Design And Power Generation Performance Analysis of A Rim-Driven Wave Energy Generator

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Design and Power Generation Performance Analysis of A Rim-driven Wave Energy Generator

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Abstract
Wave energy exploitation is getting more attention from researchers Many types of devices that can convert wave energy into electricity have been designed. At present, engineers and scientists are researching how to make a simple and efficient wave energy capture device. This paper explored the rim-driven generator. In a rim-driven wave energy generator, the rotor blade could harvest kinetic energy of wave motions. The blade is inside of the generator and the gap between the stator and the rotor is water-filled. This structure could improve the compactness and reliability of the wave energy generator. The paper studied the influence of the arrangement of the blade and the structure of the generator on the performance of the generator. Analytical models were designed to obtain generator's performance. The result could optimize the design of generator and improve the energy conversion efficiency.
Keywords: Rim-driven; PM Generator; Wave Energy; Analytical Models

1. Introduction
With the global exploitation to the ocean and deeper delving beneath the ocean's surface, various marine equipment are deploying in the ocean. The energy-intensive equipment is powered by cable. And the low-energy equipment which needs low voltage and electrical energy is powered by the battery[1]. However, its running time is short and battery needs to be replaced regularly. That results in maintenance headaches and high cost. So a power supplying way which is simple, reliable, low-cost and eco-friendly is wanted. Nowadays, ocean temperature difference energy, salt difference energy, wave energy and tidal energy are utilized to provide electric power. And intelligent management system is adopted to realize multi-energy complementation[2].
The utilization of an unconventional solution based on Rim-Driven Turbine (RDT) is studied to capture the wave energy in this paper. It can supply power for marine equipment.
In the last two decades, the proportion of renewable energy has risen continuously in energy production[3]. As one of the most popular renewable energy, wave energy is always a crucial research field and has attracted many scholars attention [4-6].
Designing a commercial wave energy generator is expensive and involves many steps

to achieve a mature product, including proof-of-principle, design and manufacture, optimization. If the generator structure can be simplified and the generating capacity can be kept, it will reduce the cost of wave energy generator and raise its popularizing rate.

Many wave energy converters have been designed [7,8]. Despite recent progress, some reliability problems still remain [9]. Now many ways are utilized to improve the reliability and conversion efficiency of Wave Energy Converters (WECs), most of them focus on increasing wave energy conversion efficiency and optimizing the power generation systems [10-13]. This paper is mainly about the design of the direct-drive permanent-magnet wave energy generator.

Wave energy generator essentially works like this: the mechanical part capture wave energy, then the intermediate gearing drives a generator to provide electricity. The generator needs to be sealed off from the sea. The sealing device raises two major issues: it will gradually fail with operation and cause additional friction. To solve these problems, some researchers utilized magnetic couplings that changes rotary seal into static seal[14]. But it will complicate the structure of wave energy generator by using magnetic couplings.

This research presents a rim-driven wave energy generator. The direct-drive generator can convert wave energy onto electricity directly. There is no need for sealing device, or for intermediate gearing. The simple structure costs less and increases the compactness and the robustness of the generator. Many scholars have studied the hydrodynamic performance of blades. Therefore, the paper does not cover these researches.

The technical work presentation is divided in 3 parts: in section II the specificity of RDT systems is presented, in section III the models and their association are described and finally section IV shows and discusses the design results.

2. Component and fundamental principle of rim-driven wave energy generator

Fig. 1 shows the structure of the rim-driven wave energy generator, including the upper channel, lower channel and generator part. Rotating structure is an radial electrical flux PM machine and is located in the rotator which surrounds blades， as shown in Fig 2. The structure has been applied to underwater propellers and tidal current generators successfully[15-18]. The research shows that this structure can reduce the device space and enhance the compactness and robustness[19,20]. Meanwhile, rim-driven structure can obtain greater torque and thrust[10]. The channel can improve the efficiency of blades and reduce vibration to protect the device.

The Up and Down Channel is designed as bell-mounted shape to accumulate the wave and store the incoming wave. The blade of the rotor can be bidirectional driven by water and wave energy can be reused. For rotating machinery, rotary seal is usually required. To avoid sealing, water lubricated bearings can be used. There is a large gap between the rotor and the stator to enhance the heat transfer capacity. The generator is immersed in seawater and some parts are easily corroded. So they require specialized handling. In this case, some anticorrosive, heat-dissipating coating can be applied to these parts.

This rim-driven wave energy generator requires no sealing in the power generation section. The permanent magnets are mounted on the rotor and the electromagnetic coils are wound on the stator cores. The rotor is mounted between the up channel and the down channel through the rolling elements. When the wave enters the device from the down channel, it pushes the blade to run. Then coils will cut the magnetic lines that will generate electricity. While the seawater returns from the up channel, it will push the blade again and the energy will be converted again. This generator solves the sealing and heat dissipation problems and improves the reliability of the wave energy generator. Meanwhile, the rim-driven wave energy generator does not need to transmit motion through the intermediate transmission mechanism and enhances the energy efficiency. It simplifies the wave energy generator structure.

Here, a permanent multipole magnet generator is adopted, which can obtain electricity at low speed. It owns many advantages, low speed, light mass, high efficiency, low noise, simple manufacture process and convenient maintenance[21,22].

