IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Counter-rotating type tidal stream power unit: Excellent performance verified at offshore test

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Abstract. A counter-rotating type tidal stream power unit, composed of tandem propellers and a peculiar generator with double rotatable armatures, was provided for verification tests at offshore. The front propeller with diameter of 1 m has three blades, and the rear propeller with diameter of 0.95 m has five blades. The blade profiles were optimized with the blade element-momentum theory and CFD, and then covered with CFRP. The front and the rear propellers connect to inner and outer armatures in a synchronous type generator with net output 1.5 kW, whose efficiency was improved by heat pipes and the modification of the armature profiles. The shafts are equipped with mechanical seals to protect electric circuits from seawater. A rotational speed control system was also prepared not only to adjust the output but also to overcome the static friction torque due to bearings, slip rings and mechanical seals while starting-up. The power unit takes the maximum output with excellent efficiency at the relative tip speed ratio specified in the unit design. The unit can start-up after maintenance works and the output can be adjusted smoothly in the stream.

1. Introduction

It is very important to exploit clean and renewable energy resources. Tidal stream, whose power can be predicted in a cyclic fashion, is dependable resources, and many types of power units have been proposed with accompanying beneficial design data. Horizontal axis type tidal stream turbines, for instance, have been designed with accompanying numerical simulations and experimental investigations [1][2][3][4]. The European Marine Energy Centre (EMEC) Ltd. established at 2003 in Orkney Island has also provided test sites for developers of tidal stream energies, namely 250 kW turbine of OpenHydro in 2006, 500 kW turbine of Tidal Generation Ltd's (TGL, now Alstom) in 2010, 1 MW turbine AR1000 of Atlantis Resource Corporation in 2011, 1 MW turbine of ANDRITZ HYDRO Hammerfest in 2012, 1 MW turbine HyTide 1000 of Voith in 2013, and so on [5].

Concept of counter-rotating type tandem propellers has also been brought to tidal stream turbines, as follows. The tandem propellers, which drive a bevel gear whose output shaft is connected to the traditional generator, has been presented [6], and the performances have been investigated in the similar mechanism [7][8][9]. Besides, Nautricity Limited has provided the prototype for demonstrating the power generation at the Null of Kintyre in Scotland [10].

One of the authors had also invented a tidal stream power unit, which is composed of tandem propellers and a peculiar generator with double rotatable armatures [11][12][13], where a rotating field magnet/winding in the generator are called the double rotatable/rotational armatures in these papers. The front and the rear propellers counter-rotate directly the inner and the outer armatures, respectively. As the result, the relative rotational speed is faster than a single propeller/armature speed while the rotational moment counter-balances in the unit, and then the unit has promising advantages as follows [14]. (a) The induced voltage, affecting on efficiency of electric power transmission, is sufficiently higher while keeping the armature diameter same as the traditional one. (b) The diameter of the armature, affecting on the unit size and weight, can be reduced while keeping the induced voltage same as the traditional one. (c) The cavitation in the propellers, affecting on material erosion, vibration and undersea noise, can be suppressed well while making each rotational speed slower. (d) The rotational moment hardly acts on the mounting bed/pile because the reaction force does not act on the outward, that is, it is extremely easy to provide the unit with large capacity for not only the constructed power station with a mounting bet/pile but also the floating station moored to the seabed with only one cable. (e) The flow has no swirling component behind the tandem propellers, because the swirling velocity component induced from the front propeller is absorbed by the rear propeller. Such technologies have been applied to exploit tidal range and stream resources [15][16].

The prototype counter-rotating type tidal stream power unit was provided in this paper not only to get the excellent power generation but also to guarantee the safety operation at an offshore in Nagasaki Bay, Japan.

2. Advanced counter-rotating type tidal stream power unit

2.1. Submerged type prototype power unit

Figure 1 shows a cross-sectional view and a photo of the prototype counter-rotating type tidal stream power unit composed of the tandem propellers and the peculiar generator explained just above, where some parts of the unit [17] were modified as described latter to improve the performance and to observe the operating conditions. The front propeller with diameter of 1 m has three blades with hub ratio of 0.25, and rotates directly the inner armature. The rear propeller with diameter of 0.95 m has five blades with hub ratio of 0.25, and counter-rotates directly the outer armature. Each number of the blades was optimized from the previous researches for wind power units [18]. The smaller diameter of the rear propeller plays an important part in suppressing that the tip vortex shedding from the front blade attacks the rear blade [19][20]. The axial distance between these propellers is 0.145 m, and the overall length measured from the nose to the tail cones is 1.52 m. The outer shaft/armature is equipped with a slip ring to get out the electric power/output. The inner and the outer shafts are equipped with mechanical seals to protect hermetically the electric circuit in the generator from the seawater leakage.

