PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

*Phil. Trans. R. Soc. A* (2012) **370**, 472–480
doi:10.1098/rsta.2011.0154

REVIEW

# Wave energy technology in China

BY YAGE YOU[1,2,*], SONGWEI SHENG[1,2,3], BIJUN WU[1,2] AND YUNQI HE[1,2]

[1]*Guangzhou Institute of Energy Conversion, and* [2]*Key Laboratory of Renewable Energy and Gas Hydrate, Chinese Academy of Sciences, Guangzhou 510640, People's Republic of China*
[3]*Graduate University, Chinese Academy of Sciences, Beijing 100049, People's Republic of China*

This paper traces the research stages of China's study of wave energy technology, summarizing the findings and deficiencies of each stage from oscillating water column, through onshore oscillating buoy to floating Duck. It also highlights the major innovations in China's new floating Duck device.

**Keywords: oscillating water column; oscillating buoy; floating Duck; fault-tolerant power take-off; underwater appendage; energy storage mooring system**

## 1. Research on oscillating water column technology

Wave energy technology research in China started in 1980. From 1985 to 2001, a major research effort was undertaken to investigate and develop oscillating water column (OWC) technology. Four OWC devices were built: onshore devices of 3 kW [1], 20 kW [2] and 100 kW [3], and a floating 5 kW backward-bent-duct buoy (BBDB) [4,5]. In these projects, our OWC devices revealed their major deficiencies, the biggest of which is their low efficiencies [6].

Based on a rough modelling, we found that the output of an air turbine rotating at a constant rate of 1000 r.p.m. in an airflow with average power of 52.5 kW is only 4 kW (figure 1) [7]. This simulation is based on the efficiency of a turbine in steady airflows with different blade attack angles (figure 2), and a power loss of 9 kW due to the friction of the turbine and generator at a rotation rate of 1000 r.p.m.

From the simulation, we can see that a turbine and a generator with large rotating inertia are not able to follow the reciprocating airflow, and will have significant power loss because of stall (when the attack angle is greater than 12.6°) and negative output (attack angle less than 4°). Inertia is the main reason for the low efficiency because it decreases the angular acceleration of the turbine. If the inertia was small enough so that the rotation rate could follow the changes in the airflow more closely, stall would not occur, and negative output would

---

*Author for correspondence (youyg@ms.giec.ac.cn).

One contribution of 18 to a Theo Murphy Meeting Issue 'The peaks and troughs of wave energy: the dreams and the reality'.

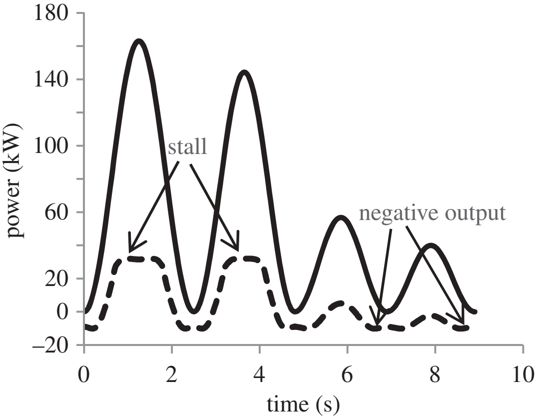

Figure 1. Output of the air turbine at a rotation rate of 1000 r.p.m. in reciprocating airflow. Dashed line, turbine output; solid line, airflow power.

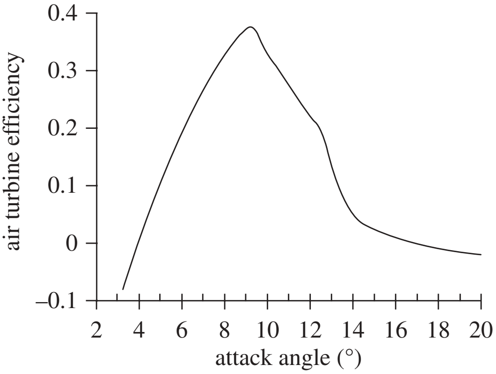

Figure 2. Efficiency of the air turbine at different blade attack angles.

be mitigated. But the acceleration of the airflow is so large that the inertia of the turbine and generator can never be small enough. The only way of avoiding stall would be by adjusting the pitch of the blades to the best attack angle [8,9]. However, negative output at dead centres of OWC can never be avoided, except when the rotation of the turbine decreases to zero.

