Development of Energy-harvesting Unit and Propulsion Unit for a Robotic Buoy System

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***Abstract*—In this paper, we described about development of a robotic buoy for Internet of maritime thins (IoMT) technology. For IoMT, stand-alone data conllector is a key technology. The energy harvesting robotic buoy is proposed in the context. The proposed system is composed of three components: propulsion system, energy harvesting system, and buoyancy control system. The proposed system can hold its position within an uniform bound without mooring, and harvests wave energy. As a preliminary study, we developed hydrodynamic model for the whole system, and conducted simulation. Through the simulation, we implemented station keeping algorithm, and investigated optimal design parameters. To verify the simulation results we constructed prototype and carried out a series of experiments: station-keeping test, and power generation test. As a result, the whole system was proved that the propulsion system has sufficient manuverability for station keeping within 3 m, and peak power generation was 8 W.**

I. Introduction

There are many consensuses on using internet of things (IoT) technology at sea, or internet of maritime things (IoMT). Maritime information system still uses fragmented data system, and processes it manually. The IoT technology allows a system to collect harmonized information and integrate it, and, moreover the technology exchanges the information with other connected system and human users, which can change the paradigm how we manufacture, and manage our information [1].

To construct IoMT technology at sea, there are four layers: Sensing and identification object, high-speed network construction, information processing, and integrated application. Among them, a key is stand-alone smart-sensing device, or robotic buoy, as a sensing and identification object. For maintenance issue, the smart sensing device must be a self-sufficient and a self-supporting system in terms of energy harvesting and survivability. In this context we propose a self-supporting energy harvesting robotic buoy.

The proposed system is composed of three components: Propulsion system, energy harvesting system, and buoyancy control system. The propulsion system maneuvers the robot buoy and enables the buoy to hold its position without mooring. A particular condition of the propulsion system is low electrical power requirement with providing consistent thrust. As a candidate of the propulsion system, Wave glider is adequate. We used wave glider for station-keeping system instead of mooring.

The energy harvesting system utilizes wave energy as power source. We developed a new wave power-take-off system, which is called Wave turbine. Wave turbine is a self-rectifying turbine that can be used beneath a floating buoy interlinked by umbilical tether. Wave turbine has several characteristics: 1) 2-layered rotors counter-rotate so that the moment generated by rotation of one rotor countervails the moment of another rotor; 2) it can generate power from not only axial flow but lateral flow due to flappable blade. Under a current, therefore, the turbines performance can be enhanced.

The buoyancy control system has two functions. The first function is evasive maneuver when strong wave such as typhoons impacts the buoy system. The buoyancy control system enables the float to dive by changing positive buoyancy to negative one. The second function is tuning natural frequency of the buoy so that resonance of the buoy enhances the performance of Wave glider and Wave turbine.

In this paper, we only described about porpulsion system and energy harvesting system. we developed hydrodynamic model for the whole system, and conducted simulation. Through the simulation, we implemented station keeping algorithm, and investigated optimal design parameters. To verify the simulation results we constructed prototype and carried out a series of experiments.

This paper organized as follows. The proposed system and system description are presented in Section II. Simulation is decribed in Section III. Experiment and Experimental results are presented in Section IV. Finally, conclusion is drawn in Section V.

II. System Description

A. Proposed Concept

The first concept of mooring-less robotic buoy system was proposed by [2]. The points they aimed at are developing self-sufficient and self-supporting robotic buoy system. In this context, The proposed system consists of a propulsion system for station-keeping without mooring, an energyg harvesting system, and a buoyancy control system for survivability. Among these systems, the energy harvesting system and the propulsion system are described in detail.

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1) Propulsion system: A practical solution to keep the position of an floating object without mooring at sea is continuous patrol within an uniform bound. While the robotic buoy keeps its position by patrolling, continuous power consumption occurs. Therefore most important virtue for the propulsion system of the proposed system is low power requirement. In this context, Wave glider is an adequat candidate, because it utilizes only wave energy to move forward. The wave glider's mechanism is described in [4] and [5] (Fig. 1).