2.2. Optimization of blade profile in tandem propellers

The blade profiles were optimized numerically with the blade element-momentum theory and the computer fluid dynamics (CFD) in systematically precious works [21][22]. The front blade in close to the hub is twisted in the radial direction so as to not take the load for giving enough stream energy to the rear propeller, because the blade work is scarcely expected at the smaller radius. At the larger radius, the blade is twisted to get the desirable angle of attack irrespective of the radial positions. The blade elements arranged in the radial direction which are supported by the framed column of SUS329J4 surrounded with epoxy resin are covered with a carbon fibre reinforced composite material (CFRP) , as shown in Figure 2.

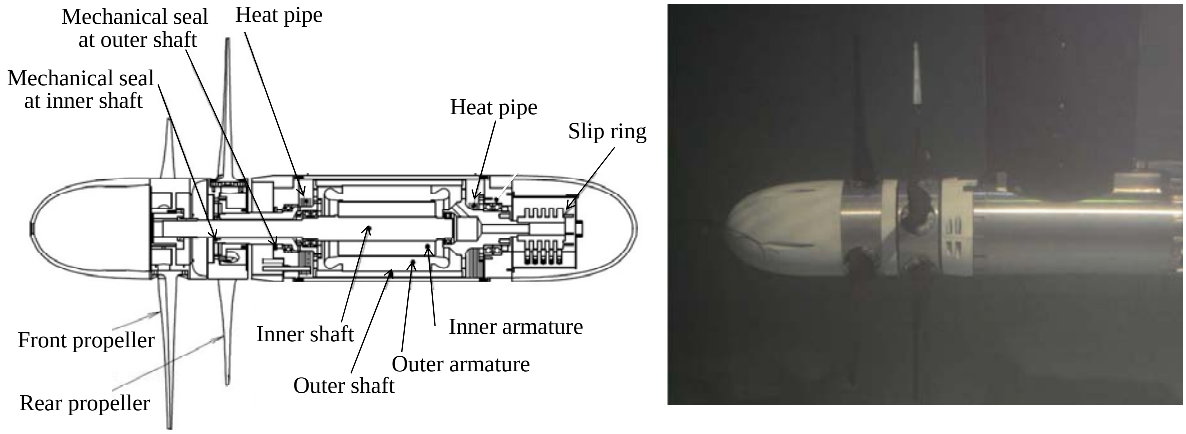


Figure 1. Counter-rotating type tidal stream power unit.

2.3. Modification of synchronous generator with double rotatable armatures

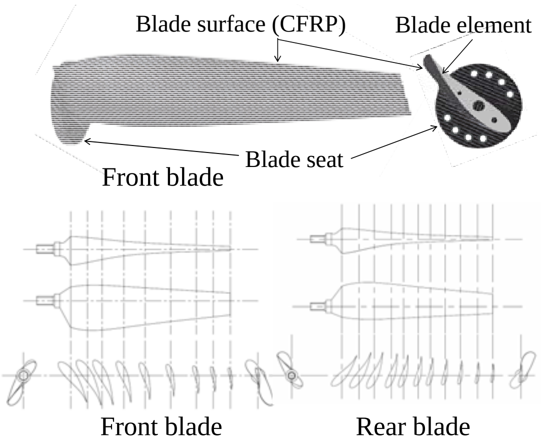
The synchronous generator with double rotatable armatures is equipped with a cooling system. The heat given off from the armatures is radiated into the seawater through a heat pipe with extremely high heat-transfer coefficient, to cool the ambient temperature in the generator. The cooling system contributes to improve successfully the generating efficiency.

To decrease not only the slot leakage flux but also the hydraulic loss of the rotating armatures and to increase the lamination factor of the winding, an iron cover surrounding the magnets were removed and an air gaps between magnets were filled cleanly with epoxy resin to suppress the hydraulic loss. Besides, the friction loss induced from the slip ring is reduced slightly. Such modifications bring to improve successfully the generating efficiency [17].