## 2. Onshore oscillating buoy

Comparing the case of a turbo-generator in the reciprocating airflow of an OWC with that of a hydraulic ram in the reciprocating motion of an oscillating body (OB) in waves, one of the differences is that the acceleration of the airflow of an OWC is dozens of times larger than that of the motions of an OB. Therefore, it is much easier for the ram to follow the motions of an OB than for the turbo-generator to follow the airflows of an OWC. In most cases, there is an energy

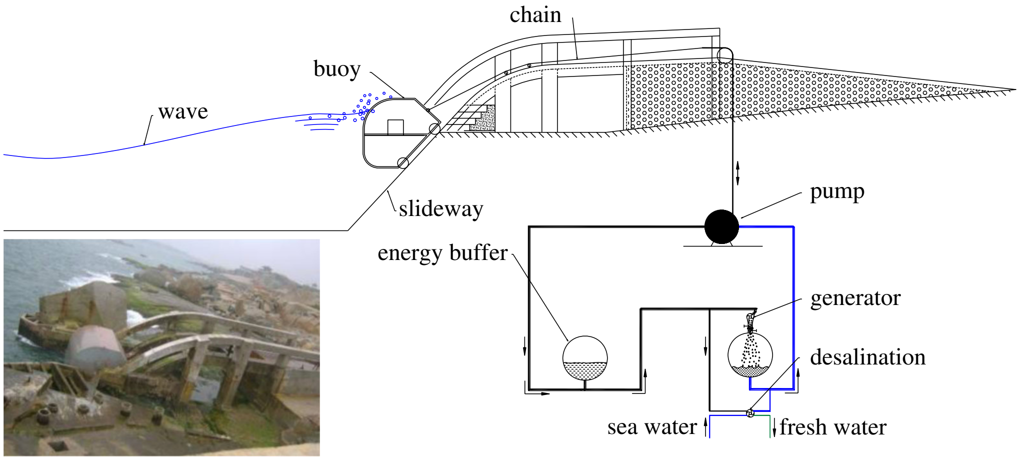

Figure 3. Sketch and photo of onshore oscillating buoy. (Online version in colour.)

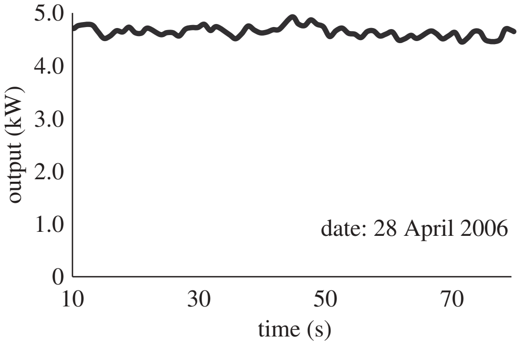

Figure 4. Stable output of the OOB in waves of significant height 0.7 m with an average period of 4 s. The maximum output was 4.9 kW, minimum was 4.4 kW and average was 4.6 kW.

buffer between the ram and the hydraulic motor, so the hydraulic power will be smoothed significantly, and the hydraulic motor and the generator will operate at a more stable rate. That is why the power take-off (PTO) system of an OB is more efficient than that of an OWC.

After 2001, we turned our attention from OWC to OB and designed an onshore oscillating buoy (OOB, figure 3), incorporating a hydraulic PTO. After 5 years of research, development and construction, the OOB was trialled in 2006.

The OOB consisted of a buoy with six wheels, enabling it to move easily inside the concrete slideway built onshore. The PTO of the OOB had a capacity of 50 kW. The buoy oscillated along the slideway, driving three hydraulic pumps by chains to convert wave power into hydraulic power. There was a buffer with a capacity of 10 MJ making the hydraulic power smooth, so that the motor-generator converted the hydraulic power into stable electrical output (figure 4).

