Design of Duck Wave Power Generation Device Based on Wave Energy

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Abstract. The study of wave power generation is more and more popular in modern science and technology for the new renewable energy, in recent years. Designing wave power generation devices with high conversion efficiency and stability, and improving the technical level for commercialization are both scientifically interesting and potentially useful. Here we achieve the stability of wave generation equipment by establishing one nodding duck energy conversion system in a wave tank. Equipped with ultrasonic distance sensor, combining screw slide and stepper motor as draft self-regulation feedback system, our device is always in the best working performance under the single-chip microcomputer STM32 auto-measuring system. The good conversion efficiency performance can be 43%. The ARDUINO module and the Labview host computer interface are equipped to real-time visualize and characterize the parameters of the device and calculate the optimal power generation efficiency. Our designed device can resist damage validly with high conversion efficiency and stability.

Keywords: Wave energy; Duck wave power generation device; Ultrasonic measurement system; Feedback adjustment system; Power generation efficiency.

1. Introduction

Wave energy is a huge renewable energy source in the ocean. Today, many marine countries are actively developing wave energy and related technologies to achieve high conversion efficiency and stability of wave power generation devices, providing reliable and safe clean energy for human beings and achieving long-term energy development¹⁻⁷. Varieties of wave energy conversion schemes have been proposed and the Duck-type wave power generation technology has also attracted wide attention for its high efficiency⁸,⁹. However, its resistance to waves and stability are poor. Under the action of irregular waves, the system efficiency is greatly reduced. In 1980, the Massachusetts Institute of Technology's Serman D. achieved a duck-type ocean wave power generation device in a harsh working environment, but the system efficiency was still less than 50%¹⁰. In 1981, Salter and Laithwaite jointly invented the gyro ritual duck-type wave energy generator to improve the stable output of power, but the reliability is high¹¹. The Edinburgh Duck wave energy converter (WEC), which mainly employs the pitch mode to capture power, is acclaimed for its high efficiency⁸. Scholars from the Guangzhou Energy Institute of the Chinese Academy of Sciences successively improved the device and developed 10 kW and 100 kW duck-type wave energy devices, which are still to be industrialized¹²,¹³. In addition, the device requires complex subsea construction technology.

In this paper, a nodding duck energy conversion system and wave tank model are established. The ultrasonic distance sensor is configured by which the wave parameter is real-time monitored. A...
self-regulation feedback is designed by screw slide and stepper motor to achieve the stability of wave generation equipment. The results show that the device is always in the best working performance based on STM32 MCU auto-measuring system and a good conversion efficiency 40% is achieved by the duck wave power generation experiment device. In addition, monitor interface of PC is designed by ARDUINO module and Labview for real-time viewing data transmission acquisition and control.

2. Working Principle and Model

2.1. "Nodding Duck" Model
In a certain sea area, the classical ocean wave theory\cite{12} gives the total energy of a small amplitude wave front water column per unit section at a certain moment as following:

\[ E = E_k + E_p = \frac{1}{8} \rho g H^2 \lambda = \frac{1}{8} \rho g H^2 v T \]  \hfill (1)

Here, \( E \) is total energy; \( E_k \) is kinetic energy; \( E_p \) is potential energy; \( H \) is wave height; \( T \) is wave period; \( g \) is the acceleration of gravity; \( \rho \) is seawater density; \( v \) is wave velocity assumed to be unchanged. Since the actual sea conditions change at any time, the power \( P \) of the wave front per meter is used to characterize wave energy levels:

\[ P = H^2 TI \]  \hfill (2)

Here \( I \) is width of the wave and our experimental setup simulates a relatively regular two-dimensional sine wave. According to Salter's Duck Wave Energy Generator theory\cite{14}, for a specific incident wave, wave energy decays with water depth exponentially:

\[ E = ve^{-\frac{2\pi y}{\lambda}} \]  \hfill (3)

Here, \( y \) is water depth, \( \lambda \) is wavelength.

The energy loss \( R \) when the absorbed energy converted into duck body movement mechanical energy:

\[ R = \int \frac{(v_n - u_n)^2}{u_n^2} dS \]  \hfill (4)

Here, \( u_n \) is undisturbed seawater speed, \( v_n \) is duck body speed.