The generator is equipped with tachometers to adjust the relative rotational speed in response to the output, a temperature indicator to observe the ambient temperature, braking systems not only to carry out a periodic inspection for the unit but also to bring the rotations to an emergency stop. These contribute to ensure the safety operation in the prototype.

2.4. Optimization of mechanical seal profile

The mechanical seal based on surface texturing technologies was developed to protect the electric circuit of the generator [23]. That is, the Rayleigh-steps are arranged at a liquid side as the lubricating mechanism to increase the hydrodynamic pressure, and the reversed steps are arranged at an air side as the sealing mechanism on the sliding surface. It was confirmed, as follows, that this



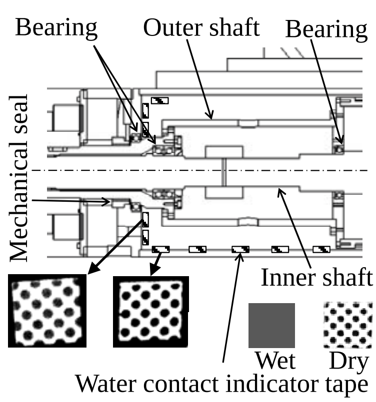


Figure 2. Tandem propellers. **Figure 3.** Mechanical seal closing off the leakage.

seal not only blocks out perfectly the leakage flow by the pumping effect but also minimizes the friction power by the hydrodynamic lubrication. The water never leaks at the ambient pressure 0.11 MPaG corresponding to the seawater depth of 11 m, and the seal brings reduction of 90% in the friction power as compared with the traditional seals.

The mechanical seals developed above were installed in the generator as shown in Figure 1, and submerged continuously in the seawater during the following verification test. Dependable performance was reconfirmed as recognized in Figure 3, where the indicator seals give evidence of keeping the dry condition in the generator.

3. Verification tests at offshore

3.1. Preparation of tests

Prior to the verification tests, durability for the material strength and vibration damage for the power unit were confirmed numerically and experimentally in the laboratory. The power unit mounted on the pile (see Figure 4) was not laid in the tidal stream at the offshore as a preliminary step, but boarded on a tail of a barge clutched/bound by a tugboat (overall length and width: 34 m and 9 m, gross tonnage: 224 ton, draft: 3.6 m) as shown in Figures 5. The power unit was mounted on the staunch pile prepared tentatively to the tests and submerged at the depth of 3.5 m measured from the seawater surface, as shown in Figure 6.

The generator was equipped with acceleration sensors in close to the slip ring and the pile was equipped with acceleration sensors and strain gauges at the end of the pile (see Figure 6) to observe the vibration and the material stress. The blades were also equipped with the strain gauges at the root to know the material stress and were equipped with the pressure sensors at the middle camber on the half height. The strain gauges were also attached to every nook and cranny, for detecting abnormal operations/conditions/circumstances during the tests.

3.2. Operation in the tidal stream

The tests were performed at the weather conditions such as the wind velocity is slower than 7 m/s and the wave height is lower than 45 cm, where the jet flow from the screw scarcely affects the tidal conditions around the power unit. The tugboat run at 1 m/s, namely the tidal stream velocity was kept constant V_S = 1 m/s as accurately as possible, where the velocity was measured by a propeller type velocity indicator with the diameter of 22 mm. The evaluation of the test results, however, may take secretly account of pitching effects of the barge.

The output was consumed with an electric resistance and measured with a power meter, while the output was adjusted sufficiently by the rotational speed control system. Test data were accumulated to data loggers at sampling frequency of 10 kHz.

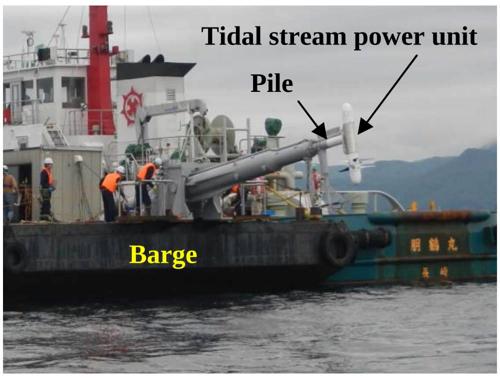


Figure 4. Preparation of the tests.

Figure 5. Verification tests.

