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Research on Laboratory Test Method of Wave Energy Converter Wave-Wire Conversion Ratio in Irregular Waves

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Abstract: The laboratory test of the wave energy converter model is an important means to evaluate the performance of the device. At present, there are few performance tests for complete specifications under the irregular wave. Referring to the test methods and standards at home and abroad, combined with the actual test work experience in the laboratory, using the irregular wave power calculation formula with the effective wave height and the spectral peak period as parameters, then the wave-wire conversion ratio test method of the wave energy converter physical model under irregular waves in the laboratory is proposed. The method is applied to the basin test experiment of the physical model of the horn-shaped backward bent duct buoy (BBDB) wave energy converter. The research results show that the established test method and process of wave-wire conversion performance have achieved good application results in the irregular waves laboratory test, and can better reflect the device operating characteristics in real sea conditions. The test results provide data support for the model design of the wave energy converter in the next test stage, the demonstration test of the prototype, and the prediction of power generation in real sea conditions.

Keywords: wave energy converter; laboratory test method; physical model experiment; IRREGULAR wave test; wave-wire conversion ratio

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1. Introduction

As alternatives to traditional energy sources, the development and utilization of ocean renewable energy have received strong support from many countries. Since 2010, China has set up a special fund for marine renewable energy to develop marine energy exploitation technology and has achieved rich results. The test work of ocean energy converters is an important means to evaluate the performance of devices. Marine countries such as Europe have started to test and evaluate ocean energy converts earlier, and there are more than ten established marine test sites, including the European Marine Energy Centre (EMEC) in the UK, the Fundy Ocean Research Centre for Energy (FORCE) in Canada and the Folke-center marine energy test site in Denmark [1]. In 2009, the EMEC published a total of 12 guidelines and standardized documents for the experiment, test, and evaluation [2], the International Electro-technical Commission (IEC) has published technical specifications for the utilization of ocean energy [3], and the International Towing Tank Conference (ITTC) has published recommended procedures and guidelines for model tests of wave energy converters [4]. Compared to developed countries, China's research on the testing technology of ocean energy converters and the construction of advanced marine test sites started late.

Wave energy, as a type of marine renewable energy, is mainly used to generate electricity through wave energy converters (WECs). The main methods of research on WECs include theoretical analysis [5–8], numerical simulation [9–12], physical model experiments [13–17], and field tests [18,19]. In the physical model test, the hydrodynamic performance, power generation, and other important parameters can be tested, which can provide experimental data and a basis for the design and achievement transformation of the prototype, and verify the accuracy of the numerical calculation model and theoretical analysis model [20]. For example, [13] introduced a new point-absorber WEC with a moonpool buoy, and a 1:10 scale physical model was tested to prove the feasibility of the system. [14] constructed a 1:50 scale model testing for a 32-oscillating water column (OWC), V-shaped floating WEC, and the results were compared with the numerical model. In [15], experiments have been performed on large arrays of up to 25 heaving point absorber type WECs, for a range of geometric layout configurations and wave conditions. In [16], a one quarter scale prototype of an autonomous two body heaving point absorber was modeled, built, and tested in Wave tank. Based on model testing results, [17] built two working experimental PTO simulators on two different wave energy converters and obtained good application effects. Laboratory model testing is not only important to evaluate the performance, but also a key component to promote the industrialization and commercial application of ocean energy. Therefore, the research on the test methods of WECs has great significance.

In the indoor model test experiments of WECs, the complete performance test conditions include the test in regular and irregular waves [4]. However, at present, many tests are limited by the test environment, most of them are for the performance test of regular waves, and the complete and standard test of irregular waves is less. Irregular wave test conditions can better reflect the operating performance of the devices in real sea conditions. Therefore, this paper mainly studies the wave-wire conversion ratio test method of the WECs physical model in irregular waves.

In this paper, by referring to the test standards and methods of WECs and combining them with the actual test work experience in the Marine Dynamic Environment Laboratory of the National Ocean Technology Center, the laboratory pool test method for a wave-wire conversion ratio of the WECs physical model in irregular waves is presented. It is applied to the test of the horn-type backward bend duct buoy (BBDB) model developed by the Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, and the test results are evaluated and analyzed. The research conclusion, the proposed test method, and the actual test process in irregular waves can provide a reference for researchers at home and abroad to carry out irregular wave tests of WECs' physical models.

2. Test Methods

2.1. Wave Energy Converters Type

The energy conversion process of WECs is mainly divided into three stages: (1) Capture of wave energy by devices, which converts wave energy into mechanical energy for the relative movement of the device as a whole or inside; (2) convert the captured wave energy into pressure or hydraulic energy through other energy transfer devices such as air pressure or hydraulic pressure; (3) the energy converted in the second stage drives the generator to generate electricity and output the available electric energy. According to the physical process of energy extraction [21–23], most WECs are mainly divided into three types: oscillating water columns, oscillating bodies, and overtopping devices. The classification methods and types of WECs are shown in Table 1:

Table 1. Classification of WECs.