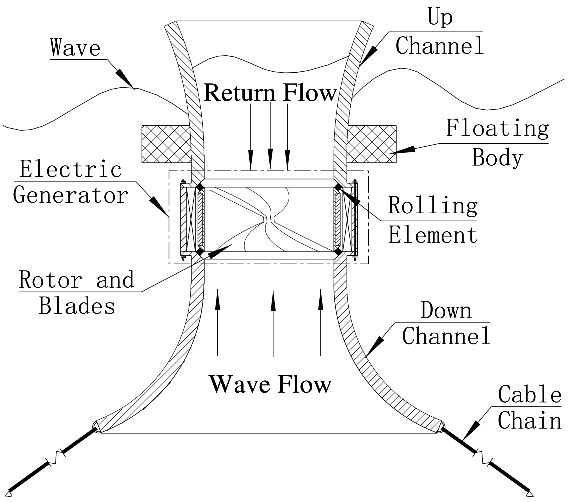


Fig. 1 Structure of the rim-driven wave energy generator

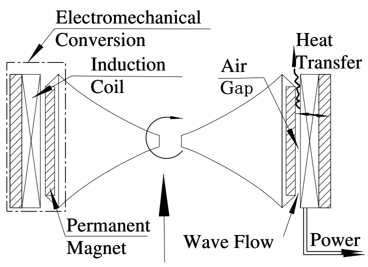


Fig 2. Rotating structure

Some scholars have studied the electromagnetic, thermodynamic and hydrodynamic properties of the rim-driven generator[9]. These situations also apply to the generator researched here. This paper mainly studies some contents which are not involved in them.

3. Wave movement and blades forces

3.1 characteristics of wave movement

The wave is made up of wind wave and swell. Actually it is irregular waves. It is composed of sine or cosine waves of various frequencies in some idealized world[23,24]. Assume that the wave moves in the xz plane, as shown in Fig. 3, and it is homogeneous, incompressible, non-viscous. The pressure of the free surface is uniform and constant, and the water movement is irrotational. The seabed is horizontal and impermeable, and the mass force is just the gravity on the water.

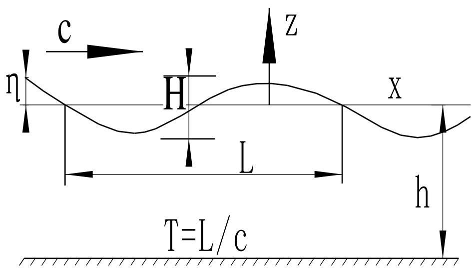


Fig. 3 Wave in the xz plane

Velocity potential function is shown below

$$\vec{V} = \nabla\varphi = \frac{\partial\varphi}{\partial x}\vec{i} + \frac{\partial\varphi}{\partial z}\vec{k} \tag{1}$$

$\vec{V}$ velocity vector, φ velocity potential function, $\vec{i}$ unit vectors in the x directions, $\vec{k}$ unit vectors in the z directions.

According to the continuity equation for incompressible fluids

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

Where $u = \frac{\partial\varphi}{\partial x}$, $w = \frac{\partial\varphi}{\partial z}$

The governing equation of a potential wave motion can be derived

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial z^2} = 0 \tag{3}$$

Under the boundary conditions, using the Bernoulli equation and the kinematic boundary condition at the free surface, the wave's kinematical equation can be obtained. However, the boundary conditions at the free surface are nonlinear and indefinite. Instead, the microwave theory can be utilized to linearize the conditions.

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial z^2} = 0$$

$$\frac{\partial\varphi}{\partial z}\Big|_{z=-h} = 0$$

$$\frac{\partial^2\varphi}{\partial t^2} + g\frac{\partial\varphi}{\partial z} = 0, z = 0$$

$$\eta = \frac{1}{g}\frac{\partial\eta}{\partial t}, z = 0$$

$$\varphi\left(x,z,t\right)=\varphi\left(x-ct,z\right)$$

$$p_z=-\rho gz-\rho\frac{\partial\varphi}{\partial t}-\frac{1}{2}\rho\left[\left(\frac{\partial\varphi}{\partial x}\right)^2+\left(\frac{\partial\varphi}{\partial z}\right)^2\right]$$

By using a separate variable method, the potential function can be obtained as

$$\varphi=\frac{gh}{2\sigma}\frac{\cosh[k(z+h)]}{\cosh(kh)}\sin(kx-\sigma t) \tag{4}$$

where σ is angular frequency, k is wave number, h is depth of water
For the water at *(x0*, *y0)*, its movement path in z direction is

$$\begin{aligned}\xi&=\int_0^t u(x_0,z_0)dt=\frac{H}{2}\frac{\cosh[k(z_0+h)]}{\sinh(kh)}\sin(kx_0-\sigma t)\\ \zeta&=\int_0^t w(x_0,z_0)dt=\frac{H}{2}\frac{\sinh[k(z_0+h)]}{\sinh(kh)}\cos(kx_0-\sigma t)\end{aligned} \tag{5}$$

Since waves are superimposed by the wave of different periods and heights, the simplest case is taken as an example. Assume that only two waves with the same height and slightly different period are superimposed.

$$\begin{aligned}\eta&=\frac{H}{2}\cos\left[\left(k+\frac{\Delta k}{2}\right)x-\left(\sigma+\frac{\Delta\sigma}{2}\right)t\right]+\frac{H}{2}\cos\left[\left(k-\frac{\Delta k}{2}\right)x-\left(\sigma-\frac{\Delta\sigma}{2}\right)t\right]\\ &=H\cos(kx-\sigma t)\cos(\frac{\Delta k}{2}x-\frac{\Delta\sigma}{2}t)\end{aligned} \tag{6}$$

The superimposed wave is still periodic and its maximum amplitude becomes twice. If there are more waves, the actual wave will become more complicated and irregular, and the force of the blade will also become more irregular. For the sake of analysis, the average value of the actual wave heights and periods is taken as the wave height and period used in this paper. The following figures (Fig. 4 and Fig. 5) show the wave height and period curves measured in the Chinese sea. It can be obtained from the figure that the average wave height is 2.5m, the maximum wave height is 7m, the period is 11s on average, the minimum is 5s, and the vertical velocity is up to 4m/s.