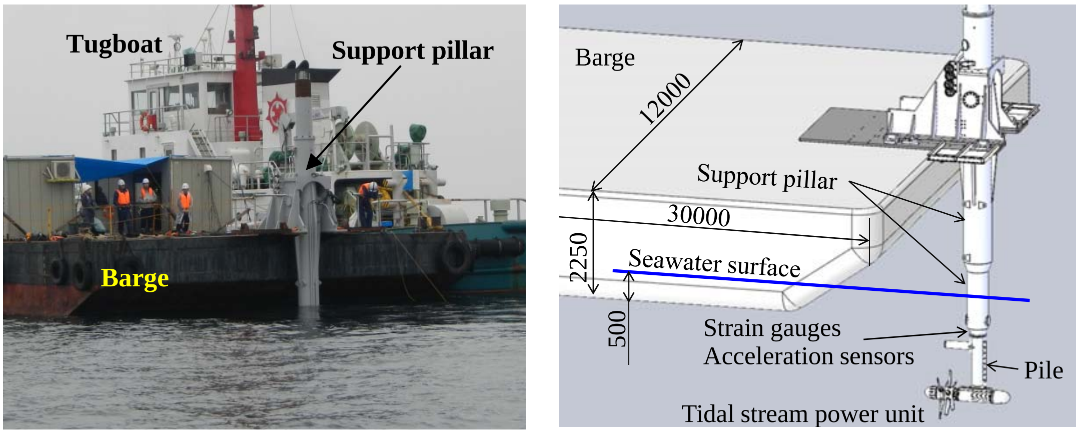


Figure 6. Submerged power unit.

4. Power generation

4.1. Normal operation

Figure 7 shows the induced voltage E, the induced current I, the tidal stream velocity V_S, the front, the rear and the relative tip speed ratios λ_F, λ_R, and λ_T which are divided by V_S, while changing the resistance, namely the load/output. The voltage E increases in proportion to the relative rotational speed λ_T while keeping the current I constant. The rear rotational speed λ_R is slower than the front speed λ_F, and each speed deviates substantially/obviously from regular speeds where the relative rotational speed λ_T is slower than 7. That is, the rotational speed should be adjusted carefully in response to the consumer demand for the electric power, because the tidal stream power unit is

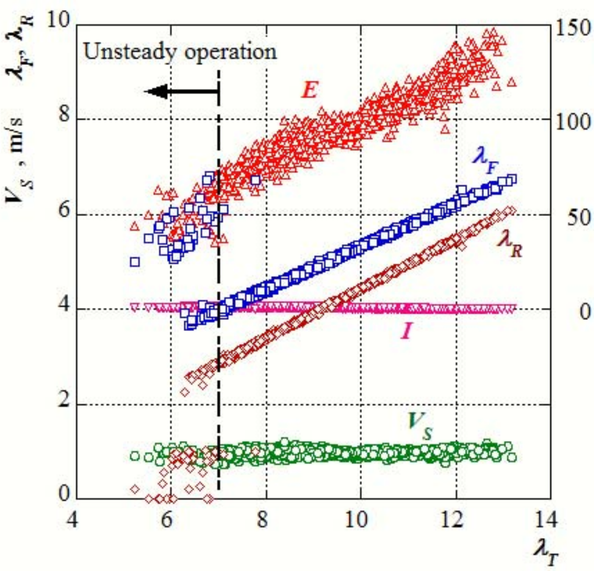


Figure 7. Voltage, current and rotational speeds.