Classification Method	Type
process of energy extraction	oscillating water columns, oscillating bodies, overtopping devices
type of fixed	fixing, floating
process of energy transfer	Mechanical, pneumatic, hydraulic
position Installation	Shore, near-shore, offshore, bottom
structure	Nod-duck, eagle, raft, hinge, swing, BBDB

2.2. Experimental Stages

WECs need to go through a series of t experimental stages from concept to commercialization, which can be divided into concept validation, design validation, system validation, and prototype demonstration.

Each experimental stage corresponds to the technology readiness levels (TRLs) of the WECs [24], with TRL 1–3 corresponding to the proof-of-concept research phase, TRL 4–5 corresponding to the component, sub-system and system validation phase in the laboratory and/or simulated operating environment, and TRL 6–9 corresponding to the phase of the prototype demonstration in the operational environment through to system validation.

2.3. Test Environment Requirements

The laboratory physical model tests of WECs are usually carried out in the wave flumes or tanks, and the test environment is selected or equipped according to the test purpose. Combined with the actual test experience and referring to the Chinese industry standard *HY/T 0299-2020* "The methods of dynamic environment model test for oceanographic observation instruments in laboratory-General" and relevant regulations, the laboratory physical model flumes or tanks environment has the following conditions [25]:

1. Test flumes or tanks are equipped with wind, wave, and current generating facilities, and can ensure accurate simulation of wind-wave-current sea state conditions. For testing WECs, the test flumes or tanks are required to have the ability to generate regular and irregular waves, and the wave-making conditions should be repeatable;
2. Test flumes or tanks effective length should be more than ten times the set wavelength, and the first and last ends should be equipped with wave-absorbing devices to minimize the build-up of reflected waves;
3. To avoid the wall effect, the distance between the physical model and the wall of the test flumes or tanks should be greater than three or four times the model characteristic width;
4. The measuring instruments for the test should be matched, and calibrated before the test, such as force sensors, wave probes, high precision power analyzer etc.

2.4. Model Design

The scale of the WECs test model should be determined according to the test stage, test purpose, test flumes or tanks size, and wave-making ability. The similar conditions of geometric similarity, kinematic similarity, and dynamic similarity should be satisfied in model design and test.

In the actual test, it is difficult to meet all mechanical similarity conditions. Therefore, the model test should generally meet Froude's law of similarity, to ensure that the gravity between the model and the prototype is similar, which is represented by the Froude number:

$$Fr = \frac{U_p}{\sqrt{g_p L_p}} = \frac{U_m}{\sqrt{g_m L_m}} \tag{1}$$

where U is the characteristic velocity, g is the gravitational acceleration, and L is the characteristic width. In the model test, the U should be the upward or downward velocity of WECs under the action of waves. The subscripts p and m respectively represent the prototype and model parameters.

In the design and test of the WECs physical model, the physical parameters between the prototype and the model should meet the scale coefficient as shown in Table 2 as far as possible. Where, the λ is scale ratio, μ is the ratio of water density in the test flumes or tanks to the actual operating sea area.

Table 2. Similarity principle scale coefficient of physical quantities of prototype and model.

Parameter	Symbol	Coefficient
length	$\frac{L_p}{L_m}$	λ
period	$\frac{T_p}{T_m}$	$\sqrt{\lambda}$
velocity	$\frac{v_p}{v_m}$	$\sqrt{\lambda}$
acceleration	$\frac{a_p}{a_m}$	1
mass	$\frac{M_p}{M_m}$	$\mu\lambda^3$
force	$\frac{F_p}{F_m}$	$\mu\lambda^3$

2.5. Wave-Wire Conversion Ratio Calculation Method

In the test of laboratory wave flumes or tanks, for different types of WECs, it is difficult to test the wave power absorbed by the device in the three stages of energy conversion process, due to their complex internal structure. However, it is relatively simple to test the electrical power through the generator or air turbine.

Therefore, referring to the definition of wave-electricity total conversion efficiency in GB/Z 40295-2021 "Power performance assessment of electricity producing wave energy converters", this paper proposes the definition of wave-wire conversion ratio, to evaluate the overall energy conversion performance of the WECs, in the laboratory physical model test. The wave-wire conversion ratio, represented by η, is defined as the ratio of the average power generated of the WECs, represented by $\overline{P_E}$, to the incident wave energy within the incoming wave width per unit time:

$$\eta = \frac{\overline{P_E}}{P_w L} \times 100\% \tag{2}$$

$$\overline{P_E} = \frac{1}{N}\sum_{i=1}^{N} P_i \tag{3}$$

where L is the width of incoming waves, P_i is the WECs output electric power obtained by a single sampling of the high precision power analyzer, and N is the total number of samples, P_w is the incident wave energy per unit width.