As an onshore wave energy converter (WEC) with the characteristics of a wave terminator, OOB has quite a large capture width ratio [6,10]. However, its reliability was not satisfactory. After operating for 29 h, an important shaft was

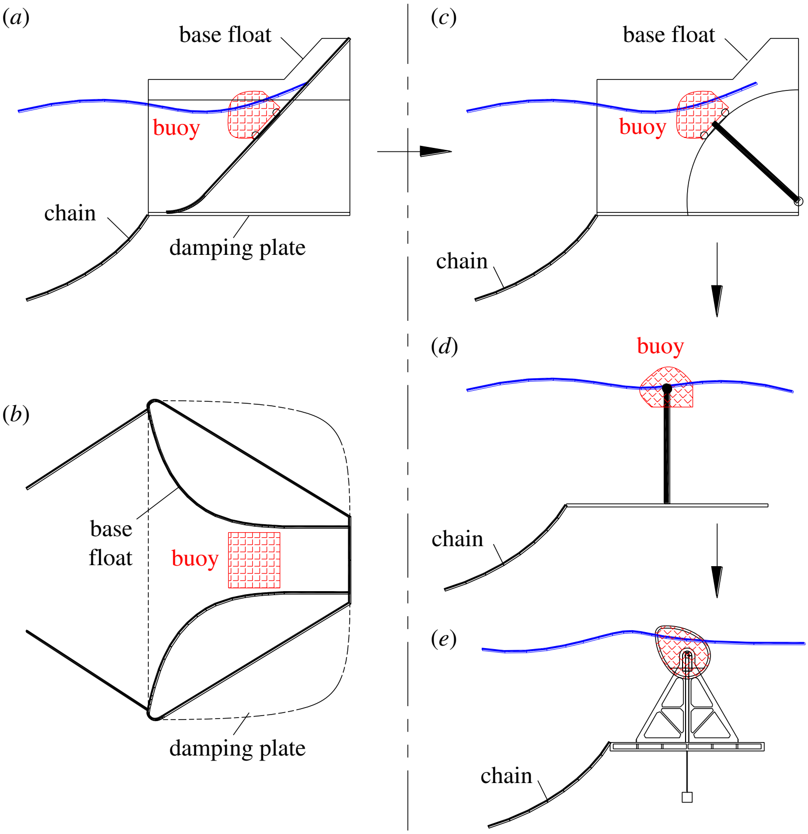

Figure 5. Evolution of the concept from the dual-float system to the floating Duck. The (*a*) cross section and (*b*) top view of the dual-float system are shown. Steps in the evolution are shown on the right, first (*c*) to eliminate collisions, then (*d*) to reduce synchronous motion between the buoy and the float, and finally (*e*) to reduce wave radiation. (Online version in colour.)

broken, causing the failure of a transmission chain, and the buoy went out of control. It fell into the sea, and went missing in a very strong typhoon 15 days later [6].

## 3. Floating Duck

The short trials of the OOB verified the high efficiency and stability of the hydraulic PTO. We subsequently began to develop a floating OB WEC, taking advantage of the PTO system to develop an efficient and low-cost WEC. Combining the ideas of OOBs and the Danish floating over-topping WEC Wave Dragon [11], we conceived a floating WEC with two floats (named a 'dual-float system', figure 5), a floating harbour and an oscillating buoy. In the floating harbour, there is a slideway, on which the oscillating buoy travels.

Soon we found the defects of this concept; it was almost impossible to avoid collisions between the floating buoy and the floating harbour, or to prevent synchronous movements. To address these problems, we decided to submerge the

Figure 6. The 10 kW floating Duck in a real sea trial. (Online version in colour.)

floating harbour to make it an underwater appendage, and replaced the slideway with a shaft, and the floating buoy with the Duck (figure 5*e*). The Duck is a great invention of Prof. Stephen Salter [12], known as a third-generation WEC with a capture width ratio as high as about 90 per cent. Its high efficiency is very important in the small wave conditions common in Chinese waters.

To develop the floating Duck WEC, we have been working on the following research matters:

- mooring system;
- construction method;
- deployment;
- typhoon survival; and
- corrosion protection.

After 3 years of research, testing and construction, a floating Duck with a capacity of 10 kW was deployed at the end of 2009 (figure 6). Sea trials showed the high efficiency of the floating Duck, though many design problems remained.

