Numerical modelling on the performance of a rolling-type wave energy converter with mooring system

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Abstract. This paper presents the performance results of the numerical study on the three-dimensional rolling-type wave energy converter with the mooring system. The novel device combines an established and reliable mooring system, making it suitable for deeper sea utilisation. The shape of the device is based on the renowned Salter’s Duck, which is capable of converting wave energy into mechanical energy through rolling back and forth. The results are obtained using the Panel Element Method package AQWA, based on linear wave theory and potential flow theory. The hydrodynamic behaviour of the device is assessed in the frequency domain, including the additional mass, the radiation damping and the wave exciting force. In the time domain, the coupling of the device motion and the dynamic response of the mooring system is performed, allowing comparisons with experimental work on a 1:16 scale model. The tension of the anchor chain is reported in detail. The relative capture width of the device under different wave conditions is also examined.

1. Introduction

With the development of society, the demand for energy is increasing[1]. In order to meet this, the global consumption of fossil fuels is increasing dramatically[2]. However, excessive use of fossil energy will lead to problems such as the destruction of the ozone layer, sudden changes in climatic condition and environmental pollution. Therefore, renewable energy is urgently favored in various countries. The ocean contains a wealth of clean energy that needs to be developed and utilized, such as wave energy, tidal energy, sea salt energy, temperature difference energy[3]. Among them, ocean wave energy has the most potential for development. According to the forecast report published by the International Energy Agency, the global available wave energy can reach 2-2.5 billion kilowatts[4-6], and the huge energy can well satisfy the electricity consumption in the world today. As the most widely distributed renewable energy in the ocean, wave energy is the sum of the kinetic energy and potential energy of ocean waves. It has the advantages of cleanliness, high energy density and obvious periodicity. The main research direction of wave energy is pointed to the power generation[7].

The utilization of wave energy can be traced back to 1770s, and Cirared in France obtained the first wave power generation patent in 1799[8]. Over the years a wide variety of WECs have been developed, nowadays there are more than one thousand prototypes[9-10]. Among the wide variety of WECs, the Nodding Duck WEC proposed by Prof. Salter[11] of the University of Edinburgh in the United Kingdom...
has attracted the attention of scholars internationally due to its exquisite design and high efficiency. Because of high efficiency in absorbing wave energy under regular wave conditions, Salter’s Duck has always been considered as one of the most promising wave power devices. Greenhow M et al.[12] proposed a two-dimensional theory to analyse the survivability of Salter’s Duck under extreme sea conditions. Professor Serman et al.[13] investigated the performance of Nodding Duck in random waves by numerical methods, and the Nodding duck was constrained through the shaft. Mei et al.[14] researched the effect of the constraint degree of the axis on power performance of Salter’s Duck by numerical means based on linear wave theory and rigid body motion theory. Most of the existing studies have carried out two-dimensional numerical simulation and theoretical analysis on Nodding Duck, but there are few numerical modelling of the Salter’s Duck with six-degree-of-freedom and three-dimensional. Barely no work has been reported so far on the coupled dynamic analysis of 3D Nodding Duck with mooring system.

In this paper, to investigate the hydrodynamic performance and energy capture efficiency of the floating rolling-type WEC more practically, the mooring system is considered. The device is researched in the following aspects: (1) In the frequency domain, the additional mass, radiation damping and wave exciting force of the device are analysed; (2) In the time domain, the motion responses of the device under different wave periods are evaluated and compared with the model test with the scale factor of 1:16; (3) The dynamic response of the mooring system at various wave conditions are assessed, and the mooring forces are discussed in detail; (4) The relative capture width of the device under different wave conditions is investigated.