The wave glider converts vertical wave's motion to

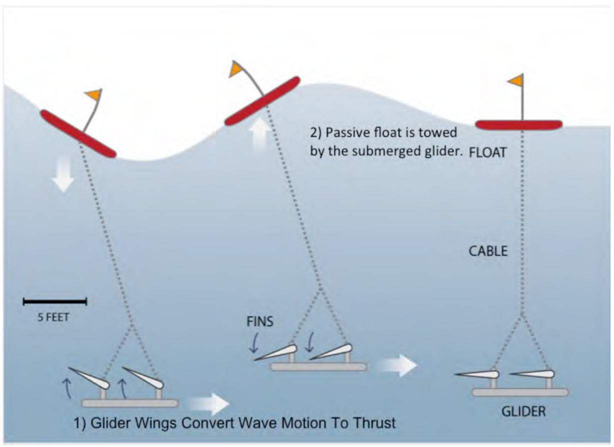

Fig. 1. Wave glider's mechanism.

horizontal forward motion by using flapping blades. The wave glider consists of a series of blades and a rudder. One of longitudinal side of blade is hinged on glider frame, which enables the blades to be flapped in respond to wave motion. The rudder controls the Wave glider's direction. For station-keeping by continuous patrol, high thrust is not needed, instead yaw moment should be enhanced. Therefore we optimized Wave glider such that the rudder size is increased, whereas the number of blades is decreased.

2) Energy harvesting system: For robotic buoy system, the energy hervesting system should satisfy movable wave-energy converting. In this context, Wave turbine was devloped. The wave turbine ustilizes the rise and fall of wave to rotate turbine. The wave turbine consists of two-layered rotor. The first rotor consists of four flapping blades which are hinged on the rotor frame in clock-wise direction. The second rotor has identical structure with first rotor but the the flapping blades are hinged in the oposite direction. The core mechanism of the Wave turbine exploits that of Wave glider (Fig. 2). The difference is arrangment of blades; in case of Wave glider, the blades are hinged on a straight lined frame, but, in case of Wave turbine, the blades are hinged on a rotor circlewise. Therefore the Wave turbine converts vertical wave's motion to rotational motion by flapping blades.

There are many options for integration with the propulsion system and the energy harvesting system. Two examples are presented in Fig. 3. In this paper, we only deal with In-a-line formation, because it is more simple than the othter.

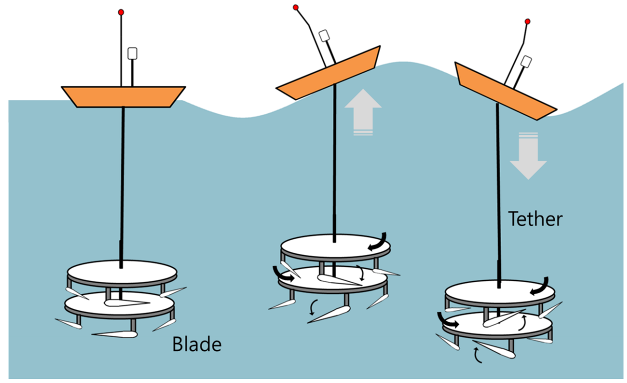

Fig. 2. Wave turbine's mechanism.

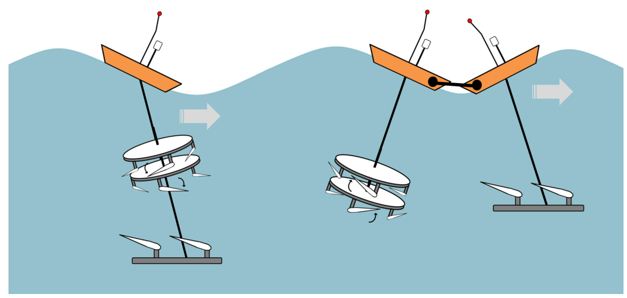

Fig. 3. Examples of integration of robotic buoy system: In-a-line formamtion (left), Towing formation (right).