The major progress of our device lies in three innovations, namely the fault-tolerant PTO, the underwater appendage technology and the energy storage mooring system.

### (*a*) *Fault-tolerant power take-off*

The working principle of our floating Duck device is as follows: firstly, the Duck is driven by waves so that it pitches about its shaft to convert wave power into mechanical energy; secondly, the Duck's motion drives hydraulic rams by wheels rolling on specially designed guides to convert mechanical energy into hydraulic

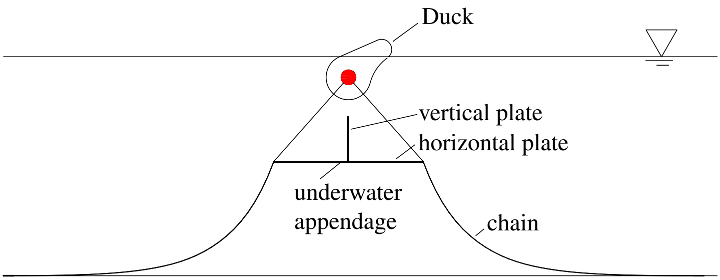

Figure 7. Sketch of the underwater appendage. (Online version in colour.)

energy (which is smoothed to a stable output by an energy buffer); finally, a hydraulic motor and an electrical generator convert the stable hydraulic energy into stable electrical energy.

The so-called fault-tolerant PTO allows a tolerance of any kind of large deformation and displacement of the Duck up to 100 mm, including the motion along the shaft. This feature avoids all machining of the shaft, allows serious distortions of the Duck, and provides for easier installation. All these features increase reliability and decrease the cost of construction.

### (*b*) *Underwater appendage*

Our underwater appendage is a structure with two plate grillages that are perpendicular to each other. The underwater appendage is welded to the shaft (figure 7). The function of the underwater appendage is to hold the shaft against pitch, surge and heave. Hydrodynamic tests showed that the underwater appendage worked very well in stabilizing the Duck, effectively lowering the force on the mooring system and increasing the reliability of the device. Apart from this, since the appendage increased the draught of the device, wave transmission was decreased and therefore more power could be captured. By this means, the conversion efficiency of the device was considerably increased.

### (*c*) *Energy storage mooring system*

For a floating WEC, damage in high seas may occur when a mooring system fails by anchor dragging and broken chains. The reason lies in the fact that the WEC has no effective horizontal restraint to stop it before the chains become taut. Calculation reveals that a loose chain has very limited potential energy before it is straightened, and a straightened chain has very limited strain-energy tolerance—usually a total of only several tens of kilojoules. Under these circumstances, once the mooring system is straightened, while the device is still moving, either the chain will break or the anchor will be dragged, since the mass of the WEC together with its added mass is several hundred tonnes.

To address this problem, we added an energy storage component to the mooring system, consisting of a ‘dynamic sinker’, a ‘static sinker’, a ‘front buoy’ and a ‘back buoy’ (figure 8), which kept the chains tight and applied considerable horizontal restraints to the device. Calculation showed that if the buoyancy of the back buoy were 185.7 kN, the net weight of the dynamic sinker 200 kN, the buoyancy of the

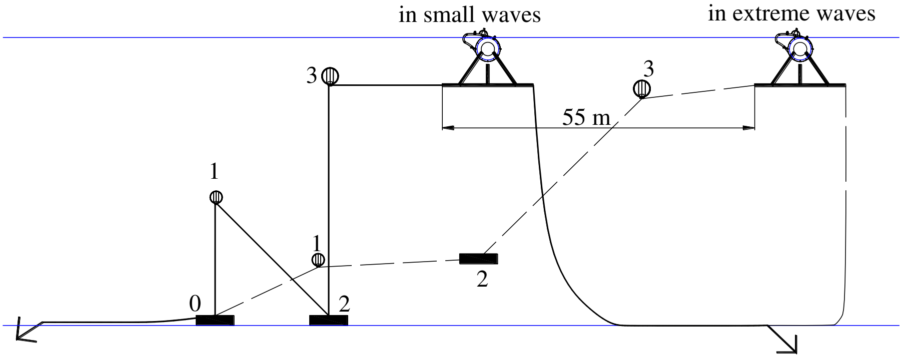

Figure 8. The energy storage mooring system: 0, static sinker; 1, front buoy; 2, dynamic sinker; 3, back buoy. (Online version in colour.)

