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Nature rules hidden in the biomimetic wave energy converters

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ABSTRACT

Some animals and plants have special functions and structures. They are the result of biological evolution and Nature's ideas. The question to answer is how to use these biomimetic ideas to design the next generation of wave energy converters. In this paper, the characteristics of the existing wave energy converters are analyzed using biomimetic ideas and then the design rules hidden in them are established. First, the characteristics of wave energy are introduced. Next, the state of the art and methods of energy extraction by the wave energy converters are analyzed. Then based on the introduction of the biomimetic design knowledge, the biomimetic features, principles, and characteristics of the wave energy converters are explained. Lastly, the association rules hidden in the biological features and engineering features are mined based on the Apriori algorithm. These rules will assist the development of the next generation of biomimetic wave energy converters and provide future research trends.

1. Introduction

With the significant increase in the global energy needs, the development and utilization of sustainable energy become more urgent. Ocean waves can provide a tremendous energy source that can be captured and converted into electricity by wave energy converters (WECs). Unfortunately, there are a number of barriers on the road to developing and commercializing WECs. The main reason for this relates to the number of requirements for WECs, including survivability [1], stability [2], eco-friendliness [3] and economics [4] amongst others that are still difficult to meet. Thus, finding new ways of solving these problems is required.

Biomimetic design can trigger design inspiration and provide additional ideas for new potential designs [5]. Using biomimetic design methods in engineering design, designers might be able to achieve new, novel and unexpected design results [6,7]. Thus the use of biomimetic design methods and principles has the potential to become an additional tool for the development of novel WECs.

In this paper, the characteristics of wave energy are summarized in Section 2 and the methods of energy extraction of the existing WECs are analyzed in Section 3. Section 4 introduces the basic concepts and classification of the biomimetic designs, whilst the bionic characteristics, working principles, and characteristics of the biomimetic WEC devices are analyzed in more detail in Section 5. In Section 6, the association rules hidden in the biological features and engineering features are mined based on the Apriori algorithm. Finally, the insights and conclusions are drawn and synthesized.

2. Wave energy

Wave energy usually means ocean wave energy. It is one of the renewable energy sources in the world and becoming the highlight of the coastal countries. These countries vigorously carry out wave energy conversion studies [8], especially in the United Kingdom with the larger investment and the more significant research outputs [9]. According to the data from the EMEC [10], the number of wave energy devices in each country has been calculated and shown in Table 1. It can be seen clearly from Table 1 that Europe and the United States have made great progress in the development and application of wave energy and developed a number of wave energy conversion devices.

Wave energy is a truly less polluting and renewable energy source following the solar energy and wind energy. Wave power generation has a number of advantages, including large energy storage, high energy density and minimal impact on the environment. At the same time, wave energy has uncertainties like being oscillatory and irregular [2]. Wave parameters, like wavelength, period, frequency, speed, steepness and crest height, do vary with different time, space, climate, and other factors, thus causing the corresponding wave energy to vary. As wave resource has high density, thus the forces acted on the devices and the related manufacturing expenses will increase accordingly. Therefore,

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Table 1
Percentage of a total of 170 WECs in different countries.

Country	%	Country	%	Country	%	Country	%
USA	24.1	Portugal	2.4	Germany	1.2	Greece	0.6
UK	18.2	Canada	1.8	Belgium	1.2	Chile	0.6
Norway	8.8	India	1.8	Japan	1.2	Singapore	0.6
Denmark	7.1	China	1.8	France	1.2	Korea	0.6
Spain	5.9	Italy	1.2	Israel	1.2	Slovenia	0.6
Australia	4.7	Hong Kong	1.2	Turkey	0.6	Wales	0.6
Ireland	3.5	Russia	1.2	Mauritius	0.6	New Zealand	0.6
Sweden	2.4	Finland	1.2	Brazil	0.6		

The challenge in the development of WECs is to design a device that can work normally on the worst storms, at the same time produce amount of energy meeting the design requirements. So far WECs have been too costly and financially demanding to promote commercial harvesting [12].

the frequencies and directions of most WEC devices are set in certain ranges [11].