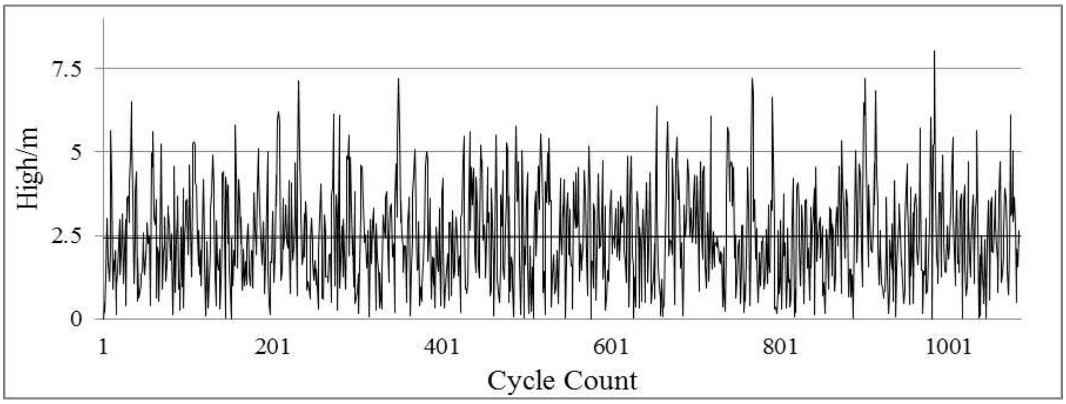


Fig. 4 Wave Height

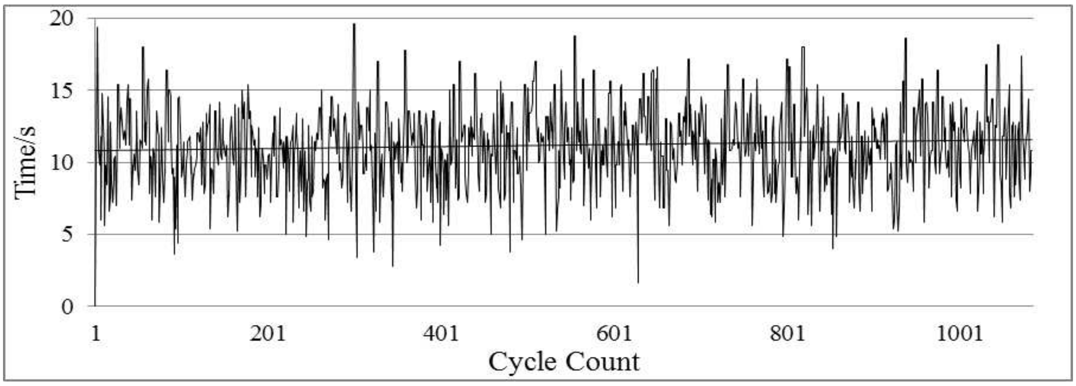


Fig. 5 Wave Period

3.2 Force on the blade

When the wave flows in the channel, it will flush the blade to turn the rotor. Waves random movement causes the force of the blade to change irregularly. When the wave is up, seawater flows into the channel and push the blade upward, as shown in Fig. 6(a). When the wave is down, the seawater flows out of the channel and push the blade downward, as shown in Fig. 6(b).

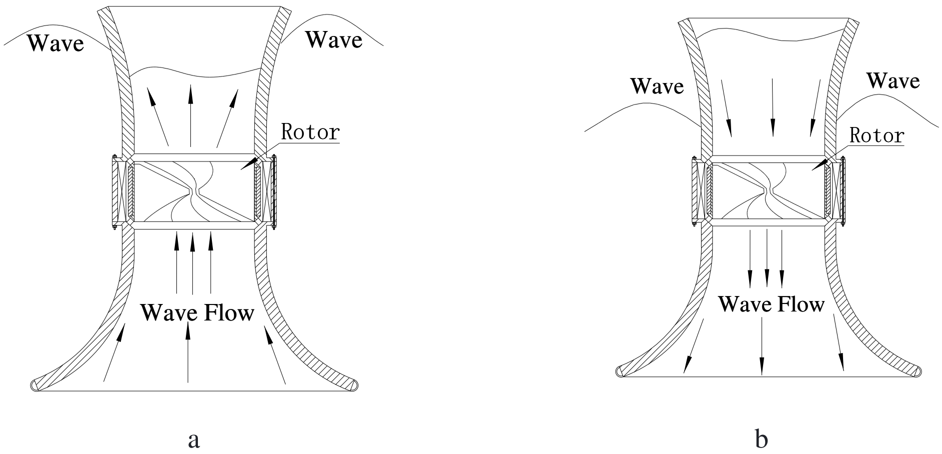


Fig. 6 Wave Flow in the channel

The blade shape is shown in Fig. 7 and Fig. 8 shows one of the blades. The rotor is uniformly distributed with blades. Fig. 9 shows the force between seawater and the blade. Seawater will push the rotor to rotate as it flows up and down in the channel. Rotational power is equal to the power of captured wave.