B. Modeling

For feasibility study, we developed hydrodynamic model of the whole system. The heave dynamics of the robotic buoy can be described as:

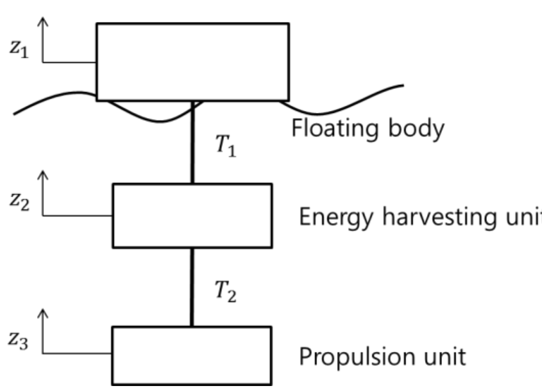

Fig. 4. Schematic image for dynamic modeling for proposed system

$$M_1\ddot{z}_1 = F_{wave} - F_{RAD1} - F_{RES1} - T_1, \quad (1)$$
$$M_2\ddot{z}_2 = T_1 - F_{RAD2} - F_{DRAG2} - F_{RES2} - T_2, \quad (2)$$
$$M_3\ddot{z}_3 = T_2 - F_{RAD3} - F_{DRAG3} - F_{RES3}, \quad (3)$$

where $M_{1,2,3}$ are inertia matrix of component 1, 2, 3 shown in Fig. 4, which include masses, and inertial moment; $\ddot{z}_{1,2,3}$ are acceleration of each component 1, 2, 3; F_{wave} is wave-induced force; $F_{RAD1,2,3}$ are radiation force on each component; $F_{DRAG2,3}$ are drag force on component 2 and 3; $F_{RES1,2,3}$ are hydro-static force on each component; $T_{1,2}$ are tensile force on tether 1 and 2. Horizontal motion of the robotic buoy system can be simplified as follows:

$$M\ddot{x} + D(\dot{x})\dot{x} = F_{th}, \quad (4)$$

where $M = diag[m_3,\ I_{zz}]$, $x = [x,\ \psi]^T$, $D(\dot{x}) = diag[C_{D,x},\ C_{D,\psi}]$, $F = [F_{th},\ N_{Rdd}]^T$. The tensile force of tether, T, can be calculated by

$$T_i = \begin{cases} if\ |z_{i+1} - z_i| > L_{tether} & T = k_e(z_i - z_{i+1} - L_{tether}) \\ otherwise & T_i = 0, \end{cases} \quad (5)$$

where z_i is heave position, L_{tether} is physical length of tether, and k_e is tensile coefficient for all i=1, 2, 3.

For detail description of Wave turbine, Wave turbine's blade model can be described as follows:

$$I_{zb}\ddot{\delta} + D_b\dot{\delta} + N_R = N_\delta - N_{fb}, \quad (6)$$

where I_{zb} is inertia moment of blades, δ is blade's angle of attack, D_b is drag coefficient, N_R is a moment casued by hydrostatic force of blades include buoyancy and gravitational force, N_δ is the flapping torque caused by vertical drag, and N_{fb} is the torque loss caused by friction.

Wave turbine's rotation is described as:

$$I_{zt}\ddot{\alpha} + D_t\dot{\alpha} = N_{tor} - N_{ft} - N_{ge} \quad (7)$$

where I_{zt} is inertia moment of Wave turbine, $\dot{\alpha}$ is angular velocity of Wave turbine about rotation axis, D_t is drag coefficient, N_{tor} is generated torque by each blade, N_{ft} is the torque loss caused by friction on turbine axis, and N_{ge} is generator's rate torque.

III. Simulation

To check the feasibility, we simulated the dynamic model using numerical software. The simulation was conducted in such a way as to investigate optimal hardware design and check the functional performance. In case of the whole buoy system, we checked the station-keeping ability whether the robotic buoy can hold its position within a uniform bound. In case of Wave turbine, we determined optimal design parameter to improve the efficiecy of Wave turbine and estimated the generated power.

A. Buoy system

We conducted station-keeping simulation with the developed hydrodynamic model. In this simulation we considered the Wave turbine as a drag object.

For station-keeping, we adopted a station-keeping algorithm from [3]. The algorithm is as follows:

$$\psi_d(t) = \tan^{-1}\left(\frac{y_d - y_G(t)}{x_d - x_G(t)}\right), \quad (8)$$
$$e(t) = \psi_d(t) - \psi_G(t), \quad (9)$$
$$T_d(t) = k_p e(t) + k_d\dot{e}(t) + k_i e(t)dt, \quad (10)$$
$$\delta(t) = \sin^{-1}\left(\frac{T_d(t)}{0.5C_D\rho A_R u|u|r}\right). \quad (11)$$

In simulation we applied a regular wave with amplitude of 0.3 m and frequency of 0.66 Hz. We assumed that the position estimation has gaussian error with an average of 0 and a standard deviation of 0.5. In addition the rudder actuator of the Wave glider has a bias error randomly within a stadard deviation of 5. Other parameters we used in simulation is presented in TABLE I.