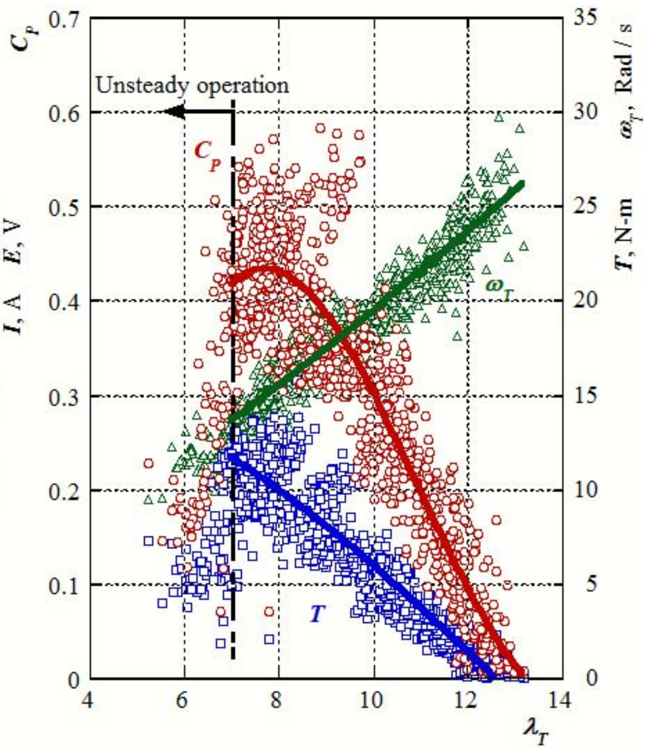


Figure 8. Output, rotational torque and angular speed.

unfortunately in unstable operation at λ_T slower than 7.

The power unit takes the maximum output with excellently high efficiency at the relative tip speed ratio slightly faster than 7, as recognized in Figure 8, where *Cp* is the output coefficient [= $2T\omega_T$ / ($\rho AV_S{}^3$), *T*: the rotational torque, ω_T: the relative angular velocity, ρ: the seawater density, *A*: the projection area of the front propeller]. Fluctuations of the rotational torque *T* and the rotational speed ω_T, which are affected by the tidal conditions at the offshore, contribute naturally the output.

4.2. *Start-up operation*

The output can be adjusted carefully by the rotational speed control system, not only at the normal operation discussed above but also at the switching the nose direction in response to the shift with the

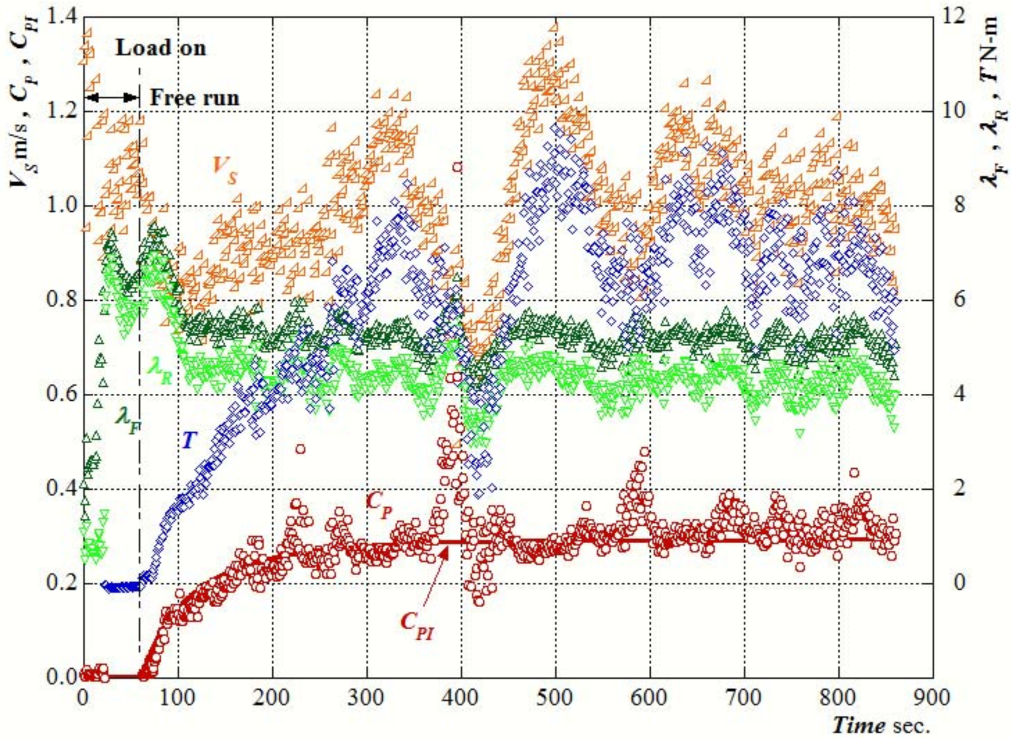


Figure 9. Performances at starting-up.

tide and/or starting-up after maintenance works. Figure 9 show the performances at the starting-up operation after an emergency shut-down while the tidal stream velocity fluctuating gustily, while the load is adjusted/controlled with the full line denoted by C_{PI}. The rotational torque, *T*, corresponds to the angular momentum change, which is affected directly by the stream velocity, fluctuates obviously in response to the velocity V_S. The rotational speeds, λ_F, λ_R, scarcely respond to the stream velocity, because the fluctuation of the rotational speed is suppressed not only by the inertia forces of the propellers and the armatures with the shafts but also by the generating load.