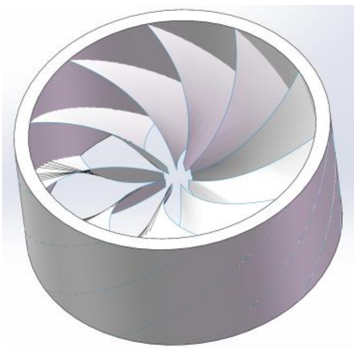


Fig. 7 Blades in the rotor

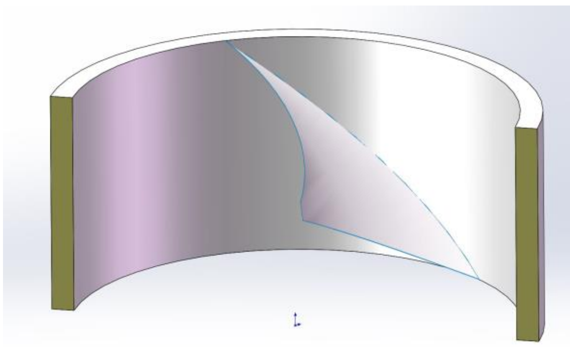


Fig. 8 One blade

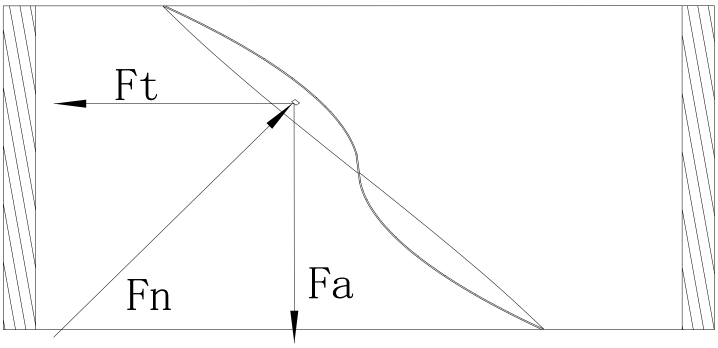


Fig. 9 Force between seawater and the blade

While seawater impacts the blade to push the rotor to rotate, it will flow out along the surface of the blade, as shown in Fig. 10.

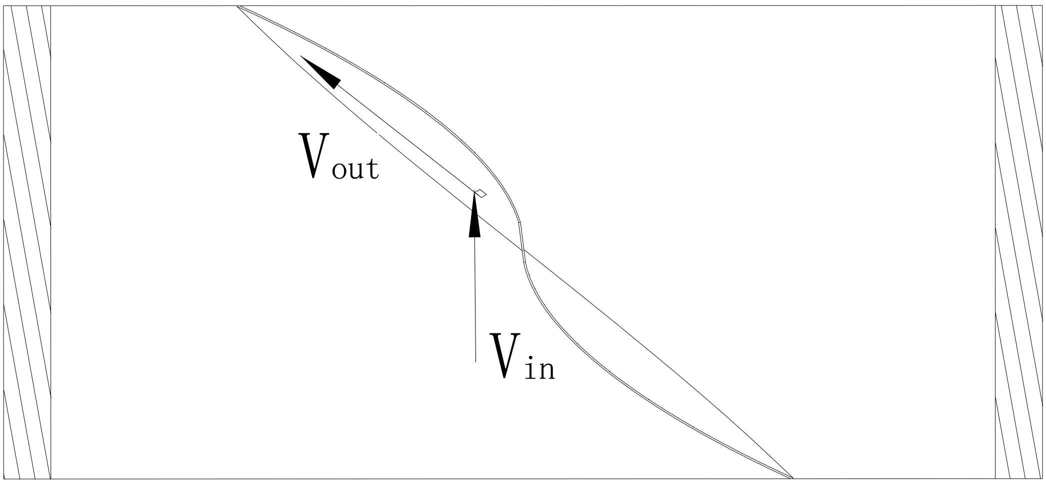


Fig. 10 Seawater Velocity

Based on Momentum Equation, a tiny volume water with mass m has a momentum that is

$$F_n \Delta t = 2\cos\left(\frac{90^\circ + \theta}{2}\right) m \left|\vec{v}\right| \tag{7}$$

Then F_t and m can be expressed as

$$F_t = F_n \sin(\theta) \tag{8}$$

The mass through the blade is

$$m = v \Delta t s(r) \rho \tag{9}$$

Where θ is the inclined angle of the blade, v is the speed of the water, Δt is the time, $s(r)$ is the area of the blade at radius r.

The torque that a blade can generate is

$$T=\int_0^R F_t \mathrm{d}r=\int_0^R 2\cos\left(\frac{90°+\theta}{2}\right)s(r)\rho|v|^2\sin(\theta)\mathrm{d}r \quad (10)$$

From Eq. (10), the tangential force is the maximum when θ is about 42 degree. θ can affect the force on the blade. It can provide a reference for improving the performance of the turbine. Since the vertical velocity of the wave is random, the power generation performance was analyzed at different velocities.

