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Experimental study on primary efficiency of a new pentagonal backward bent duct buoy and assessment of prototypes

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ABSTRACT

To improve the wave energy conversion efficiency of backward bent duct buoy (BBDB), a pentagonal BBDB model was designed and fabricated for experiments in a wave flume (2D) as well as in a wave basin (3D). Incident wave height, wave period, water elevation in the air chamber and pressure difference between indoor and outdoor of the air chamber were measured. The test results show that the maximum value of capture width ratio (CWR) of the model in the wave flume is about 119.1%, which is much better than the highest value 79.1% obtained under the same experimental conditions in historical documents. Under regular wave, the maximum value of CWR tested in the wave basin is about 146.8%, which is equivalent to the highest value in historical documents and has relatively wide bandwidth. Under irregular waves, the maximum average value of CWR tested in the wave basin is about 87.2%, which is superior to the highest value 52% in historical documents. The combination of experimental results of the model and the latest research achievements of air turbine can help to break the thoughts that wave energy utilization technology can't balance low cost and high efficient conversion.

1. Introduction

The ocean has a rich reserve of wave energy, which is a kind of widely distributed, clean and renewable energy. Since a father and a son named Girard [1] got the first patent for wave energy utilization in France in 1799, people gradually have paid attention to the wave energy conversion theory and technology, and a variety of wave energy conversion technologies [1–6] have emerged in endlessly. The study of floating-structure technology is the mainstream field of wave energy conversion in the various technologies, and it can be divided into single and double (multiple) floating-structure technology. The single floating-structure technology has high reliability because of lack of the relative motion of the structure parts and can save materials, so it can pave the way to utilization wave energy resources at a low cost and high reliably. The Backward Bent Duct Buoy (BBDB) technology is the prominent representative for single floating-structure technologies. A BBDB converter consists of an L-shaped duct, a buoyancy chamber, an air chamber, an air turbine and a generator. The working medium is air and it belongs to the technology of Oscillating Water Column (OWC). The OWC technology has the advantages of simple mechanism, low cost of manufacturing and transportation, no moving parts in the water, and low effect of marine life. The authors realize that the BBDB converter captures wave energy under the action of waves, makes itself oscillating to obtain a large mechanical energy and then through the subsequent conversion system (the duct, the air chamber, the air turbine and the generator) converts mechanical energy to electrical energy. Due to the use of its mechanical energy, the BBDB technology is expected to achieve high conversion efficiency.

Since the concept of the BBDB converter was first proposed by Yoshio Masuda [7] in 1986, scholars from China, Japan, India, Ireland, etc. have carried out many experimental studies in 2D and 3D tanks. The experimental studies on the conversion performance from wave power to pneumatic power and electric power are shown in Table 1. The Capture Width Ratio (CWR) is defined as the ratio of the pneumatic power to the incident wave power in the width of wave crest through the converter. Constructed prototypes for sea trials are shown in Table 2.

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Table 1
Development of experimental studies on BBDB conversion efficiency.

Year	BBDB scale Length*Breadth* Height (mm)	Maximum CWR			Maximum overall wave to wire efficiency
		Regular waves in 2D tank	Regular waves in 3D tank	Irregular waves in 3D tank	Regular waves in 3D tank
1995 [9]	663*510*480	40.5% (China)			
1997 [8]	923*510*480	73.3% (China)			
1998 [10]	3860*2200*1760		204.5% (China)		37% (China)
1999 [11]	1670*870*900		172.8% (India and Japan)	52% (India and Japan)	
2000 [12]	1183*510*480	79.1% (China)			
2001 [13]	1183*510*480		150.7% (China)		
2008 [14]	1050*600*563	35% (Japan)			
2011 [15]	850*780*600	70% (Japan)	78% (Japan)		49% (Japan)

Table 2
Development of prototypes for sea trials.