For the calculation of incident wave energy under irregular waves, the results of different methods vary greatly. The results show that the irregular incident wave energy calculation method, in the laboratory, using ITTC and related empirical formulas has a good effect [26], and there are:

$$P_w = \frac{\rho g^2 H_s^2 T_E}{64\pi} \tag{4}$$

where H_s is the significant wave height, ρ is the density of water, T_E is the energy period and is defined by:

$$T_E = aT_p \tag{5}$$

where T_p is the peak period, and α is the shape parameter. When the irregular spectrum is P-M spectrum, a = 0.86, and JONSWAP spectra, a = 0.9.

The EMEC recommended guide "Tank Testing of Wave Energy Conversion Systems" gives the calculation method of irregular wave power in the time domain:

$$P_w = \frac{\rho g^2 H_s^2 T_z}{64\pi} \tag{6}$$

where H_z is the average period from zero-crossing analysis of time series.

3. Test Case

3.1. Model

This test model is the horn-shaped BBDB designed by the Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences. The wave-wire conversion characteristics of the model was tested under regular and irregular wave. The BBDB was first proposed by Masuda in 1986 [27], and the Guangzhou Institute of Energy Conversion has begun to study the BBDB wave energy conversion technology in 1989, and showed excellent energy conversion characteristics and economy [28,29]

This test device is a new wave power generation model developed by further optimizing the shape of the Backward Bent. The actual length is 3.78 m, the incoming wave width is 1.61 m, the height is 2.72 m, and the weight is 961 kg. The physical model is shown in Figure 1.

Figure 1. BBDB wave energy converter model with horn type.

3.2. Test Facilities

This test was carried out in the multifunctional hydrodynamic laboratory of the National Ocean Technology Center (NOTC). The laboratory issued the first indoor test report for a wave energy conversion system in China and has a domestic advanced multi-functional wave-making basin and wind-wave-flow circulation flume, which can conduct wind-wave-flow environment coupling tests. The laboratory environment is shown in Figure 2.

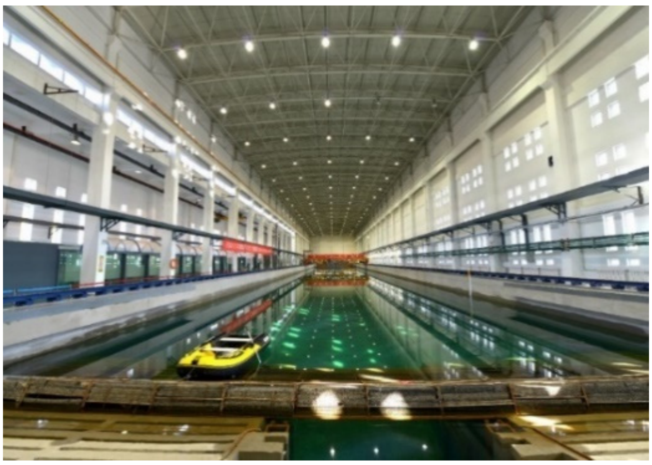


Figure 2. Multifunctional hydrodynamic laboratory of NOTC.

The multi-functional wave-making basin was 130 m long, 18 m wide, 6 m deep, and the maximum working depth is 5 m. It is equipped with a motion platform and track, which can simulate various marine environments such as wind and waves, and can carry out tests and experiments for all kinds of marine instruments and equipment prototypes or large-scale models. The index parameters of the wave-making basin are shown in Table 3.

Table 3. The experimental equipment and main indicators of multi-functional wave-making basin.

Facility	Indicators	Range	Accuracy
Wave-making system	Wave Hight	0.02–0.6 m	±4%F.S.
	Wave period	1.0–5.0 s	±4%F.S.
Wind-making system	Wind velocity	0–10 m/s	±5%F.S.
Motion platform	Move velocity	0–4 m/s	±4%F.S.

3.3. Test Scheme

3.3.1. Incident Wave Paraments Measure

In the test process, the wave height data should be collected and processed by the wave data acquisition sensor, and through the statistical analysis of the collected irregular wave height data, the incident wave energy can be calculated in real time. According to the regulations of wave hydrodynamic model test in Chinese industry standard *JTS/T 231-2021* "Technical Specification of modeling Test for Port and Waterway Engineering", the irregular waves basin test and data acquisition have the following reprovisions [12]:

(1) The significant wave height of irregular wave should not be less than 2 cm, and the peak period should not be less than 0.8 s; (2) the wave data collection interval should be less than 1/10 of the significant wave period; (3) for the continuously collected wave height data, in the stable wave making process of the wave maker of the test, there should be no less than 100 complete waves, and no less than 300 in the multiphase irregular waves test.