4. Generator design and performance analysis

4.1 The model of generator

In this paper, a permanent magnet generator model was set up. Its parameters are shown in Table 1.

Table 1 The Parameters of Permanent Magnet Generator

Type	Value	Type	Value
Magnet Arrangement	Radial	Stator's Outer Diameter	650mm
Phases Number	3	Stator's Inner Diameter	590mm
Slots Number	186	Length	300mm
Poles Number	60	Rotor's Outer Diameter	586mm
Conductors per Slot	12	Rotor's Inner Diameter	540mm
Number of Strands	5	Slot's Depth	20mm
Wire Diameter	0.8mm	Slot's Tooth Width	5mm
Winding Layers	2	Coil Pitch	3
Parallel Branches	1		

Fig.11 shows the structure of the model. The outer consists of the stator and winding which are fixed between the up channel and the down channel. The inner consists of the rotor, permanent magnet (PM) and blades. PMs distribute on the surface of the rotor evenly. Blades are assembled on the inner surface of the rotor.

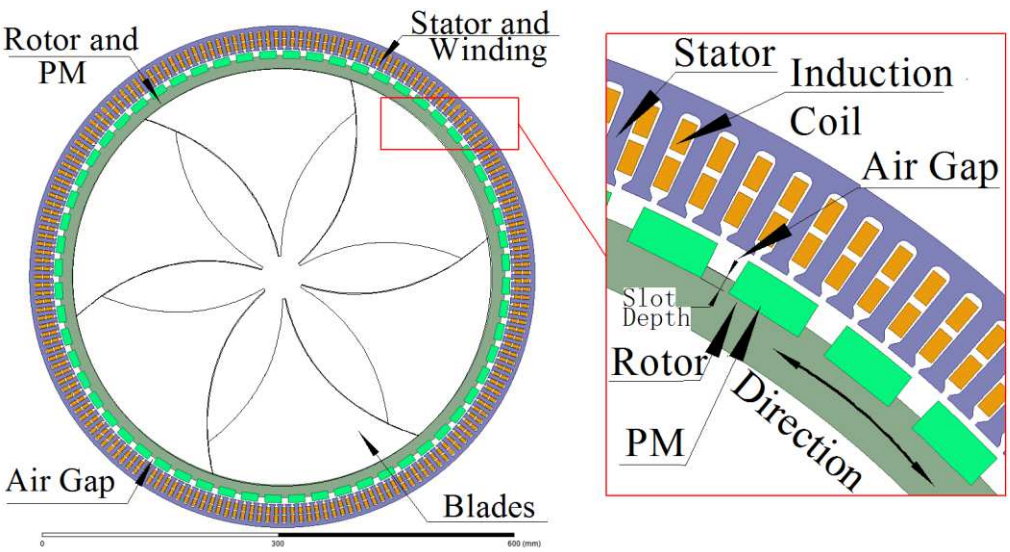


Fig. 11 Structure of the model

Fig. 12 shows the windings, rectifier and load used in simulation[25]. Voltmeters and ammeters connected to the load and circuit are utilized to measure voltage and current to analyze generating performance. The inductor and resistor on each winding replace the inductor and resistor of the actual winding.

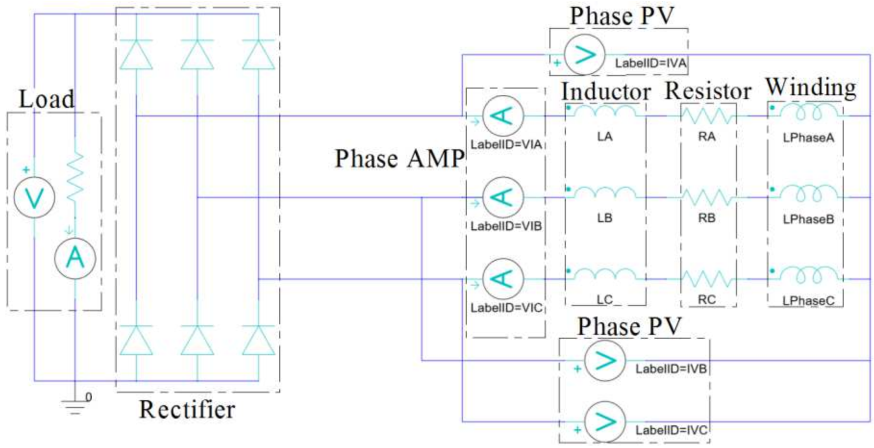


Fig. 12 Windings, Rectifier and Load

4.2 Performance analysis

Permanent magnets are fixed in grooves of the rotor. The groove depth will affect magnetic path and cause power losses. The influence of different groove depths was analyzed. Fig. 13 shows the partial enlarged drawings of grooves that were analyzed, including surface-mount, partly-bury and all-bury.

