the studies and applied valid methods of design and construction to the demonstration prototype.

III. DEMONSTRATION PROTOTYPE KAIRYU

In this chapter, detail and specification for 100kw demonstration prototype Kairyu are shown. The Kairyu is used for demonstration test.

A. *Principal specification*

1) Designed rated power output : 100kW (50kW×2qty)
2) Rated current velocity : 1.5m/s (3knot)
3) Total length : 18m
4) Total width : 18m
5) Turbine diatmeter : 11m

B. *Components*

Main components of Kairyu shown in Fig.6 are as follows.

- Buoyancy control device; ballast water management controls balance of weight and buoyancy.
- Attitude control device; ballast shifting among three pods change the position of center of gravity so that it control trim and heal.
- Generator; variable torque enables to control the turbine rotation speed in any current velocity.
- Blade pitch angle control device; pitch angles of 4 turbine blades are controlled independently.
- Mooring line; HMPE rope that has high strength, low elongation, and lightness is introduced.
- Power cable; Electric transmission is through riser cable and subsea cable. They also include optical fiber cable, therefore monitoring at the shore side is possible.

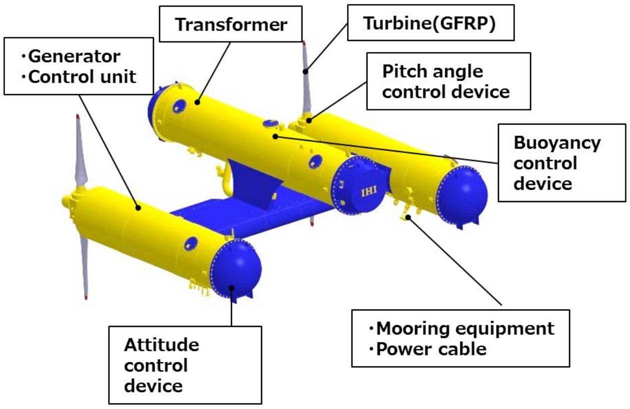

Fig. 6. 100kw turbine demonstration prototype Kairyu

C. Control

Things controlled for Kairyu operation are submergence height, attitude (Heal/Trim), and generated power.

1) Submergence height

It is required to control submergence height in various phases such as submerging from the sea surface, maintaining submergence height in the operational range, and rising up to the sea surface. Equilibrium of forces for the floating type ocean current turbine system is made by buoyancy, thrust of turbines, and tension of the mooring line. The vertical position depends on the balance of them. Consequently, the method to control the submergence height of Kairyu is the buoyancy control device and turbine thrust force. These two types of control are carried out only when needed. For example, if the submergence height of Kairyu approaches outside of the operational range they will work. And if the submergence height is within it, it will not. This sequence maximizes the efficient of power generation totally.

2) Attitude (Heal/Trim)

It is necessary to maintain heal and trim angle to be in the vicinity of 0°. Attitude control is carried out by attitude control device. With shifting ballast among three pods, heal and trim angle of Kairyu can be controlled simultaneously. However, Kairyu has the longitudinal and lateral stability due to the positional relation between center of gravity and center of buoyancy. Thus, active control by the attitude control device is not used continuously but only when needed. With regards to yawing, Kairyu follows ocean current direction and is operating without control because of weather vane effect since it is single line mooring.

3) Power generation

In order to prevent the generator from getting overload, the generated power has to be kept below the rated value under the condition of ocean current with high velocity. The generated power can be controlled with the turbine blade pitch angle. When the generated power exceeds the threshold, blade pitch angle will be changed and power generation efficiency becomes lower so that it decreases the power generation.

D. Construction and preliminary check

Construction has been done in IHI Yokohama works. Integration and preliminary check has been executed in Japan Marine United Yokohama shipyard as provided in the Fig.7. What we carried out in preliminary check are operation check of actuators, instrument output confirmation, and implementation of inclining experiment in order to identify and adjust the position of center of gravity.