Figure 10 shows the performance at the change of the load while the unit is operated continuously, when the output is adjusted in response to the red line C_{PI}. The output can be changed smoothly even at the fluctuating tidal condition s. Besides, signals from the acceleration sensors and the strain gauges ensure that the power unit is in safety operations at the offshore.

5. Concluding remarks

The counter-rotating type tidal stream power unit, composed of tandem propellers and a peculiar generator with double rotatable armatures, was provided for verification tests at the offshore. The

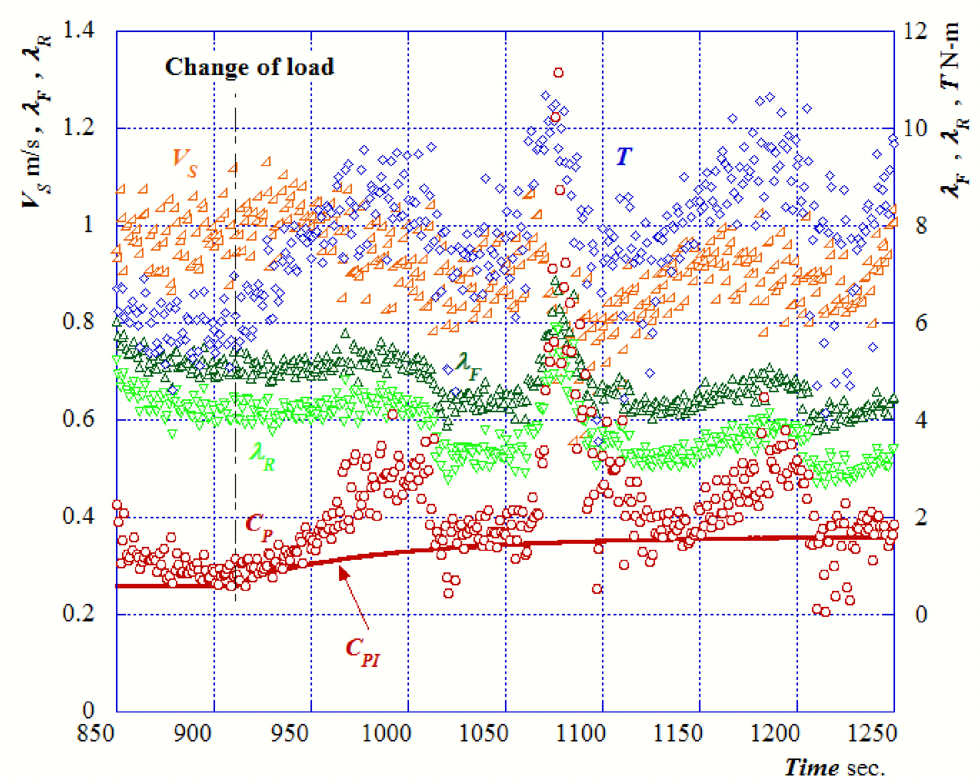


Figure 10. Change of the load while the unit is being running.

profile of the tandem was optimized numerically and the efficiency of the generator was improved by equipping with heat pipes and modifying the armature profiles. The shafts are equipped with the mechanical seals to protect the electric circuits from seawater. The rotational speed control system was also prepared not only to adjust the output but also to overcome the static friction torque due to bearings, slip rings and mechanical seals while starting-up. The power unit takes the maximum output with excellent efficiency at the relative tip speed ratio specified in the unit design. It was also confirmed that the unit can be start running after maintenance works and the output can be adjusted even while unit is running. Besides, it was ensures that the counter-rotating type tidal power unit is in safety operation even at offshore.

Acknowledgement

This verification tests for power generation and safety operation, were performed as “Development Project of Counter-Rotating Type Tidal Stream Power Unit” supported by the New Energy and Industrial Technology Development Organization (NEDO) in Japan. The authors wish to gratefully thank concerned parties in NEDO and Kowa Kogyo Co., Ltd which supports the tests.

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