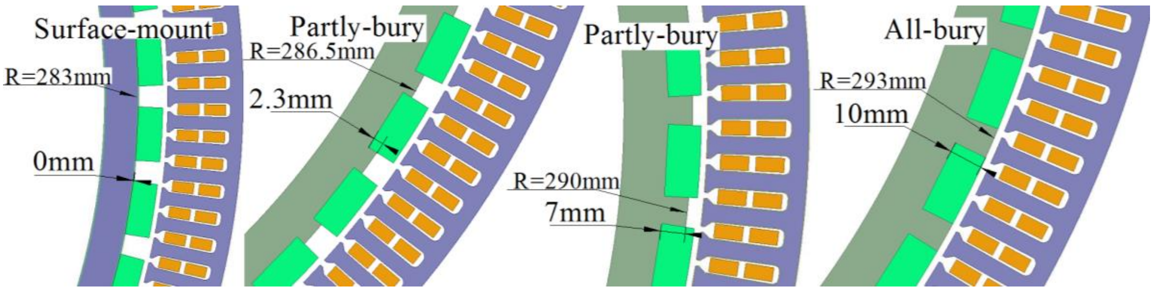


Fig. 13 Analyzed Grooves

Finite element method(FEM) was applied to analyze models to obtain the generator performance at different speeds. When the groove depth is different, the rotor radius is changed. So the rotor radius is set as the variable here. A larger radius means a deeper groove. By analysis of models, generator power and torque were obtained at different speeds. Fig. 14 is magnetic field distributing graph with different groove depths.

From Fig. 14, a deeper groove can get a stronger magnetic field on the groove. It would cause additional eddy current loss that degrades the generator performance.

Fig. 15 shows the generated power with different groove depths and speeds. The results showed that the groove would affect power generation performance. A deeper groove would get a lower generated power. Table 2 shows the average generated power with different groove depths and speeds. Fig. 15(d) shows their changing trend.

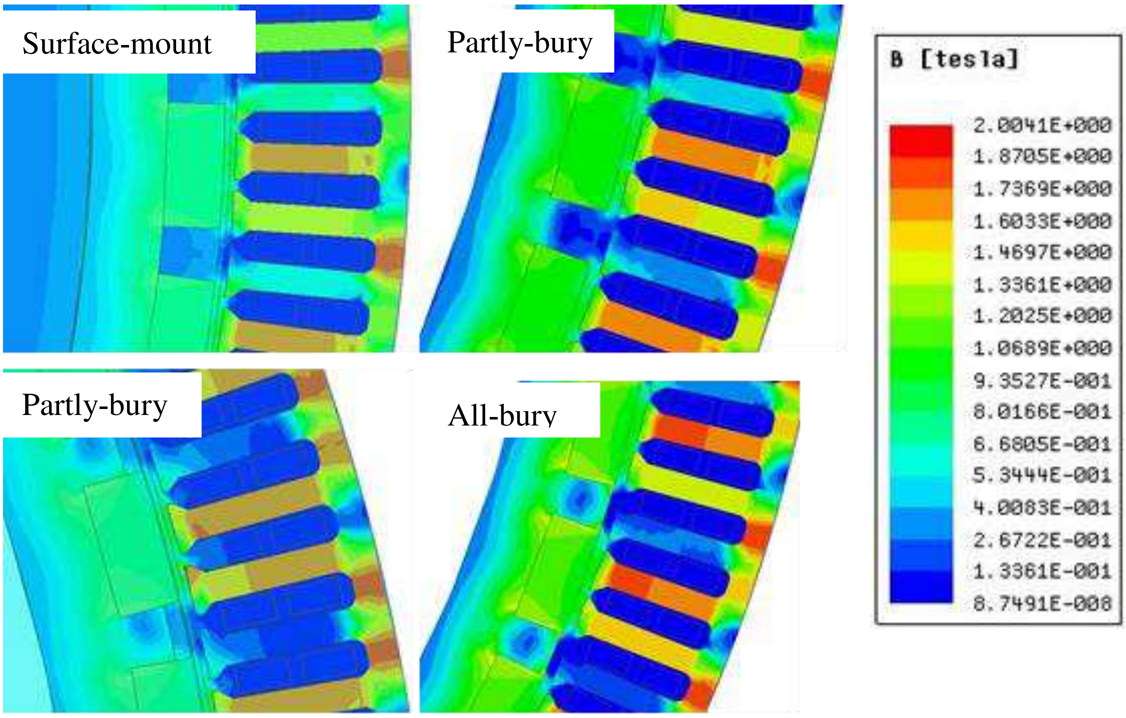


Fig. 14 Magnetic field distributing graph

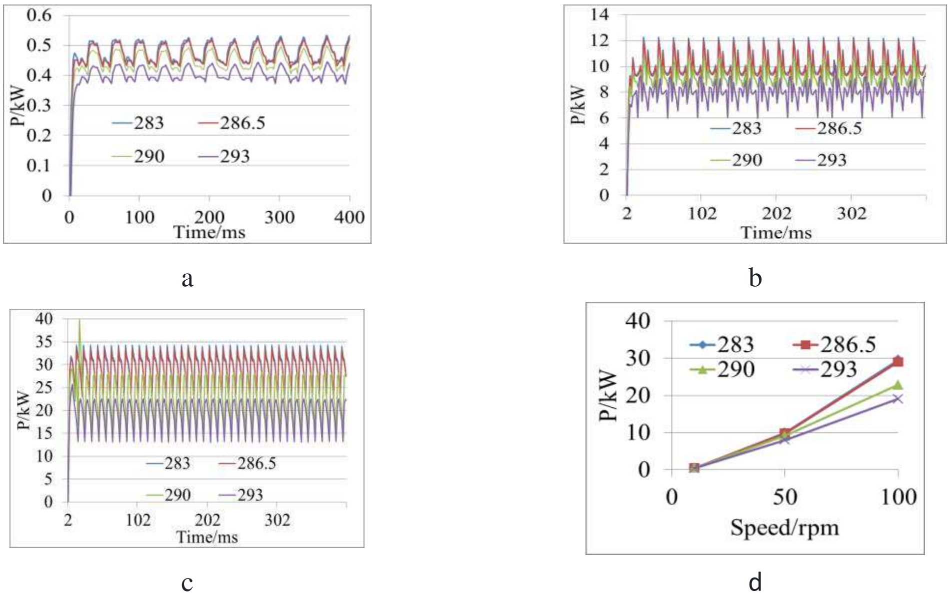


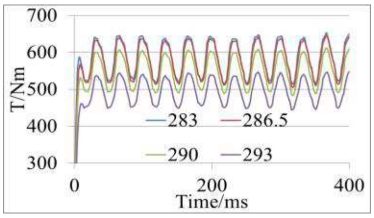
Fig. 15 generated power with different groove depths and speeds