During the test, one digital wave probe was selected to collect the wave height data in real time, and another one was selected as a backup. The selected digital wave probes have been certified by the National Center of Ocean Standards and Metrology, the instrument model is YWH200-W, its measuring range is 0–1000 mm, and the accuracy is 0.3%F.S. Before the test, the selected wave probe should be calibrated, and Figure 3 shows the wave probe and calibration facility.

(**a**) (**b**)

Figure 3. Wave probe(**a**) and calibration facility(**b**).

The calibration method of the wave probe is as follows: first, select not less than four water depth values through the measuring cylinder, then obtain readings in the data acquisition system. Taking the reading as the input value and the water depth value as the output value, and fitting the curve of each wave probe reading, the fitting results are shown in Figure 4, and R^2 is the correlation coefficient.

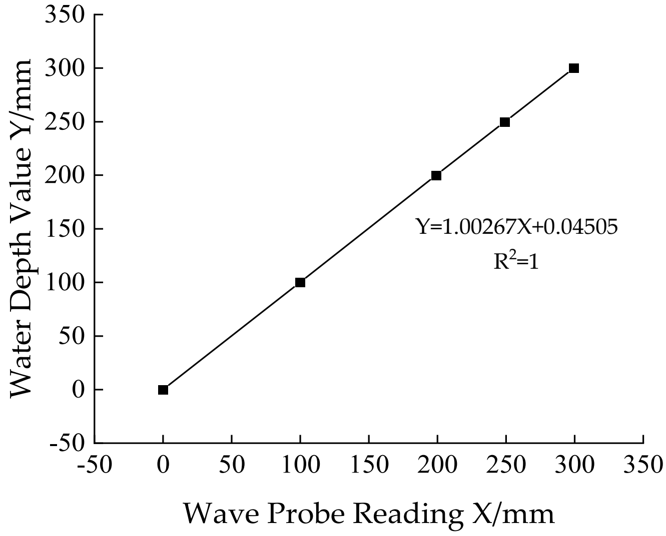


Figure 4. Fitting curve of wave probe calibration.

After calibration, the wave probe was placed according to the test layout (see 2.4) and real-time data were collected during the test. The sampling frequency was set as 50 Hz. Then, it is necessary to calibrate the wave-making basin, that is, input the test wave parameters into the control system of the wave maker, record the input values and output values, and adjust the wave-making transfer function to make the wave height of the test area meet the test requirements. Wave height data were processed and irregular incident wave energy was calculated according to Section 2.5.

3.3.2. Electric Power Measure

After the WECs model is placed in the test area according to the test layout, the output electric power is collected by the high precision power analyzer, which has been certified and the instrument model is HIOKI3390. The main performance parameters are shown in Table 4.

Table 4. The performance parameters of HIOKI3390 high precision power analyzer.

Project	Range	Accuracy
Voltage	15/30/60/150/300/600/600/1500 V	±0.05%rdg. ±0.05F.S.
Current	0.4/0.8/2/4/8/20/40/80/200 A	±0.05%rdg. ±0.05F.S.
Electric power	6.0000 W–2.2500 MW	±0.05%rdg. ±0.05F.S.
Sampling frequency	0.5 Hz–150 kHz	/

The selected high-precision power analyzer has been certified by metrology. The instrument model is HIOKI3390, and the main performance parameters are shown in Table 4. During the test, the power generation system of the horn-shaped BBDB model is connected to high-precision power analyzer in the motion platform, and the load is connected. The wire lead is passed forward through the power analyzer current clamp to measure the output current, and the voltage clamp is connected to the load to measure the output voltage with a sampling frequency of 20 Hz.

Figure 5 is the test site of the power analyzer, and the average output power is calculated according to Formula (3). Finally, according to Equation (2), the wave-wire conversion ratio of the horn-shaped BBDB model is calculated.

Figure 5. High-precision power analyzer test site.

3.4. Test Layout

This test layout is shown in Figure 6. The layout of the test model and instrument is as follows:

(1) Layout of test model: Referring to the industry standard " Technical Specification of modeling Test for Port and Waterway Engineering ", the distance between the test area and the wave maker should be more than six times the wavelength, so the test model is arranged in the test area 90 m away from the wave maker.

(2) Layout of wave probe: To avoid the radiation influence in the wave field of the test model and ensure the accuracy of wave height data acquisition, the wave probe is placed 60 m away from the wave maker and 0.5 m away from the basin side wall to collect the wave height data in real time.

(3) Layout of power analyzer: the output electrical signal of the test device is led to the motion platform through the electrical wire, and the electrical wire is forward through the current clamp of the power analyzer and connected to the battery load, and the voltage clamp of the power analyzer is connected to the load.

(4) Layout of the wave-making control system: the integrated wave-making control system is arranged in the control room. The tester controls the wave-making system in the control room and monitors the working condition of the wave-maker in real time.