Fig. 7. Preliminary check at shipyard

IV. TEST METHOD

A. Towing test

The purpose for the towing test was to obtain the power generation performance and execute gain tuning for the submergence height and attitude control. Arrangement for the towing test is as shown in Fig.8. Gravity base anchor was hung by barge at a depth about 100m. Kairyu is moored with the mooring line from the anchor. The arrangement follows mooring condition on the seabed. However, we could control the current velocity as we wanted in the arrangement for towing test. It has been conducted for five days in west water area of Kagoshima prefecture as shown in Fig.9.

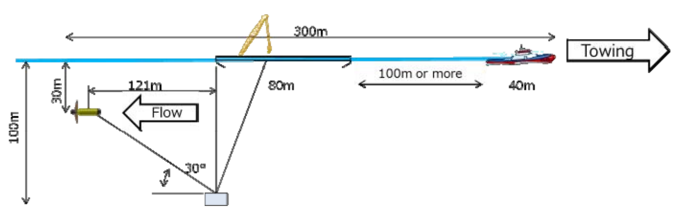

Fig. 8. Arrangement for towing test

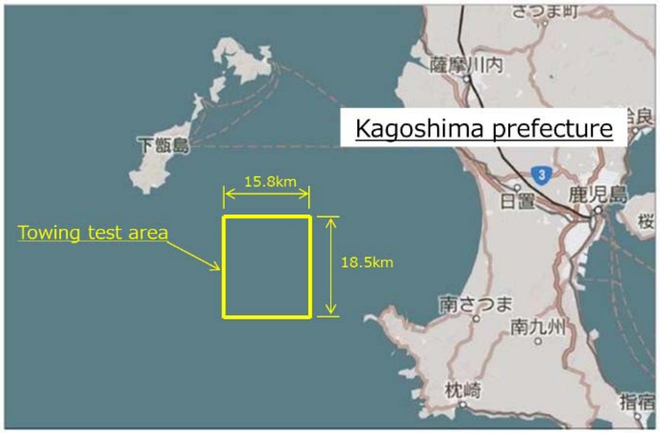

Fig. 9. Test site for towing area (Source: https://www.n-survey.com/online/gmap2.htm)

B. *Demonstration test*

The purpose of the demonstration test was to obtain power generation in Kuroshio Current and confirm the stability of the submergence height and attitude at mooring condition on the seabed. Arrangement for the demonstration test is shown in Fig.10. Kairyu is installed with mooring line and gravity base anchor on the seabed at a depth of 100m. Generated power is transmitted between Kairyu and power receiving facility located on the barge through riser cable along with mooring line and subsea cable whose length is approximately 2km. In addition to power transmission, data from each instrument is transmitted through the cable as well for remote monitoring at the base on the barge. The demonstration test has been conducted for four days at the site as shown in Fig.11, which is indicated at north of Kuchinoshima island.