The result of the station-keeping simulation is shown in

TABLE I
Parameter values used in station-keeping simulation.

Parameter	**Value**
Mass of floating body M_1	16.4 kg
Mass of Wave turbine M_2	20 kg
Mass of Wave glider M_3	11.3 kg
Density of water ρ	1030 kg/m^3
Blade size	1 x 0.15 (length x width, m)
The number of blade, n	3
Rudder size	0.2 x 0.15 (width x height, m)
Volume of floating body V_1	0.05645 m^3

Fig. 5. The red X-marker is both start point and target point. As a result, the buoy system held its position within 8 m. The position error depends on not only current but also rudder size. We optimaized the Wave gldier such that the Wave glider has bigger rudder than that of conventional Wave glider, instead we decreaded the number of blades.

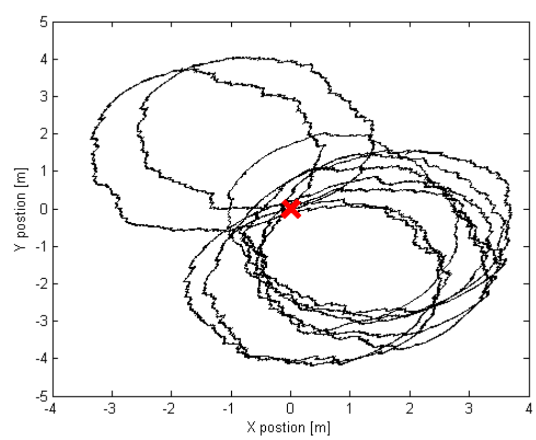

Fig. 5. Station keeping simulation. Red marker: target position and inition position.

B. Wave turbine

To increase the efficiency of the Wave turbine, we conducted optimization by quantitative simulation. The design parameters which affect the Wave turbine's power generation were considered as: blade size, blade's angle of attack, and turbine's hub size. The design parameters are investigated in such a way as to have higher rotational speed, because the high roational speed means high kinetic energy.

For blade-size simulation, we changed blade length, l, and chord, c, ratio as: $R_{l/c}$=[1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. The rotational speed was standized in such a way as:

$$Standard\ value = \frac{\dot{\alpha} - \bar{\dot{\alpha}}}{\sigma}, \tag{12}$$

where $\bar{\dot{\alpha}}$ is average of rotaional speed, and σ is standard deviation of rotational speed. The results is shown in Fig. 6. As a result, when $R_{l/c}$=5, the Wave turbine rotates with maximum speed.

For blade's angle of attack, we changed maximum angle

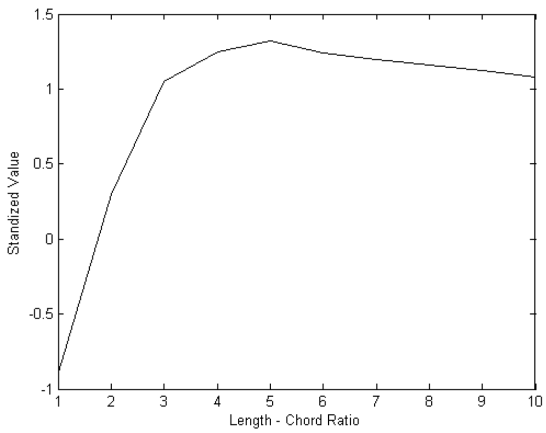

Fig. 6. Wave turbine's rotational speed variation with changing the blade length-chord ratio.

of attack from 6 ° to 24 °. The results is shown in Fig. 7. As a result, the Wave turbine's rotation was maximized at around 15 °.

For the turbine's hub size, the ratio of hub radius, r, and blade's chord length was varied as: $R_{r/c}$=[1, 2, 3, 4, 5, 6]. As a result, when $R_{r/c}$=2.5, the Wave turbine had maximum rotation speed (Fig. 8). Therefore the optimal ratio of hub size and blade length was calculated from optimal $R_{l/c}$ and optimal $R_{r/c}$, which was 0.5.