The total efficiency \( \eta \) of the duck body device capturing wave energy is as follows:

\[ \eta = (1 - R_{\text{min}}) (1 - e^{-\frac{4\pi d}{\lambda}}) \]  \hfill (5)

Here, \( d \) is depth of the wave board underwater, \( R_{\text{min}} \) is the minimum value of \( R \) from formula (4). To achieve high conversion efficiency, the back wheel radius \( r \) of canine wave energy device must be designed to meet:

\[ 0.16\lambda < r < 0.2\lambda \]  \hfill (6)

2.2. Producing Wave Method
Based on the principle of the piston wave machine, the movement law of wave plate \( A \) is as follows:

\[ A = \begin{cases} \frac{t}{2T} \cdot A_0 \cos (\omega t), & t \leq 2T \\ A_0 \omega \cdot \cos (\omega t), & t > 2T \end{cases} \]  \hfill (7)
Here, the balance position is $x=0$ for the dynamic boundary moving left and right periodically. $A_0$ is the stroke of the wave board, $t$ is time, $T$ is period, $\omega=2\pi/T$.

The produced wave function is:

$$\eta(x,t) = \frac{4A_0\omega^2\cosh(kd)\sinh(kd)}{kd\sinh(2kd) + 2kd} \cos(kx - \omega t)$$

(8)

Here, $d$ is the depth of the draft merged in water; $k$ is wave number.

Our device uses a single-chip microcomputer to control parameters $A_0$, $d$, and $\omega$ of the stepping motor based on a trapezoidal acceleration/deceleration.

2.3. Ultrasonic Measuring System

The ultrasonic measuring system is shown in Figure 1. Two floats are real-time focused by ultrasonic distance measuring module to stay on the wave surface. And the module sends the signal to the host computer through the ARDUINO module. Wavelength and amplitude are red through the Labview human-computer interaction interface.

![Figure 1. Ultrasonic measurement system.](image)

The wave period is obtained by processing the abrupt signal of a single float with the following formula:

$$\lambda = \frac{v}{f}, \quad v = \frac{S}{t_1 - t_2}, \quad f = \frac{1}{T}$$

(9)

Here, $t_1$ is time signal for the first float to the highest position, $t_2$ is time signal for the second float to the highest position. The time signal is quantified using the minimum unit time of the data collected by the ARDUINO module.

The wavelength can be given by the number of collection points $n$, $m$ as following:

$$\lambda = \frac{nS}{m}$$

(10)

Here, as shown in Figure 2, $n$ is the number of data points collected by the first float twice in middle of the highest value, $m$ is the difference of the number of data points collected by the first float and the second float reaching their middle of the highest value for the first time, respectively.

$$H = H_{\text{max}} - H_{\text{min}}$$

(11)

$H_{\text{max}}$ is the highest wave height, $H_{\text{min}}$ is the lowest wave height.
2.4. Working Principal of the Transducer

The cross-section of the energy conversion device is shown in Figure 3. The central axis consists of a spindle and a couplet to support the entire transducing system for rotation; the soft material ensures the rotation of the spindle while preventing the duck body from entering the water; the bidirectional bearing ensures the frictionless rotation; the 1:30 shifting gear box is to amplify speed; the flywheel structure ensures that the generator continues to rotate rapidly and improves stability of power generation; the one-way bearing ensures the energy conversion system working in one direction, which is the core part of the whole device.

2.5. Calculation of Power Generation Efficiency

The output voltage of the duck wave energy transducing device is shown in Figure 4. The power generation period is approximately half of the wave period. A pulse wave model was constructed, and the effective power Peff, the highest instantaneous efficiency Pmax can be calculated as following:

\[
P_{\text{eff}} = \frac{1}{T} \int_0^\frac{T}{2} \frac{U(t)}{R} dt
\]  

(12)
\[ P_{\text{max}} = \frac{U_{\text{max}}^2}{R} \]  

(13)

Figure 4. Output voltage of the generating set.

2.6. Duck Wave Power Generation Device Schematic

![Diagram](image)

1-Cropping system 2-Wave 3-Energy conversion device 4-Duck wave device 5-Rail 6-Float 7-Ultrasonic module 8-Push plate 9-Stepper motor with gears 10-Rack

Figure 5. Schematic diagram of the duck-type wave power generation device.