2. Numerical model

The rolling-type WEC for numerical simulation in this paper is a modified version based on the renowned Nodding Duck, and the three-dimensional conceptual design is shown in figure 1. The calculations are carried out in AQWA, a reference commercial code based on linear wave theory and potential flow theory. Being based on potential flow theory, viscous effects, like shear stresses and flow separation, are not taken into account. The solutions for the hydrodynamic coefficients, wave exciting force, response amplitude operator, mooring force and the relative capture width are calculated. The panel size parameter, an input of AQWA used for subdivision of patches when refining the mesh, is set to be 0.05m, following a convergence study that was performed before the simulation.

Figure 1. Example of a numerical mesh.

3. Numerical results

3.1 Hydrodynamic coefficients

The hydrodynamic coefficients of the rolling-type WEC under different wave periods are shown in Fig. 2, which are calculated in the frequency domain. \( \mu_{ij} \) and \( \lambda_{ij} \) are the added mass and radiation damping, and the indexes 1 to 6 refer to six degrees-of-freedom motion (sway, surge, heave, pitch, roll and yaw), respectively.
Figure 2. Added mass and radiation damping.

Figure 2 shows that $\mu_{11}$ and $\mu_{55}$ increase to the maximum at first, then decrease slowly and finally tend to be stable with the increase of the incident wave period. As the incident wave period increases, $\mu_{33}$ increases nonlinearly with a gradually-decreased growth rate. It can be found in this figure that $\mu_{33}$ is larger than $\mu_{11}$ and $\mu_{55}$ due to the unique shape of the rolling-type WEC. The outflow and inflow of the front beak promote the movement of the surrounding water. As a result, the reaction force of water on it increases, and the added inertia force also becomes larger.

3.2 Wave exciting force

Figure 3 presents the wave exciting force, the amplitude of which is proportional to the amplitude of incident wave in monochrome wave under the hypothesis of micro-amplitude motion. It can be observed that $F_x$ increases to its maximum value with the increase of the wave period, then it decreases. $F_y$ increases nonlinearly with a gradually-decreased growth rate. $M_y$ increases to its peak value with the wave period at first, then decreases steadily, and finally becomes stable.

Figure 3. Wave exciting force.

3.3 The coupled dynamic motion for rolling-type WEC

Compared with the nearshore WEC, the floating rolling-type is suitable for deeper sea area, so it needs mooring to ensure safety. The existence of mooring system will inevitably affect the motion response and force of the device under wave loads. Therefore, it is necessary to take into account mooring system when analyzing the motion response of the device. The time-domain coupled model is shown in figure 6, in which the device is moored by four anchors. The fairlead of the mooring system is located at the center of the rotating axis.

3.3.1 Validation of the numerical model

To validate the numerical prediction carried out with AQWA, a set of experimental result is selected for comparison. Figure 4 shows the comparison between the numerical prediction and the experimental result for the roll motion of rolling-type WEC in regular waves. The wave height is 0.02 m and the wave period is 1.15 s. It is evident from this figure that the numerical and experimental results have a good
agreement in the steady range.

3.3.2 Roll motion
Figure 5 presents the roll response amplitude operator (RAO) of the rolling-type WEC with respect to fifteen different incident wave periods ($T=0.8, 0.9, 1.0, 1.05, 1.1, 1.15, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8, 2.0, 2.2$ and $2.4$ s).

It can be observed that the roll RAO of the WEC drops significantly except for the periods close to $T=1.05$ s, which corresponds to the occurring resonance phenomenon.

Figure 4. Numerical and experimental results for the roll motion of the WEC in regular waves.

Figure 5. Roll RAO of the rolling-type WEC.

3.4 Mooring system
The device is moored by four anchor chains as shown in figure. 6, the initial anchoring angles of the No. 1, No. 2, No. 3 and No. 4 anchor chains are all 45 degrees. As the device operates in the working condition, the anchor point on the seabed not migrate, hence the anchor points of the four anchor chains are all set as fixed points in the numerical simulation.

Figure 6. Mooring set-up.