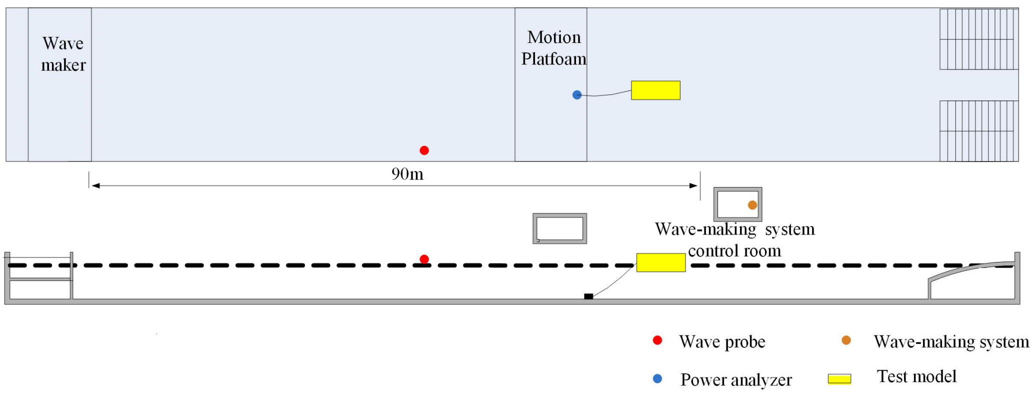


Figure 6. Test layout.

4. Test Result and Analysis

In this test, a total of 15 sets of irregular wave tests were performed, and the wave number in each group was 120. JONSWAP spectral analysis method was used to statistically process the irregular wave data, and the spectral peak enhancement factor was 5. According to Equation (2), the irregular incident wave power, within the incoming wave width of the test model, is calculated, and the wave-wire conversion ratio of the device is obtained. The test results are shown in Table 5.

Table 5. The irregular waves test results.

No	Significant Wave Height (H_s)/mm	Peak Period (T_p)/s	Incident Wave Power (P_w)/W	Average Output Electric Power $(\overline{P_E})$/W	Wave-Wire Conversion Ratio (η)/%
1	172.8	2.423	50.08	10.08	20.13
2	142.4	2.432	34.13	4.53	13.27
3	141.2	2.616	36.10	8.63	23.91
4	157.5	2.616	44.91	8.61	19.17
5	163.1	2.621	48.26	10.60	21.97
6	142.9	2.621	37.04	7.60	20.52
7	146.4	2.621	38.88	8.02	20.63
8	145.0	2.643	38.46	7.95	20.67
9	181.9	2.643	60.53	14.07	23.25
10	183.8	2.653	62.03	11.69	18.84
11	176.1	2.664	57.18	11.98	20.95
12	173.4	2.783	57.92	8.64	14.92
13	114.1	2.789	25.13	1.97	7.84
14	155.3	2.789	46.56	7.74	16.62
15	167.8	2.945	57.39	8.75	15.25

Figure 7 shows the wave-wire conversion characteristics of the horn-shaped BBDB test model in irregular waves with peak period and significant wave height. As can be seen from Table 5, in all irregular waves test conditions, the test model had the maximum wave-wire conversion ratio when the peak period was 2.616 s and the wave height was 141.0 mm, and Figure 8 is the test data of irregular wave and output electrical power at this condition. When the ITTC method is used to calculate the irregular wave power, there are eight groups of test conditions with wave-wire conversion ratio greater than 20%, and the maximum is 23.91%; when the EMEC method is used, the maximum is 30.17%. The difference between the two calculation methods is 6.26%. The source of the difference is that the characteristic wave period used between Formula (4) and Formula (6) is different, namely T_E and T_z, and T_E is related to T_p. For irregular waves, T_p can better reflect the wave periodic characteristics, so ITTC method is recommended to calculate the incident wave power.