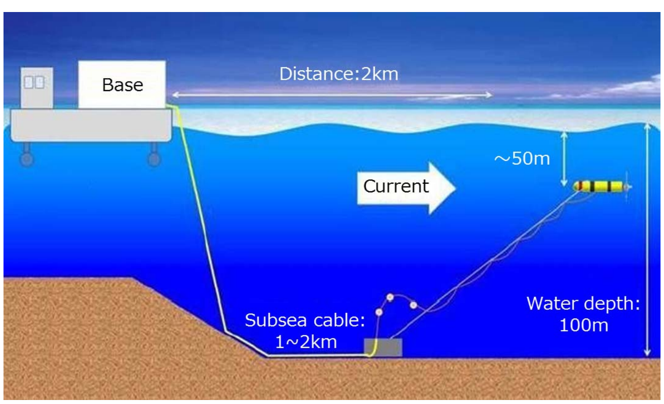

Fig. 10. Arrangement for demonstration test

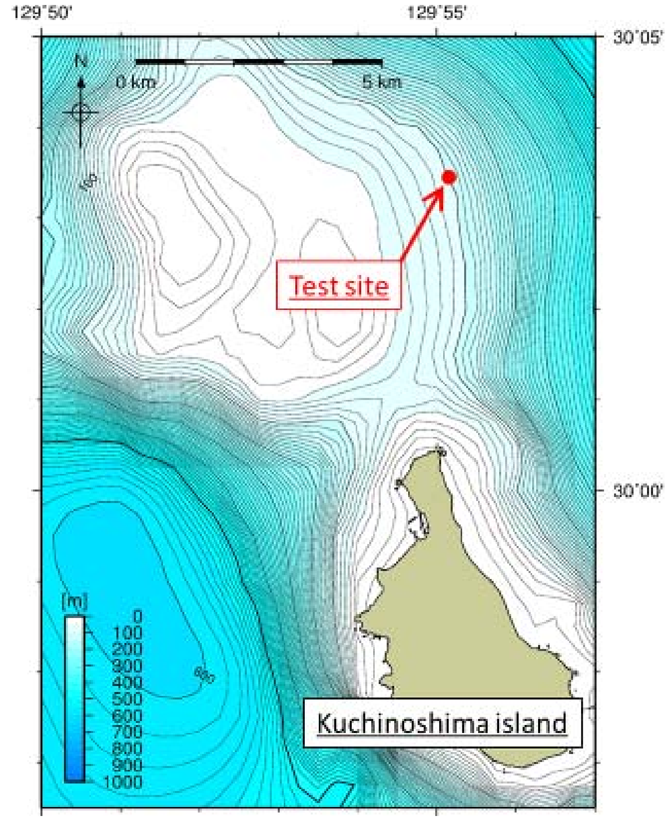

Fig. 11. Test site for demonstration test

V. TEST RESULT

A. *Installation*

One of the target for the demonstration test was to establish installation feasibility. Kairyu has been carried to near Kuchinoshima Island on a ship and installation works have been implemented there. The unloading from the barge to the sea surface was done by lifting with floating crane and the picture is as provided in Fig.12. Kuchinoshima Island is an isolated island, and the wave height in the water area is comparatively higher than the coastal area. Lifting point was planned based on the estimated wave height so that safety lifting could be conducted. The wave height around the area was estimated with a simulation of wave transformation and an appearance probability of wave direction as shown in Fig.13. Accordingly, the lifting point was smoothly determined at the site and the wave condition was just close to the result of the simulation as indicated in Fig.14. The process of installation of the gravity base anchor, mooring line, riser cable, and subsea cable have been completed for 3 days, which is on schedule. This indicates that the procedure of installation is feasible. Fig.15 shows the picture of Kairyu installed at the test site.

Fig. 12. Installation work beside Kuchinoshima Island

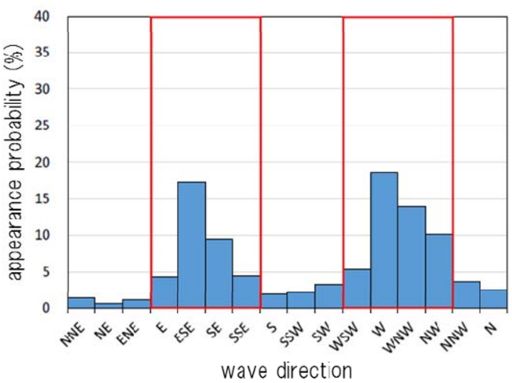

Fig. 13. Appearance probability of wave direction around Kuchinoshima

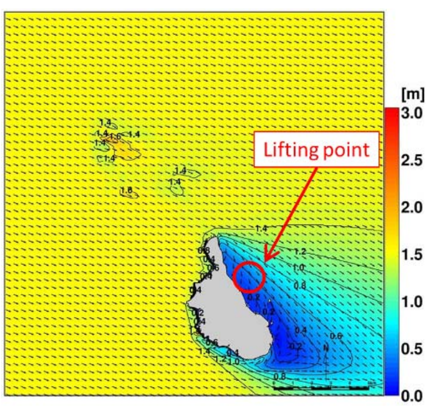

Fig. 14. Lifting point and wave height with west direction

Fig. 15. Kairyu deployed off Kuchinoshima Island

B. Submergence height and attitude stability

Another purpose of the demonstration test was to see the stability of the motion. Submergence height, heal, and trim angle of Kairyu were measured with the instrument installed on Kairyu. Time history appended in Fig.16 shows submerging from the sea surface and power generating under the sea surface. Submerging started with the pumping the sea water into the ballast tank, and the power was generated after submergence height was stable at the certain depth under the sea surface. In the Fig.16, the measured values are well consistent with and within the target for the control. As a result, submergence height and attitude were controlled within the target, and it was confirmed that the motion of Kairyu in the operation was stable in Kuroshio Current.