3.4.1 Mooring force
In this section, the coupled dynamic response of mooring system is performed in time domain. In this regard, to better reflect the mooring force, the maximum, minimum and the average forces are counted. The mooring tension of the device in regular waves with respect to the wave period is shown in figure 7. The wave height $H$ is equal to 0.16m in the numerical model. It is evident from this figure that the maximum, minimum and the average seaside mooring tensions (No. 1 and No. 2) are larger than those of leeside (No. 3 and No. 4). Then the device deviates from equilibrium position under the wave load and moves along the direction of incident wave, which causes the increase of the tension of No. 1 and No. 2 and the decrease of the tension of No. 3 and No. 4. The forces of No. 1 and No. 2 are the same,
and that of No. 3 and No. 4 are the same. This is because the No. 1 and No. 2, and the No. 3 and No. 4 mooring anchors are symmetrical in the XoZ plane. The maximum and average forces of No. 1 and No. 2 increase firstly and then decrease with the increase of wave period, and finally stabilize, while the minimum forces are less sensitive to the incident wave period. With the increase of wave period, the maximum, minimum and the average forces of No. 3 and No. 4 fluctuate in a smaller range.

![Figure 7. Mooring forces of the device at different wave periods.](image)

3.4.2 Relative capture width

The relative capture width of the device is calculated and analyzed from the perspective of wave. In a monochrome regular wave, the total wave energy contained in a wavelength per unit width is given by:

$$E_w = \frac{1}{8} \rho g H^2 \lambda$$

where $\rho$ is the water density; $g$ is the gravitational acceleration; $H$ is the wave height and $\lambda$ is the wavelength.

The primary efficiency $\eta$ of the rolling-type WEC in regular waves can be determined as:

$$\eta = \frac{H_i^2 - H_r^2 - H_d^2}{H_i^2}$$

where $H_i$ is the wave height of incident wave; $H_r$ is the wave height of reflected wave and $H_d$ is the wave height of the diffracted wave.

Figure 8 presents the relative capture width of the rolling-type WEC as a function of the incident wave period. The wave height $H$ is equal to 0.02 m and the wave periods are 0.8, 0.82, 0.85, 0.88, 0.91, 0.94, 0.97, 1.01, 1.05, 1.09, 1.14, 1.19, 1.25, 1.31, 1.37, and 1.45 s, respectively. As can be detected from the figure, the relative capture width of the device is higher in a small period wave, reaching more than 90%. At a short wavelength, only a small part of the incident wave passes through the device, indicating that most of the wave energy is absorbed. As the wave period increases, the wavelength increases with the constant depth of the numerical tank. At a long wavelength, the wave diffraction effect is enhanced, indicating that the wave diffracted energy through device increases. As a result, the relative capture width of the device declines in a larger wave period. When the wave period is in the range of 0.8 to 1 s, the efficiency is over 90%. But when the wave period is 1.19 s, the efficiency is only
41%.

Figure 8. Relative capture width of the device under different wave conditions.

4. Conclusions
In this paper, the numerical model of the three-dimensional floating rolling-type WEC with mooring system is established by using Panel Element Method based on three-dimensional potential flow theory and linear wave theory. The hydrodynamic coefficients, wave exciting force, response amplitude operator (body motions), mooring force and the relative capture width are reported and discussed in detail.

(1) The rolling response of the device increases firstly and then decreases with the increase of wave period. The maximum rolling response of the device occurs approximately at a time when the incoming wave frequency coincides with the rolling natural frequency of the device.

(2) The numerical results show a good agreement with the experimental work on a 1:16 scale model, which verifies the accuracy of the numerical model. However, the numerical predictions are slightly larger than the experimental results due to the ignorance of the viscous effect.

(3) The seaside mooring forces are larger than that of the leeside at all wave conditions. Also, the seaside mooring forces are more sensitive to the wave period, comparing with the leeside mooring forces.

(4) At small wave periods, the efficiency of the device can reach more than 90%, while at large wave periods, the efficiency declines due to the enhanced wave diffraction.

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