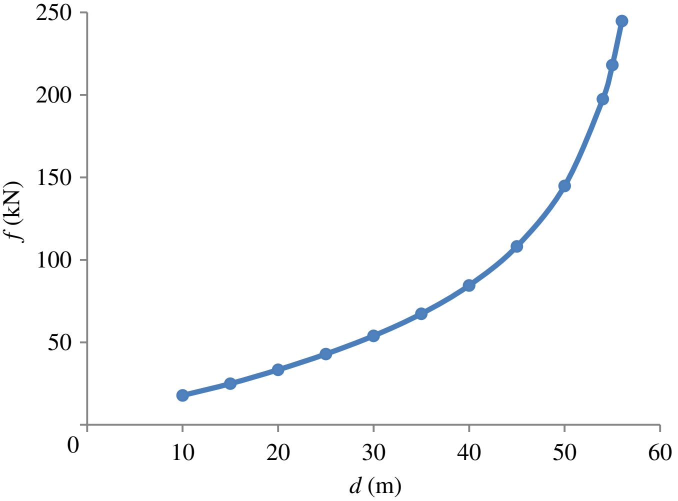

Figure 9. Horizontal resistance $f$ of the mooring system plotted as a function of horizontal displacement $d$. (Online version in colour.)

front buoy 90 kN, the lengths of the chains from the underwater appendage to the back buoy, to the dynamic sinker, to the front buoy and to the static sinker were 20 m, 40 m, $20\sqrt{2} \approx 28.28$ m and 20 m, respectively (figure 8), then the potential energy of the whole system was about 6.53 MJ, when the Duck was pushed 55 m back by waves. This is about 100 times greater than the total potential energy of the ordinary mooring system at failure. Experiments showed that the energy storage mooring system decreased the strains of the chain and anchor significantly.

The calculation of the horizontal restraining force as a function of horizontal displacement involves an eight-variable set of nonlinear algebraic equations. To solve the equations, a Lie group was used to transfer the algebraic equations to ordinary differential equations, which were numerically solved by a Runge–Kutta method [13]. Figure 9 shows results for the conditions defined above.

## 4. Discussion

In an overview, the development of WECs in China has gone through three stages represented by the technologies of OWC, oscillating buoy and floating Duck. Efforts have been made to decrease the generating cost of WECs. After initial designs exhibited low efficiency, high mechanical loss and unstable output of OWCs, we turned to the development of the OOB, but its high construction cost led us to develop a floating Duck design. Until now, the technological advance has been positive; the recent development of the floating Duck has the features of high efficiency and low construction cost, though its viability needs to be improved by long-duration sea trials. Other research activities in China that are not mentioned above include pendulum research since 1992 [14], the linear generator buoy [15,16] and an overtopping device [17] since 2008.

Wave energy converters have to accommodate large forces at low velocities. This may benefit construction costs significantly. Though large forces imply large structural components, low velocities decrease the demand for precision machining and installation difficulties. These usually account for a significant part of the total cost.

Different circumstances will yield different solutions. OWCs may be less efficient in short-period waves than in long-period waves. But they are good enough for supplying electricity for navigation buoys. They are small in size, light in weight, low in cost and very reliable—so far we have not found other WECs to be competitive in these conditions.

Many thanks to Prof. Stephen Salter and Prof. Johannes Falnes who passed on knowledge of the Duck and point absorber and have provided many papers and textbooks. Besides, the idea for the energy storage mooring system came from Prof. Salter. Also, many thanks to Prof. Francis Farley who invited the first author to attend the meeting; and many thanks to the Royal Society for financial support for the travelling and accommodation. The researches are supported in part by grants from: the National High Technology Research and Development Programme of China, no. 2006AA05Z426; Key Projects in the National Science and Technology Pillar Programme, no. 2008BAA15B01; National Natural Science Foundation of China, no. 50679079; and Ocean Energy Specific Fund GHME2010GC01.