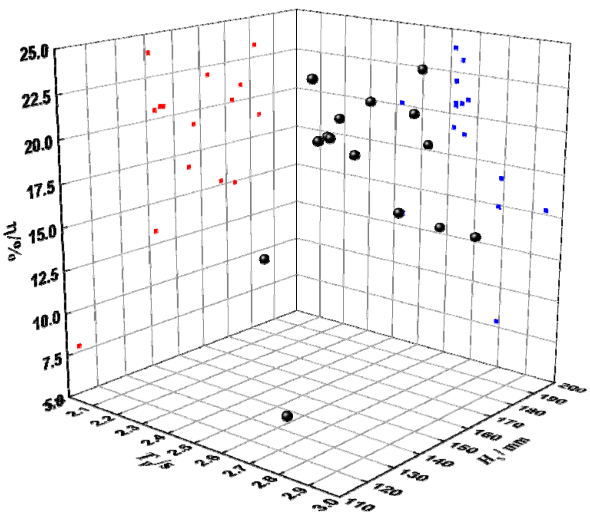
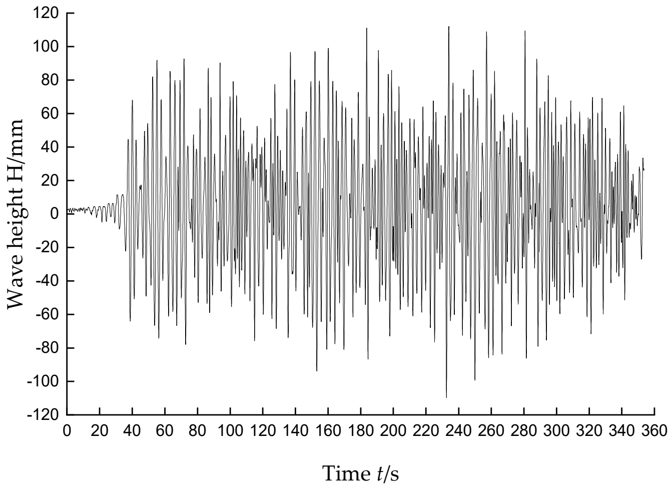
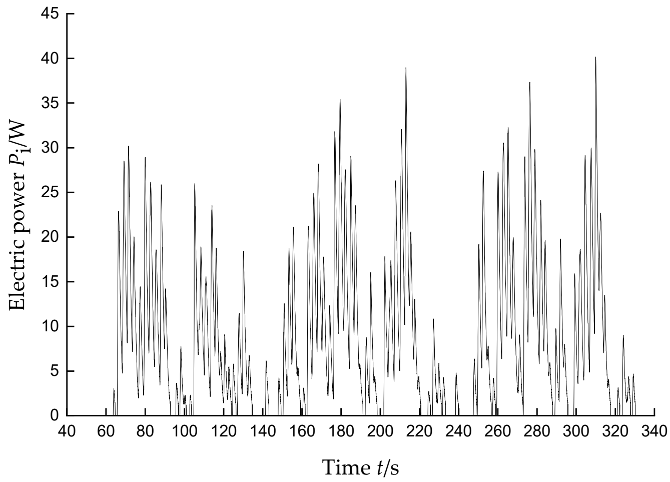


Figure 7. The wave-wire conversion characteristics of test model in irregular wave.

In addition to this test, the multifunctional hydrodynamic laboratory of NOTC has carried out the performance tests of two BBDB physical models developed by the Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences (shortened to "Generation Model 1" and "Generation Model 2" according to the sequence of test time), including regular and irregular waves test, and issued the test reports. The test site is shown in Figure 9.

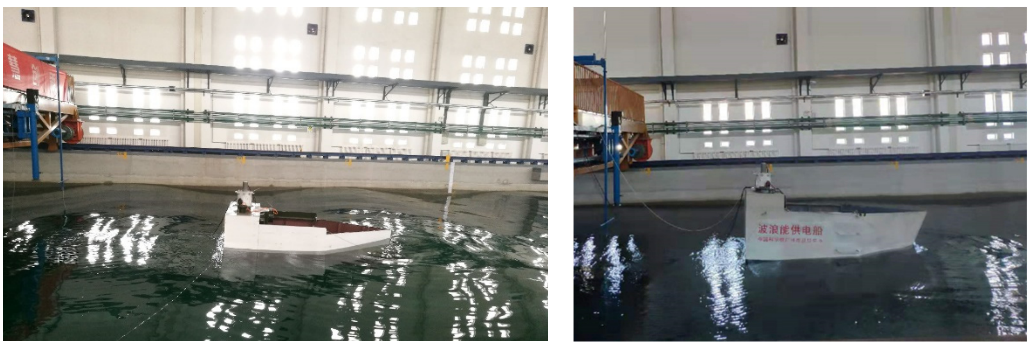


(**a**)



(**b**)

Figure 8. The data of wave height and electric power with maximum wave-wire conversion ratio.



(**a**) Generation Model 1 (**b**) Generation Model 2

Figure 9. The test site of the BBDB wave energy conversion laboratory physical model.

Table 6 shows the regular wave test results of the three BBDBs physical model, and the regular incident wave power is calculated according to the linear wave theory, and the average output electric power is calculated according to Equation (3). In the regular waves test of these test models, 58 groups of tests were carried out, and the number of waves was 50 in each test condition. Table 7 shows the maximum wave-wire conversion ratio of three generation models in the irregular wave tests. The test results show that the maximum wave-wire conversion ratio of horn-shaped BBDB is 63.36% when the wave period is 2.580 s and the wave height is 104.0 mm. There are 22 groups of test conditions in which the wave-wire conversion ratio is greater than 50%.

Table 6. Regular wave test results of three test models.

Model	Maximum Wave-Wire Conversion Ratio (η)/%	Average Period (T_m)/s	Average Wave Height (H_m)/mm	Incident Wave Power (P_w)/W	Average Output Electric Power $(\overline{P_E})$/W
Generation Model 1	35.65	2.45s	137.0	80.47	28.69
Generation Model 2	50.73	2.56	129.0	65.67	33.32
Horn-shaped Model	63.36	2.58	104.0	42.90	27.18

Table 7. Irregular wave test results of three test models.

