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Experimental verification of a floating ocean-current turbine with a single rotor for use in Kuroshio currents[☆]

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A B S T R A C T

Ocean currents have excellent potential as future renewable energy resources. In order to harness the kinetic energy of marine currents, we propose a new ocean-current turbine. In general, ocean currents have sufficiently large cross sections. Thus, the turbines are moored to the seabed and function like kites in the water flow. In the future, turbines will be installed approximately 100 m deep to avoid the influence of surface waves; this is especially important during typhoons. To operate such turbines in the middle layer of a marine current, it is necessary to cancel the resulting rotor torque. Therefore, our turbine is designed with a float at its top and a counterweight at its bottom. Owing to buoyancy and gravity, the turbine maintains a stable position. We describe towing experiments carried out to confirm the float and counterweight configuration and show that the results verify hydrostatic stability and electric power generation for the proposed turbine.

1. Introduction

There are several different oceanic energy forms: wave, marine currents, tidal currents, and thermal energy. Many studies are currently being carried out in order to realize commercial operation worldwide [1,2]. Ocean currents are also a promising source of sustainable energy because the flow of water provides regular and predictable energy. On the other hand, research and development are difficult technically and potentially costly. However, the demand for renewable energy sources has increased since the Fukushima nuclear power plant disaster in 2011.

Japan is in a suitable location for harnessing the power of ocean currents because the Kuroshio ocean current runs steadily near the Japanese seaside [3]. The Kuroshio current is a strong ocean current in the western North Pacific Ocean. The current flow is approximately 500 m deep and 100 km wide with a flow speed of 1–1.5 m/s [4–6]. This appears to be a rather slow flow, but it is sufficient for generating electricity because the density of water is 800 times higher than that of air. The Kuroshio current has a power density equivalent to that of a wind flow at 9–14 m/s. Moreover, the Kuroshio current is an energy resource with only small fluctuations in flow, regardless of the time of day or the season. As mentioned above, an ocean-current turbine has many advantages for power production; these include:

- Stability

  Ocean currents flow constantly.

- Availability

  The volume of the water flow is very large.

- Predictability

  The flow speeds and paths have been investigated thoroughly.

- No visual impact

  The turbine operates beneath the water surface.

Tidal-current turbines have technologies in common with ocean-current turbines. At the European Marine Energy Centre (EMEC), several tidal-current turbine projects are currently underway [7]. Most of these projects have adopted horizontal-axis turbines mounted onto the seabed. This means that, even though

☆ Fully documented templates are available in the elsarticle package on CTAN.

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the turbines operate underwater, their horizontal-axis nature makes them efficient. On the other hand, mainly ocean-current areas such as Japan, Florida (USA) [8], and Taiwan, which face the Kuroshio current or Gulf stream, have been investigated with a view to extraction of energy from current flow. Several groups are developing ocean-current turbines using a floating body moored to the seabed. The key problem in these systems is how to cancel the resulting rotor torque. One of the typical methods used to achieve this cancellation is a twin-turbine system [8–10].

The present work intends to propose a new type of turbine that utilizes ocean-current power. To realize this power take-off system, many technical problems have to be solved, e.g., problems related to installation, cost, maintenance, environment, and electricity transmission. However, the most essential point is to develop a robust, efficient, and maintainable turbine. To overcome the above issues, we propose a new ocean-current turbine.

The structure of this paper is as follows. First, the conceptual design and energy farm plan are presented. Second, the prototype turbine is constructed for initial proof-of-principle experiments. Then, towing tests done at sea are described; these were performed to verify the stability of the floating body. In addition, turbine performance measurements carried out in a towing tank are compared with corresponding numerical results. Finally, conclusions are summarized.

2. Theory

2.1. Ocean-current turbine principle

Ocean currents run through deep areas of the sea. In the case of the Kuroshio current studied here, its depth is over 500 m. This is a good example application because it is typical of current flow depths below the surface. To harvest the energy of an ocean current, turbines offer an efficient solution.

To convert the kinetic energy of an ocean current into electricity, the turbines must operate within the flow. Therefore, they are moored to the seabed. A schematic diagram of our turbine system is shown in Fig. 1. The turbines are positioned approximately 100 m below the surface; because the cross section of the Kuroshio current is sufficiently large, they can capture the flow well. Another advantage of working far from the sea surface is the lack of influence from waves and wind, especially in a typhoon.