## References

1 Liang, X., Gao, X., Zheng, W., Yu, Z., Jiang, N., Hou, X. & You, Y. 1990 Experimental wave power plant at Pearl River estuary. In *Proc. Int. Conf. on New and Renewable Energy, Beijing, China, 14–18 June 1990.* Beijing, People's Republic of China: International Academic Publishers.

2 Yu, Z., Jiang, N. & You, Y. 1994 Power output of an onshore OWC wave power station at Dawanshan Island. In *European Wave Energy Symp.: Proc. Int. Symp., Edinburgh, UK, 21–24 July 1993* (eds G. Caratti & G. Elliot). East Kilbride, UK: National Engineering Laboratory.

3 You, Y., Zheng, Y., Shen, Y., Wu, B. & Liu, R. 2003 Wave energy study in China: advancements and perspectives. *China Ocean Eng.* **17**, 101–109.

4 Liang, X., Jiang, N., Wang, W. & Sun, P. 1997 Research of 5 kW backward-bent-duct buoy wave power device. *J. Ocean Eng.* **17**, 55–63. [In Chinese.]

5 You, Y. & Yu, Z. 1995 The simulation of a backward bend duct wave power device. In *Proc. Second European Wave Power Conf., Lisbon, Portugal, 8–10 November 1995*, pp. 389–395. Glasgow, UK: Brown, Son & Ferguson.

6 You, Y., Zheng, Y., Ma, Y., Wu, B., Yan, X., Sheng, S., Li, C. & Li, H. 2006 Report of R&D of oscillating buoy wave energy generation system. Report of Guangzhou Institute of Energy Conversion, Guangzhou, China. [In Chinese.]

7 You, Y., Zheng, Y., Ma, Y., Yan, X., Sheng, S., Li, C. & Li, H. 2006 Report on research of key technologies of stand-alone wave power generation system. Report of Guangzhou Institute of Energy Conversion, Guangzhou, China. [In Chinese.]

8 Taylor, J. R. M. & Caldwell, N. J. 2000 Design and construction of the variable-pitch air turbine for the Azores wave energy plant. In *Proc. 3rd European Wave Energy Conf., Patras, Greece, 30 September–2 October 1998* (ed. W. Dursthoff), pp. 328–337. Hannover, Germany: University of Hannover.

9 Oceanlinx. 2009 *Oceanlinx. Technical information.* See http://http://www.oceanlinx.com/assets/FactSheets/oceanlinx_technical_facts_sheet_v3_eng.pdf.

10 Su, Y., You, Y. & Zheng, Y. 2002 Investigation on the oscillating buoy wave power device. *China Ocean Eng.* **16**, 141–149.

11 Kramer, M. & Frigaard, P. 2005 Reflectors to focus wave energy. In *Proc. 6th European Wave and Tidal Energy Conf., Glasgow 29 August–2 September 2005.* Glasgow, UK: Energy Systems Research Unit, University of Strathclyde.

12 Salter, S. H. 1974 Wave power. *Nature* **249**, 720–724. (doi:10.1038/249720a0)

13 You, Y., Zhai, J. & Wang, M. 2010 Lie group method for nonlinear algebraic equations. Report of Guangzhou Institute of Energy Conversion. Guangzhou, China.

14 Yang, Q., Li, H., Li, D., Jiang, H., Li, X. & Liu, S. 2000 Research and development of Daguan Island 30 kW pendulum wave power station. Report of National Ocean Technology Center, Tianjin, China. [In Chinese.]

15 Wu, B., Lin, H., You, Y., Feng, B. & Sheng, S. 2010 Study on two optimizing methods of the oscillating type wave energy conversion devices. *Acta Energ. Solaris Sin.* **31**, 769–774.

16 Wu, B.-J., Sheng, S.-W., Zhang, Y.-Q. & You, Y.-G. 2010 Wave-power conversion characteristic for a vertical complicated cylinder. *J. Harbin Eng. Univ.* **31**, 1023–1028.

17 Liu, Z., Hyun, B.-S., Hong, K. & Jin, J. 2010 3D Numerical investigation on reservoir system for an overtopping wave energy convertor. In *Proc. 9th (2010) ISOPE Pacific/Asia Offshore Mechanics Symp., Busan, Korea, 14–17 November 2010.* Cupertino, CA: International Society of Offshore and Polar Engineers (ISOPE).