Model	Maximum Wave-Wire Conversion Ratio (η)/%	Peak Period (T_p)/s	Significant Wave Height (H_s)/mm
Generation Model 1	19.33	2.45	258.0
Generation Model 2	20.55	2.50	273.0
Horn-shaped Model	23.91	2.61	141.2

As shown in Tables 6 and 7, with the continuous optimization of the BBDB wave energy conversion technology at the Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences, compared with the two previous models, the maximum wave-wire conversion ratio of the horn-shaped model in the regular wave test has been significantly improved, respectively, by 27.71% and 12.63%, showing better energy conversion performance. However, in the irregular wave test, the wave-wire conversion ratio of the horn-type model only increased by 4.58% and 3.36%, respectively.

Compared with the regular waves test results, in the irregular waves, the maximum wave-wire conversion ratios in the three models are 54.22%, 40.50%, and 37.73% of the regular waves, respectively. Since the irregular wave test conditions are closer to the actual operating sea conditions, the wave energy converters need to optimize the design of irregular wave characteristics, improve the wave-wire conversion ratio under the irregular wave tests, and provide a reference for the future prototype design in the actual sea condition test and operation. It is worth mentioning that in this BBDB model test, due to Froude's law of similarity, it is necessary to consider the impact of air compressibility when predicting the output power or wave-wire conversion ratio of the prototype. For example, to ensure the correctness of the prototype power prediction, the calculation methods of air chamber output power that consider model scales and air compressibility should be used.

5. Conclusions

Based on the reference to the literature and laboratory test work, this paper proposes the test method of WECs physical model performance in the irregular waves, which has a good application effect in the actual test of BBDB. The results show that in this irregular wave test, by comparing the regular wave test results, the maximum wave-wire conversion ratio is 37.73% of the regular wave, and the irregular wave test can better reflect the operating characteristics of the WECs in the actual sea state. In future wave tank tests, the PTO damping optimal test under irregular waves can be carried out for the test model, to better predict the maximum wave-wire conversion ratio of the prototype under real sea state.

The test results can provide data support for the optimization design of the model and prototype of WECs, for the further improvement of the wave-wire conversion ratio, the test and operation of the prototype, and the power prediction in the real sea state. The test method and process of practical application, proposed in this paper, can provide a reference for WECs laboratory model testing and research at home and abroad.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ma, C. *Marine Energy Development and Utilization Progress 2020*; China Ocean Press: Beijing, China, 2022; pp. 37–60.
2. Holmes, B. *Tank Testing of Wave Energy Conversion Systems*; European Marine Energy Centre (EMEC): Orkney, UK, 2009. Available online: https://www.emec.org.uk/tank-testing-of-wave-energy-conversion-systems/ (accessed on 20 October 2022).
3. International Electrotechnical Commission. *Marine Energy-Wave, Tidal and Other Water Current Converters-Part 1 Terminology: TS 62600-1*; International Electrotechnical Commission (IEC): Geneva, Switzerland, 2019.
4. International Towing Tank Conference. *ITTC Recommended Procedures Guidelines: Wave Energy Converter Model Test Experiments*; 29th ITTC Ocean Engineering Committee: Paris, France, 2021. Available online: https://www.ittc.info/media/9745/75-02-07-037.pdf (accessed on 20 October 2022).
5. Budar, K.; Falnes, J. A resonant point absorber of ocean-wave power. *Nature* **1975**, *256*, 478–479. [CrossRef]
6. Budal, K. Theory for Absorption of Wave Power by a System of Interacting Bodies. *J. Ship. Res.* **1997**, *21*, 248–254. [CrossRef]
7. Falnes, J.; Kurniawan, A. *Ocean Waves and Oscillating Systems: Linear Interactions Including Wave-Energy Extraction*, 2nd ed.; Cambridge University Press: Cambridge, UK, 2020.
8. Price, A.A.E.; Dent, C.J.; Wallace, A.R. On the capture width of wave energy converters. *App. Ocean Res.* **2009**, *31*, 251–259. [CrossRef]
9. Eriksson, M.; Isberg, J.; Leijon, M. Hydrodynamic modelling of a direct drive wave energy converter. *Int. J. Eng. Sci.* **2005**, *43*, 1377–1387. [CrossRef]
10. Johanning, L.; Smith, G.H.; Wolfram, J. Measurements of static and dynamic mooring line damping and their importance for floating WEC devices. *Ocean Eng.* **2007**, *34*, 1918–1934. [CrossRef]
11. Muliawan, M.J.; Gao, Z.; Moan, T.; Babarit, A. Analysis of a two-body floating wave energy converter with particular focus on the effects of power take-off and mooring systems on energy capture. *J. Offshore Mech. Arct. Eng.* **2013**, *35*, 031902. [CrossRef]
12. Goggins, J.; Finnegan, W. Shape optimisation of floating wave energy converters for a specified wave energy spectrum. *Renew. Energy* **2014**, *71*, 208–220. [CrossRef]
13. Liu, H.; Yan, F.; Jing, F.; Ao, J.; Han, Z.; Kong, F. Numerical and Experimental Investigation on a Moonpool-Buoy Wave Energy Converter. *Energies* **2020**, *13*, 2364. [CrossRef]
14. Kelly, T.; Dooley, T.; Campbell, J.; Ringwood, J.V. Comparison of the Experimental and Numerical Results of Modelling a 32-Oscillating Water Column (OWC), V-Shaped Floating Wave Energy Converter. *Energies* **2013**, *6*, 4045–4077. [CrossRef]
15. Stratigaki, V.; Troch, P.; Stallard, T.; Forehand, D.; Kofoed, J.P.; Folley, M.; Benoit, M.; Babarit, A.; Kirkegaard, J. Wave Basin Experiments with Large Wave Energy Converter Arrays to Study Interactions between the Converters and Effects on Other Users in the Sea and the Coastal Area. *Energies* **2014**, *7*, 701–734. [CrossRef]
16. Bosma, B.; Lewis, T.; Brekken, T.; Von Jouanne, A. Wave Tank Testing and Model Validation of an Autonomous Wave Energy Converter. *Energies* **2015**, *8*, 8857–8872. [CrossRef]
17. Beatty, S.; Ferri, F.; Bocking, B.; Kofoed, J.P.; Buckham, B. Power Take-Off Simulation for Scale Model Testing of Wave Energy Converters. *Energies* **2017**, *10*, 973. [CrossRef]
18. Allen, J.; Iglesias, G.; Greaves, D.; Miles, J. Physical Modelling of the Effect on the Wave Field of the WaveCat Wave Energy Converter. *J. Mar. Sci. Eng.* **2021**, *9*, 309. [CrossRef]
19. Xia, H.; Wang, X.; Li, Q.; Jia, N.; Chang, H.; Zhao, Z. Comparison and analysis of wave parameters in field test of wave energy converters. *Acta Energ. Sol. Sin.* **2022**, *43*, 251–255. [CrossRef]
20. Wang, X.; Zhang, Y.; Yu, Y.; Guo, Y.; Jia, N. Site testing and analyzing of wave energy converter. *Acta Energ. Sol. Sin.* **2020**, *41*, 15–20. [CrossRef]