3. Wave energy converters (WECs)

3.1. The current state of the WECs

WECs can harness energy from waves and convert it into useful power. They utilize the circular movement of waves to turn a turbine or a generator or convert the motion directly to electricity [13]. In order to reduce costs and improve availability, significant research has been carried out that includes the following aspects:

- Energy extraction. Research has been carried out on designing and optimizing energy extraction in order to improve the efficiency of extracting energy. A dual-channel WEC [14] and a cycloidal WEC [15] were designed to produce a steady stream of electricity in unidirectional irregular deep ocean waves. On the other hand, the efficiency of the device in absorbing energy, capturing wave power, energy extraction and energy exchange was optimized by using the biomimetic design methods [16].
- Power Take Off (PTO)/turbine. Some researchers focus on the development of novel PTO systems. A drag type water turbine [17] and a new radial self-rectifying air turbine [18] were developed for power take-off. Other researchers are studying the more effective power take-off system to convert the motion of WECs into usable electricity. The optimization of PTO effective parameters has been presented using a biomimetic algorithm to optimize the power output and energy transfer [19].
- Energy modeling research. There are some mathematical models provided for designing point absorbers WEC, oscillating water column WECs and oscillating wave surge converters [20] in order to acquire electricity from waves. These numerical models can be used to calculate the hydrodynamic responses in waves and the power produced.
- Optimization, operation, and control systems of arrays. Relations between the hydrodynamic coefficients were researched and used for optimizing the power output system of the wave farm [21].
- Wave energy testing facilities. Some experimental studies and test facilities design [22] were carried out to study the movement and energy conversion performance of the WEC with swing arms and floaters.
- Mooring system. Some new mooring systems for floating devices adapted to the wave energy have been developed to increase safety or better interaction with the converter [23].

It can be found from above analysis that the role of biomimetic design is not to be ignored in the development of WECs and the biomimetic design is used for designing and optimization of devices. Moreover, energy extraction research receives more attention. A WEC with low cost, high efficiency, high survivability and being eco-friendly provides a novel solution for energy extraction.

3.2. Methods of energy extraction

Different devices use a number of various methods for extracting wave energy. Hence, methods for extracting wave energy have also many different types. The common methods for energy extraction include heave, pitch, surge, overtopping and oscillating water column. As new ideas continue to develop, new methods for energy extraction are being explored.

Thus for the development of WECs, it is very important to extract energy from ocean waves with low cost and high economics. To meeting these requirements there is not an easy design approach available to date, but nature could provide assistance to solve this problem, using the biomimetic design method.

4. Biomimetic design

Biomimetics can be used for solving complex human problems by imitating models, systems, and elements of nature [6]. Biomimetic design can be applied to inspire engineering innovation with the help of different analogies based on the function, principle, shape, structure, material, process, organizational strategy, and behaviors of the various biological entities. It is publicly viewed as an innovative and novel solution to actual engineering problems and has been applied to develop renewable energy generation techniques [24].

There are two methods to support biomimetic design. One method is solution driven. The exploration of potential applications is inspired by an interesting biological phenomenon. The other method is problem-driven. The searching for biological analogies is stimulated according to a given problem in this method. The problem-driven method is more widely applied to design and optimize the WECs [25].

5. Bio-inspired WECs

To improve the performance of the devices, some developers design novel WECs inspired by biological phenomena. This section illustrates the use of a general biomimetic design method by examples. In addition to the working principle of the various devices, the technical characteristics of the device are analyzed. The advantages and disadvantages of the devices are also highlighted.

5.1. Mimicking the single feature

5.1.1. Mimicking the function - bioWAVE

The bioWAVE is a wave power system inspired by the moving and reorienting of kelp plants (Fig. 1a). Kelps are the kind of large seaweeds and grow in shallow oceans with low-temperature. Kelps consist of blades, the handle, and the holdfast. The blades are flat or leaf-like structures and their tips are gradually narrowed (Fig. 1b). They are usually 2–5 m long, 20–30 cm wide with a thin edge. The blades grow from long stem-like the stipes. The bottoms of them have root and anchor the kelps to the seafloor [27].

Not only can the bioWAVE move back and forth like kelps, but also lay flat on the sea floor during storm conditions. This new underwater power generator that was developed by an Australian company is equipped with all these features. The bioWAVE is fixed or anchored by a triangular foundation to the ocean floor similar to kelps. Then, the device can capture the wave energy with wider and deeper range. When waves move, the blades are pushed back and forth. The column is made to move back and forth relative to the foundation. It would drive permanent magnet motors and convert the low-speed oscillation movement into the high-speed rotation movement.

The bioWAVE WEC has some specific features, such as high