IV. Experiment

A. prototype

To verify simulation results, we constructed prototype and conducted a series of test. At first, the Wave glider was optimiazed in such a way as to enhance the Wave glider's yawing motion, because our Wave glider was not oriented for long journey but oriented for station keeping. Therefore we made the Wave glider's rudder bigger than conventional

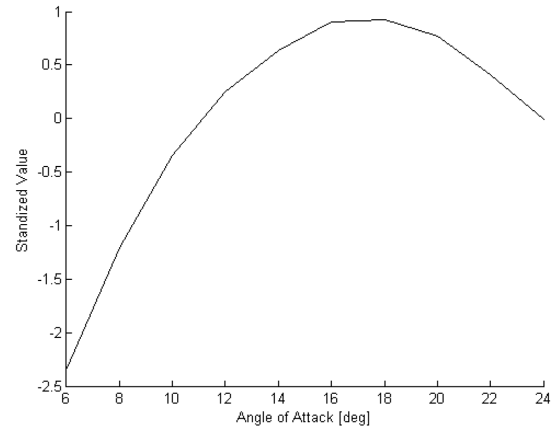

Fig. 7. Wave turbine's rotational speed variation with changing the blade' angle of attack.

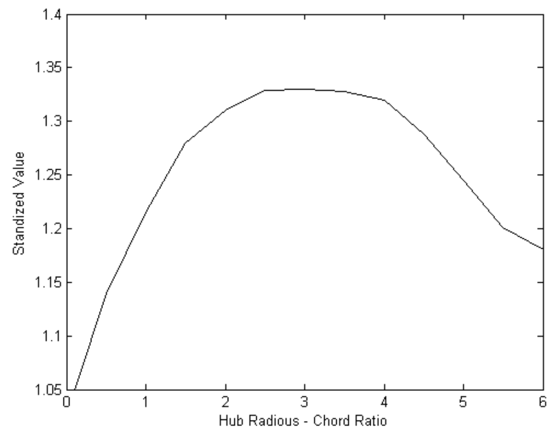

Fig. 8. Wave turbine's rotational speed variation with changing the hub radius-blade chord ratio.

Wave glider, and we decreased the number of blade.

For Wave turbine, we focused on designing turbine axis. The turbine axis was designed simply. The turbine axis was composed of three-coaxial-rotary system. The first coaxial rotary system is the generator shaft. The second coaxial rotary system is turbine axis cylinder itself. The last coaxial rotary system is slip-ring shaft. These three rotary systems rotate independently.

For blade's material we used acrylonitrile butadiene styrene (ABS), because its density is almost same with water, which enable the blades to flap freely without effect of gravitational force.

B. Station-keeping test

To test the maneuverability of the whole buoy system we built, tank test was conducted in wave basin. A resistant body causing drag was attached at between the floating body, and the wave glider. The resistant body emulated the drag of Wave turbine, which was a flat plate measured 80 x 80 cm and weighted 22.7 kg. The environmental setup of the wave basin was 0.3-m wave height and 0.4-Hz frequency. To measure the horizontal position, a camera was mounted on the top of basin. The horizontal trajectories was measured by tracking visual marker on the buoy. In this test, the control of the wave glider was operated by human operator manually.

The results is shown in Fig. 10. For 25 minute test, the buoy holds its positon within 3 m area. Even though this test was conducted manually, the maneuverability of the buoy system was proved as sufficient as an ability for station keeping.

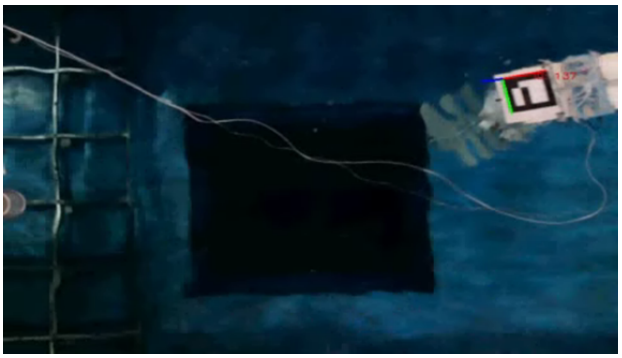

Fig. 9. Station keeping test conducted in wave basin.