3. Experimental Process and Analysis of Results

The experimental test and theoretical calculation data of the wave-making system are shown in Table 1. It can be seen that the error is within 8%. Based on the actual water tank length, we select the wavelength range of 35-45 cm. The wave front width is set to be 15 cm, and the outer wheel radius is 7 cm combining with theoretical calculation.

|   | Push plate draft (m) | Stroke (m) | Cycle (s) | Measured wavelength (m) | Measured wave height (cm) | Theoretical wave height (cm) | error | Wave energy (w) |
|---|---------------------|------------|-----------|-------------------------|---------------------------|-------------------------------|-------|-----------------|
| 1 | 0.1                 | 0.1        | 0.6       | 0.34                    | 10.5                      | 10.23184886                   | -2.62%| 0.942216579     |
| 2 | 0.1                 | 0.1        | 0.8       | 0.37                    | 6                         | 6.037864755                   | 0.63% | 0.43746973      |
| 3 | 0.1                 | 0.1        | 0.8       | 0.4                     | 6.4                       | 6.300380437                   | -1.58%| 0.476337524     |
| 4 | 0.1                 | 0.1        | 1         | 0.37                    | 4                         | 3.864233443                   | -3.51%| 0.223984502     |
| 5 | 0.1                 | 0.09       | 0.6       | 0.28                    | 7.5                       | 8.15307515                    | 8.01% | 0.59825371      |
According to Table 1, three power generators with a rated power of 1-2w are tested: small permanent magnet alternator, small three-phase brushless generator and DC generator. The tested results are shown in Figure 6. Here, two small permanent magnet alternators are connected in parallel to facilitate the measurement and visualization of the experimental data. It can be seen the output power can reach 0.73 w with an external 147 ohm load and a speed of 12000 rpm of the transducer. Given the friction and service life of the transducing structure, as well as the high speed, the small permanent magnet alternator has a small resistance and is a superior motor.

Selecting parameters such as the motor stroke, motor rotation period, the depth of the draft merged in water, combined with the ultrasonic measuring device, theoretical calculations, using the Labview computer host system to real-time display working state of the device, the wave height and wavelength of the waves, and the output wave energy value (the input power of the power generation system), the voltage value is generated by the duck wave power generation device and is transferred to the Arduino module of the host computer system. Hence, the output power and the final power generation efficiency are calculated and displayed. The cycle-efficiency relationship is shown in Figure 7. We find that the power generation efficiency increases gradually with the wave period, and reaches a maximum value. After that, the increasing of the period, which makes the wavelength deviate from the optimal working wavelength and further the optimal working state of the nod duck, leads to reduced efficiency.

![Figure 6. Power generation test: rotating speed-power diagram.](image)

![Figure 7. The period-efficiency diagram.](image)
The test found that the efficiency of the device increases with the increase of the height of the wave, while the swing of the "head duck" becomes larger and larger. As the amplitude exceeds 90° of the horizontal line, the transducer will “turn over” and fail. Hence, ultrasonic measurement is used to record the wave height interval of the best working condition, to serve as the basis for the feedback adjustment and self-stabilization system. When the wave height detected by the ultrasonic measuring system exceeds the interval, the signal is sent to the stepping motor through the single-chip microcomputer, and the height of the "doodle duck" is automatically adjusted by the screw-sliding table. Our duck-type wave power generating device can be always in the best working condition in real time.

4. Conclusion
The components of the whole device have reached the stability as an experimental platform, and the sea wave simulation device is built with a rigid structure to stabilize the simulated wave with a theoretical error within 8%. Irregular glass slag is used to eliminate waves and stabilize the wave shape, reduce interference of reflection wave, avoid standing waves to facilitate observation, measurement and data acquisition. The efficiency of the device can be captured more than 17%. The waves work on the power generation system in one direction, and the duck body responds sensitively. And the working state is self-stabilized. By adjusting the center of mass, the duck body automatically recovers the initial angle of attack and ensures energy efficiency. The transducer uses the flywheel to store energy and stabilize the voltage output. The generator device runs stably, and overcomes the problems of sealing, mechanical transmission and the experimental results are well reproducible.

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