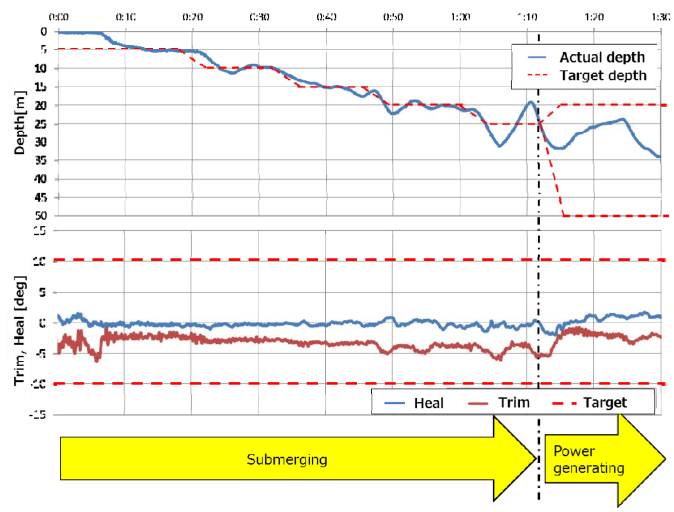

Fig. 16. Time history for the submergence height and attitude in demonstration test

C. Power Generation

Power generation performance was obtained in the towing test and power generation in Kuroshio Current was achieved in the demonstration test. The relation between power generation and current velocity in the towing test is shown in Fig.17. In this figure, designed power curve for the towing test and measured power curve with the standard deviation are consistent well. Additionally, maximum output exceeds

100kw, which is designed rated output. However, the value of standard deviation is large near the upper limit set in this test case. It is supposed that the variation of the standard deviation could be caused by flow fluctuation, turbulence, velocity profile and so on. The velocity profile in the ocean must be more complicated. In addition to that, the wake due to Kairyu affects the power generation. Hence, further study for the power generation especially for the velocity around turbine blades and reducing the fluctuation of generated power will be conducted.

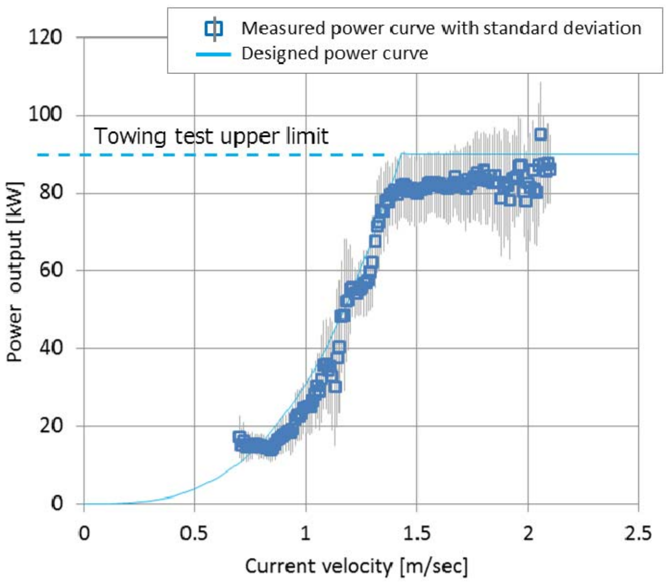

Fig. 17. Measured power curve with standard deviation

VI. Conclusion

- 100kw demonstration prototype for ocean current turbine system has been developed and demonstration test has been executed off Kuchinoshima island in Kuroshio current area.
- Installation work has been implemented at the test site, and confirmed feasibility of installation procedure.
- It is confirmed that submergence height and attitude can be stably operated with the control in Kuroshio current.
- Power generation was achieved, however there is still room for further study, especially for the incident current velocity around turbine blade.

Acknowledgment

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