Table 2 Average Generated Power

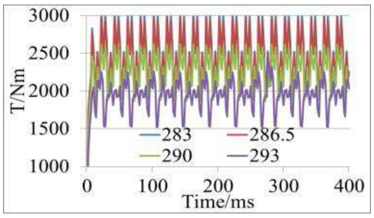
Radius \ Speed	Power/kW			
	283mm	286.5mm	290mm	293mm
10rpm	0.478	0.471	0.448	0.405
50rpm	9.953	9.830	9.173	8.009
100rpm	29.537	29.047	22.857	19.101

According to the above analysis, the output power will decrease with groove depth increasing. Comparing Radius=283mm with 293mm, the output power decreases about 15.3%, 19.8% and 35.3% at the speed of 10rpm, 50rpm and 100rpm, respectively. With the increasing of the speed, the groove impact on the output power becomes more serious. However, when the groove depth is shallow, there is quite little impact. For example, when the groove depth is 3.5mm, comparing Radius=283mm with 286.5mm, the output power decreases about 1.4%, 1.2%, 1.6% at the speed of 10rpm, 50rpm, 100rpm, respectively.

Fig. 16 shows the torque generated by counter electromotive force of different groove depths at different speeds. The torque is the resisting moment needed to be overcame when the generator works. Fig.x indicates that a deeper groove generates a smaller torque. This rule does not change with speed. Nevertheless, the torque approximately equals the torque generated by Radius=283mm when the groove depth is relatively shallow. Fig. 16(d) shows the change curves of average torque.Table 3 shows the average torque in Fig. 16.



a



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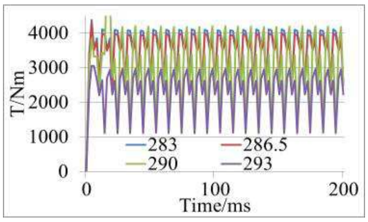

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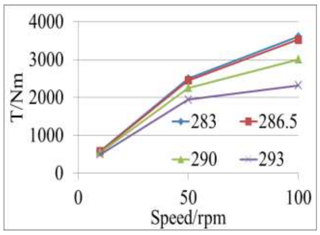


d

Fig. 16 Torque generated by counter electromotive force

Table 3 Average Torque

Radius / Speed	Torque/Nm			
	283 mm	286.5 mm	290 mm	293 mm
10rpm	585	579	549	495
50rpm	2495	2454	2252	1941
100rpm	3608	3525	3006	2321

As the groove would decrease magnetic density on the surface of the rotor, the resisting moment reduces with the increasing of the groove depth.

When the generator starts to work, it needs to overcome the magnetic torque between the permanent magnet and the stator. The resisting torque is the maximum when Radius=283mm according to the above analysis. Hence, the starting torque of

Radius=283mm was analyzed here. Fig. 17 shows the starting torque at different speeds. With the startup speed becoming high, the resisting torque becomes large. It is about 35Nm at 10rpm.

Fig. 18 shows the working torque of the generator at different speeds. As the operation speed increasing further more, the average working torque increases and the torque fluctuation extent becomeslarger.