Year	Events
1986 [7]	The concept of BBDB technology was first proposed by Yoshio Masuda.
1990 [9]	The twin-hull BBDB wave power generation navigation buoy with weight of 1.76 t was constructed for sea trial over 1 year in China (Three built in all).
1993 [9]	The WBF2.86 × 2.2A BBDB generation navigation buoy with cuboid front and cylindrical behind buoyancy chamber and weight of 2.5 t generated power 26 W at 0.15 m wave height and 2.75 s wave period in China.
1994 [8]	The SWBF2.86 × 2.2 BBDB generation navigation buoy with weight of 2 t generated power 40 W at 0.15 m wave height and 2.41 s wave period in China (Three built in all).
1995 [16]	The 5 kW BBDB wave-activated generation device with the weight of 19 t was on sea trials in China, and its instantaneous power recorded is up to 5.7 kW.
2006 [17]	The OE Buoy prototype with the weight of 28 t went on sea trials for more than three years, and withstood the test of several major hurricanes in Ireland.

Obviously, Japanese scholars firstly proposed the BBDB technology, then Chinese scholars carried out numbers of experimental studies on the conversion performance of several BBDB models, Indian and Japanese scholars also carried out experimental studies on the conversion performance of several BBDB models. Some prototypes are constructed for sea trials, and one of the prototypes was operated reliably more than three years. However, the results tested in the wave tanks showed that the CWR of the BBDB models in regular waves is less than 80% in 2D tank, and the maximum CWR in irregular waves is 52% in 3D tank. Therefore, in order to improve the conversion performance of the BBDB technology, a new BBDB model was designed through theoretical analysis and tested in this paper based on the previous researches and new idea on the BBDB technology, and more precise mathematical model, measuring instruments and means, were used to study the CWR of the new model in a variety of conditions. According to the experimental results, appropriate parameters and conditions can be found, and this will be the basic data for designing low-cost, high reliable, high-performance and easy-maintenance BBDB wave power devices.

2. Wave energy conversion theory and experimental data processing method of the BBDB converter

The BBDB converter converts wave energy into electrical energy through air. In regard to the energy conversion of the BBDB converter, first, the BBDB converts wave energy into pneumatic energy as the primary conversion. Second, the turbine on the BBDB converts the pneumatic energy into mechanical energy of the turbine as the secondary conversion. Third, the generator on the BBDB converts the mechanical energy into electrical energy as the third conversion. This paper studied the primary conversion of the new BBDB converter in the laboratory. During the energy conversion of a BBDB converter in a wave flume (2D), energy is conserved as the following [18,19]:

$$E_{wave} = E_1 + E_2 + E_3 \tag{1}$$

where E_{wave} is the total energy of incident waves, E_1 is the energy captured by the BBDB converter, E_2 is the reflected wave energy caused by the converter and E_3 is the transmitted wave energy through the bottom of the converter. Obviously, if E_2 decrease and E_3 is a constant, E_1 will increase. The shape of the converter has a great effect on E_2. On the stern of the BBDB converter, there is a large opening. This opening will not make waves when the converter is pitching and surging, which objectively lead E_2 to decrease.

In the experiments, the pressure difference between the air chamber and atmosphere is not beyond 2 kPa and it is not beyond 2% of atmospheric pressure which is 101.325 kPa. So the condition of incompressible air flow can be met during the energy conversion of the converter. Suppose that air flow is incompressible, the pneumatic average output power P_{air} is given via the pressure difference and water level difference of the air chamber as the following [8]:

$$P_{air} = \frac{1}{n}\sum_{i=1}^{n}(L_{i+1} - L_i) \times \Delta P_i \times S/\Delta t \tag{2}$$

where ΔP_i is the pressure difference between the air chamber and atmosphere for the i-th, which is measured via pressure difference sensor, L_i and L_{i+1} are the i-th and i+1-th sampling water levels in the chamber respectively, which is observed via the wave height meter, S is waterline cross-sectional area of the air chamber, n is total sampling number and Δt is sampling time interval.

The average air flow of the chamber is

$$Q_{av} = \frac{1}{n}\sum_{i=1}^{n}|L_{i+1} - L_i| \times S/\Delta t \tag{3}$$

The average pressure difference of the chamber

$$\Delta P_{av} = \frac{1}{n}\sum_{i=1}^{n}|\Delta P_i| \tag{4}$$

These two parameters are important to design air turbines for the oscillating water column converters.