For a wave at sea, fluid particles at a depth equal to half the wavelength or more are essentially free of wave interference. Suppose the axis of a turbine is 100 m below the surface and its top is about 50 m below the surface. In this case, the turbine would be safe in the presence of wavelengths up to 100 m. In practice, operating depth should be decided according to the current profile and wave assessments. In many environments vortex flows, sea mammals, fish, and chemicals must also be considered in turbine installation.

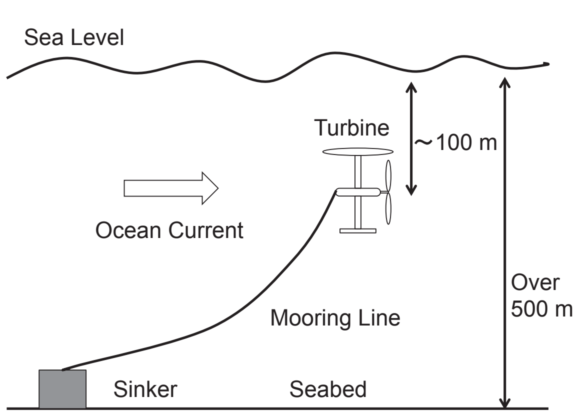

Fig. 1. Schematic diagram of an ocean-current turbine.

Figure 2 shows the conceptual design of the proposed turbine. The turbine is equipped with a float at its top and a counterweight at its bottom. Owing to buoyancy and gravitational force, the turbine body maintains its attitude stably by canceling the rotor torque. In other words, buoyancy and gravity act together as a righting moment. Of course, this righting moment also provides stability in pitching motion. As shown in Fig. 2, the condition for stable operation is expressed as

$$G \sin \theta + F \sin \theta > T \tag{1}$$

where G is the gravitational force on the counterweight, F is the buoyancy of the float, T is the blade torque, and θ is the roll angle. All forces should be normalized by their distance from the rotor axis. In this design, a spheroid float is adopted because the drag should be kept small. In addition, we consider that an axisymmetric shape is better for suppressing pitching and rolling motions. The drag coefficient of a spheroid depends on its aspect ratio. All of the power-generating components, i.e., the electric generator, gear box, and drive train, are placed in the nacelle.

2.2. Features

Our turbine uses a single horizontal-axis rotor to generate electricity. Various horizontal- and vertical-axis turbines have been proposed to extract power from ocean currents (see, for example, [11]). In general, horizontal-axis turbines have higher power efficiency than vertical-axis turbines.

Another typical method used to cancel undesirable rotor torque is use of a twin-turbine system [8–10]. Such systems are equipped with counter-rotating rotors and generators. In the case of a twin-turbine system, each rotor must be controlled in order to maintain a balance between torque and thrust. An additional mechanism may be needed to keep the body stable when the rotor is not in operation. Our system is always stable owing to its float and counterweight configuration. In other words, the functions of electricity generation and body stabilization are clearly separated in our design. This allows our design to provide more flexibility than others. For example, by adding a buoyancy control system to the float, the operation depth can be set simply to capture the optimum current. If more body stability is needed, it is realized by increasing

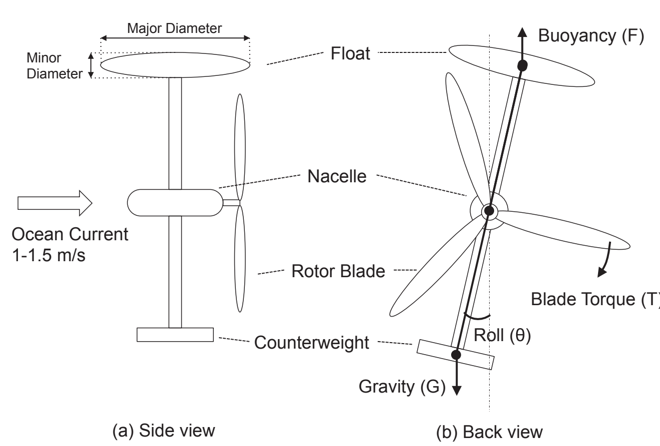

Fig. 2. Schematic diagram of the ocean-current turbine: (a) side view and (b) back view.