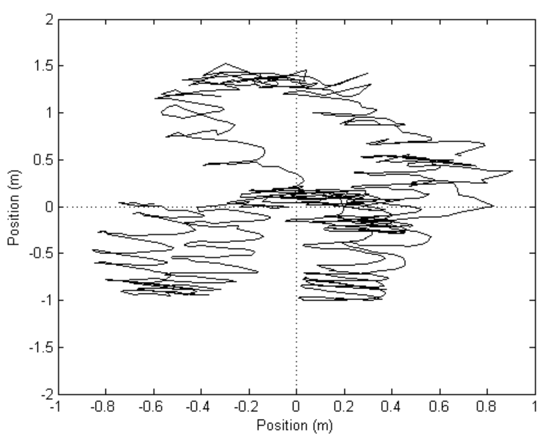

Fig. 10. Trajectory of the buoy over 25-minute test.

C. Power generation test

To obtain electrical power generated from Wave turbine, power generation test was conducted in wave basin. The wave properties were the wave length of 30 cm and the frequency of 0.4-Hz. The generated power from the wave turbine was estimated by AD converter of AVR. The estimated power was transmitted to laptop via Wi-Fi module.

Estimated electrical power is shown in Fig. 12. The peak power was 8 W and average was 0.52 W. The obtained data

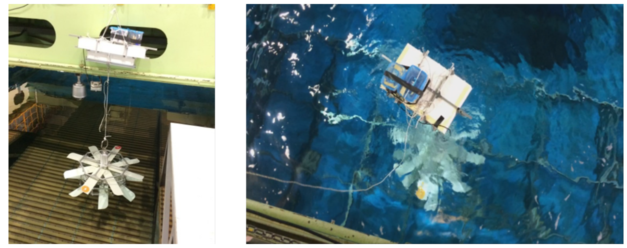

Fig. 11. Electrical power generation test using the Wave turbine; launching (left) and the wave turbine in wave (right)

was scattered. Two reasons were considered. Firstly, the drags applied on rotational direction was large than our expectation. Secondly, it could be because communication system did not deal with buffer data properly. So, these were fixed, and additional test was conducted.

The 2nd power generation test was conducted in indoor-

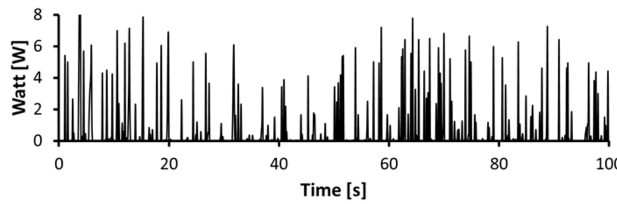

Fig. 12. The obtained data in the 2nd electrical power generation test.

water tank, because the wave basin had been in maintenance. A locomotive motion actuator was developed before the test. The locomotive actuator emulates the regular wave, which consists of: an AC motor, aluminuim frame and wire. The wave condition was set as: 0.3 m with the frequency of 0.5 Hz.

During test, Peak generated electrical power was 8 W, and average was 1.67 W. Scattered data problem in the previous test was improved. The instantaneous rotational speed was 20 rpm on average. All obtained data are described in Fig. 13.

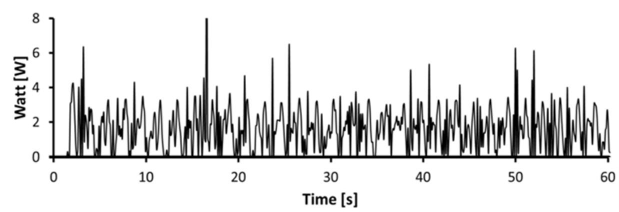

Fig. 13. The obtained data in the 2nd electrical power generation test.

V. Conclusion

We proposed a wave-energy harvesting robotic buoy for IoMT. A key for realize IoMT technology is self-supporting sensing object to collect data and to relay communication. In this context, we tested energy harvesting ability and station keeping ability without mooring.

At first, we simulated station keeping algorithm to be implemented Wave glider, and determined optimal design parameters of Wave turbine by quantitative simulation with hydrodynamic model. The determined optimal value is as follows: the ratio of blade length and chord length, $R_{l/c}$ = 5; maximum angle of attack, AOA= 15°; the ratio of hub radius and blade's chord length, $R_{r/c} = 2.5$. In experiment, we checked the manueverablility of the buoy system, which held its position with 3 m accuracy. The wave turbine generated 8-W peak power. As a future work, we will develop the fully developed system with that buoyancy control system, and will implement station keeping algorithm to the buoy.

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