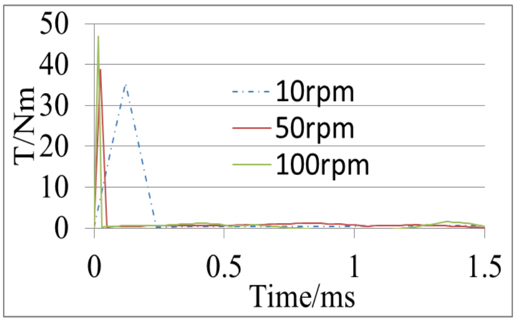


Fig. 17 Starting torque

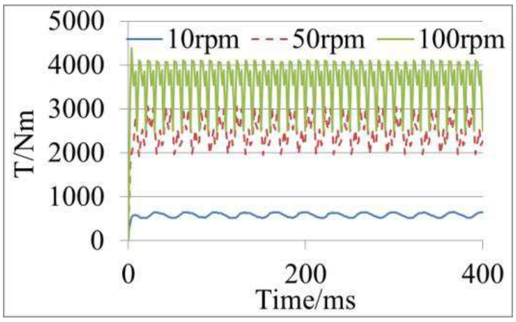
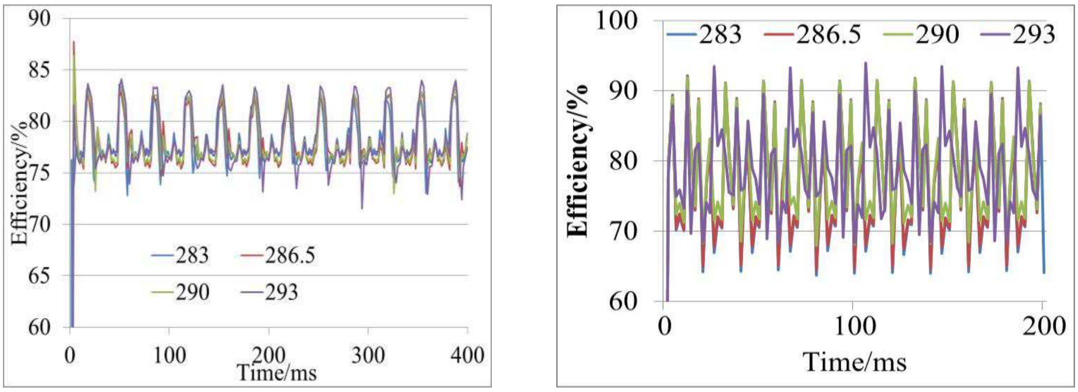


Fig. 18 Working torque

The efficiency of different groove depths at different speeds was obtained by analyzing the output power and input torque, as shown in Fig. 19.



a. 10RPM

b. 50RPM

Fig. 19 Efficiency of different groove depths at different speeds

Average efficiency could be calculated from Fig. 19, as shown in Table x. Fig. x shows the average efficiency curves of different groove depth.

Table 4 Average Efficiency

Radius / Speed	Efficiency/%			
	283 mm	286.5 mm	290 mm	293 mm
10rpm	78.1	77.9	78.0	78.2
50rpm	76.7	77.0	78.1	79.1
100rpm	78.9	79.3	78.4	82.9

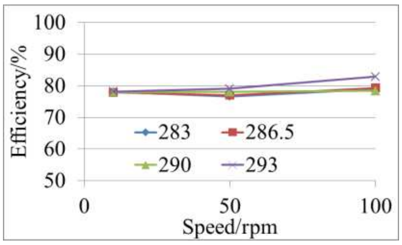


Fig. 20 Average efficiency curves

According to Table 4 and Fig. 20, the efficiency of the generator is not significantly impacted by the speed and the groove depth; there is scarcely a difference at low speed.

To analyze the influence of different speeds on generator performance, Radius=283mm was taken as an example and the result is shown in Fig. 21. As the speed increasing, the amplitude of the efficiency changes seriously.That is related to the torque fluctuation caused by the counter electromotive force, but has weakly effect on the average efficiency.

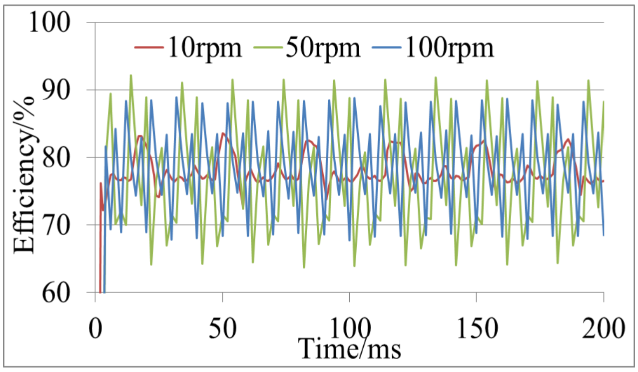


Fig. 21 Efficiency at different speeds

5. Discussion

Considering the above analysis, the output power of the generator increases with the increasing of the speed. The small groove depth has weakly influence on the output power, but the big one will cause serious power loss. For example, there can be 35.3% power loss when the speed reaches 100rpm. A deep groove will make the additional weight and size of the generator. However, the deep groove can fix and protect the permanent magnet, especially at high speed. So the groove depth should be as small as possible to meet the design requirements. In addition, a large groove depth will weaken the magnetic intensity on the surface of the rotor, reducing the working torque, enlarging design size for specified output power.

The output power is related to the size of the generator. The sizes of the up channel and the down channel can be adjusted to fit the generator size. When permanent magnets are surface-mount, the generator can get the best performance. Forces from the stator act on permanent magnets, so permanent magnets are needed to be fixed on the groove. In addition to making the groove on the surface of the rotor, some non-magnetic materials can be utilized to fix the PM, including adhesive, nonmetallic covering. As the generator works underwater, the water in the gap between the rotor and the stator can take the heat away. Therefore, the generator has good cooling performance. The rotor can be supported in water-lubricated bearings which many scholars have studied.

6. Conclusion

A rim-driven wave energy generator was designed in the paper. It is not needed to be sealed and directly driven to generate electricity. This design can improve the performance of underwater power generator. The waves and its interaction with the blade were analyzed. The influence of the groove and the speed on the performance of the generator was studied. The paper provides a reference for the design of the rim-driven generator and also gropes a new method to utilize the wave energy.

7.Declarations

7.1 Availability of data and materials

All data has been included in the paper.

7.2 Competing interests

The authors declared no competing interests with respect to the research, authorship, and/or publication of this article..

7.3 Funding

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7.5 Authors' contributions

The author Zhang Jian participated in the main work of this article writing, data analysis and submission. The author Ren Yaoyao conducted the performance analysis and parameter selection, and provided relevant content of the performance analysis in the paper. The author Hou Xiangying provided the finite element analysis model and simulation data in this paper,and checks the content of section III. The author Zhang Hong provided guidance for the structural design, and participated in the proofreading and polishing of the paper.

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