21. Antonio, F.D.O. Wave energy utilization: A review of the technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 899–918. [CrossRef]
22. Liu, Y.; Wu, S.; Wang, D.; Wang, R. Research progress of ocean wave energy converters. *J. Shandong Univ. (Eng. Sci.)* **2021**, *51*, 63–75. Available online: http://gxbwk.njournal.sdu.edu.cn/CN/10.6040/j.issn.1672-3961.0.2021.234 (accessed on 20 October 2022).
23. Webb, I.; Seaman, C.; Jackson, G. *Oscillating Water Column Wave Energy Converter Evaluation Report*; The Carbon Trust: Oak Ridge, TN, USA, 2005; pp. 1–196. Available online: http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/marine-energy-accelerator/pages/default.aspx (accessed on 20 October 2022).
24. Mankins, J.C. *Technology Readiness Levels: A White Paper*; NASA, Office of Space Access and Technology: Washington, DC, USA, 1995.
25. Lu, K.; Li, J.; Wang, H.; Han, L.; Song, Y.; Zhu, X.; Xion, Y. *The Methods of Dynamic Environment Model Test for Oceanographic Observation Instruments in Laboratory-General*; Ministry of Natural Resources, People's Republic of China: Beijing, China, 2020.
26. Lu, K.; Wang, H.; Han, L. Calculation method of incident wave power of irregular wave for wave energy conversion model systems. *Acta Energ. Sol. Sin.* **2020**, *41*, 36–40. [CrossRef]
27. Masuda, Y.; McCormick, M.E. Experiences in pneumatic wave energy conversion in Japan. In *Utilization of Ocean Waves—Wave to Energy Conversion*; ASCE: Reston, VA, USA, 1986; pp. 1–33.
28. Wu, B.; Chen, T.; Jiang, J.; Li, G.; Zhang, Y.; Ye, Y. Economic assessment of wave power boat based on the performance of "Mighty Whale" and BBDB. *Renew. Sustain. Energy Rev.* **2018**, *81*, 946–953. [CrossRef]
29. Wu, B.; Li, M.; Wu, R.; Chen, T.; Zhang, Y.; Ye, Y. BBDB wave energy conversion technology and perspective in China. *Ocean Eng.* **2018**, *169*, 281–291. [CrossRef]