Hydrodynamic and Circuit Simulation and Analysis of an Integrated Wind-wave Generator by AQWA® and SIMULINK®

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Abstract. The wind and the wave on the ocean are often in sync with each other. Under some extreme sea conditions, individual fans on generators will bear higher stress due to the impulse of the wave. The paper discusses the numerical stress simulation of the vertical column of the intermediate fan with and without the pendulum plate component individually and performs circuit voltage simulations of the generating parts on SIMULINK®. By analyzing the force on the fan column, we conclude that the generator may eliminate wave impulse to a certain degree through the combination of fan and pendulum structures. The generator could protect itself from the scour of the wave with the mutual protection of both the fan and the pendulum parts. The electric simulation also indicated that to receive a stable output of voltage, rectification and filtering processing on the circuit should be applied.

1. Introduction
Currently, the theoretical storage of wave energy is about 70 million kilowatts, which has broad development value and application value.[1] In the aspect of wind power generation, the coastal area has a large power grid capacity and power load. The value of offshore wind energy is about three times the size of onshore wind energy. Besides that, offshore wind power is three times more efficient than onshore wind power. Nowadays, land-based wind generators are relatively developed so that the new focus gradually moved to offshore wind power generation.[2] This is not only conducive to the development of the marine economy and reducing emissions, but also of great strategic significance for the control and construction of islands away from the mainland. In recent years, China has successively built several GW scale offshore wind power generation zones around the coast, but the expense of dwelling offshore wind power equipment is high. To enhance power generation efficiency, combine offshore wind power generation with wave energy generation, and realize multi-level utilization of marine energy, is particularly important.[3]

2. Structure and parameters for the simulation model

2.1. Composition of the generator
The structure of the integrated wind-wave generator is shown in Figure 1.[4]

It is composed of two components: the fan generator and the pendulum generator.
2.2. Parameter selection for the simulation model

2.2.1. Overall simulation process. The stress of the central column is calculated in the following steps:

- Carrying out the overall mechanical design according to the actual design requirements and environmental conditions of the fan pendulum platform, to determine the overall size of the platform and determine the quality parameters of the pendulum center of gravity.
- Establishing finite element model. According to the main parameters of the platform obtained from the overall design of the platform, the fan pendulum integrated finite element model was established, and divided the mesh.
- Analyzing results derived from AQWA®.

2.2.2. Model development. However, in this simulation experiment, the scour of the wave on the fan column should be analyzed, so the actual situation can be simplified. And the pendulum as well as the initial direction of the wave, are placed at the angle of 0°. The data in Table 1. are from the seaside test prototype experiment, which is the foundation of the whole simulation.

Table 1. Design parameters of integrated wind-wave generator

| Component name       | Parameter1 | Parameter2 | Parameter3 |
|----------------------|------------|------------|------------|
| Fan generator        | Bottom radius 0.5 m | height 3 m | \           |
| Pendulum generator   | height 2 m | thickness 0.6 m | length 4 m |

Note: In AQWA®, the internal structure of the models does not matter as shown in Figure 2.

2.2.3. Depth analysis of draught. On the DesignModeler®, We divide the whole model into three parts and set the depth of the water 0.3 m. The results are shown in Figure 3.

2.2.4. Coordinates of the center of mass of components. Here the coordinates to be set are vital in the subsequent calculation. Due to the fixation of the central column, we may neglect its relevant mechanical parameters. The data of main components centers of mass are shown in Table 2.
Table 2. coordinates of centers of mass of the pendulum (mm)

| Component   | X    | Y    | Z    |
|-------------|------|------|------|
| Fan         | -2052.504 | -514.135 | 1500.000 |
| Pendulum    | -1992.710  | 701.220  | 1500.000 |

2.2.5. *Wave frequency.* The wave frequency is related to the previous mesh sizing procedure. By definition, we chose 0.01592Hz.

3. Results and Discussion

After completing these operations, we solved the problem. To verify that the calculation results were correct, we may make a judgment by the following principles:

1. Additional mass tends to be a constant;
2. Radiation damping tends to be zero.

The results are demonstrated in Figure 4 and Figure 5.

![Figure 4. force on fan column with pendulum](image)

![Figure 5. force on fan column without pendulum](image)

According to the comparison, we can know that when the pendulum exists, the force acting in the column is smaller than that without a pendulum. In the case of the pendulum, the maximum force is
2.773 \times 10^4 \text{N/m} \text{ while in the absence of a pendulum, the maximum force is } 3.82 \times 10^4 \text{N/m}. \text{ Therefore, we can conclude that the pendulum has an obvious eliminating effect on the force of the column at a certain wave frequency, which also indicates that after adding the pendulum part, it greatly alleviates the scour of the wave to the fan column.}

4. Voltage stability simulation

4.1. Establishment of the mathematical model

When the pendulum moves in the direction of the center of the pendulum, the generator on one side will be driven, while the generator on the other side will be zero. When the pendulum moves in the other direction of the center of the pendulum, the driving force in the generator will be opposite. Because of the existence of unidirectional bearing, the system will have two stages: meshing and detachment. When the system is engaged, the equation of motion of one motor is:

\[ M_{ry} - I_w \ddot{\theta} - C_w \dot{\theta} - K_w \theta - I_b \dddot{\theta} - M_{pto} - mgL \cos \theta = I\ddot{\theta} \]  \hspace{1cm} (1)

\( M_{ry} \) is the exciting moment, expressed as

\[ M_{ry} = M_r \sin(\omega t + \phi) \]  \hspace{1cm} (2)

\( M_{pto} \) is the moment produced for a PTO device, expressed as

\[ M_{pto} = C_{pto} \dot{\theta} + I_{pto} \ddot{\theta} \]  \hspace{1cm} (3)

\( I_w, C_w, k_w, \) and \( I \) are the additional moment of inertia, damping coefficient, stiffness coefficient, and moment of inertia around the rotating shaft of the pendulum plate, which can be obtained by ANSYS ® /AWQA ® calculation. \( I_b \) is the moment of inertia of the shaft, \( C_{pto} \) and \( I_{pto} \) are the equivalent damping coefficients and the equivalent moment of inertia coefficients of the PTO device at the pendulum Angle, \( \theta \) is the swing angle of the pendulum plate, the \( m \) is the mass of the pendulum plate, the \( g \) is the acceleration of gravity, and the \( l \) is the distance from the center of gravity of the pendulum plate to the rotating shaft. From equation (1), it is known that it is a nonlinear equation in the meshing stage, so it is difficult to find its analytical solution.

The equation of motion of the pendulum plate when the system is out of phase is:

\[ M_{ry} - I_w \ddot{\theta} - C_w \dot{\theta} - K_w \theta - I_b \dddot{\theta} - mgL \cos \theta = I\ddot{\theta} \]  \hspace{1cm} (4)

Equation of motion of generator shaft is:

\[ C_{pto} \dot{\theta} + I_{pto} \ddot{\theta} = 0 \]  \hspace{1cm} (5)

Equation (5) is a differential equation with an exponential form solution, that is, the velocity of its departure stage will appear exponential decay, and the solution is:

\[ \frac{d\theta}{dt} = \dot{\theta}_0 e^{\frac{C_{pto}}{I_{pto}}(t-t_0)} \]  \hspace{1cm} (6)

According to the above analysis, the equation of motion of the pendulum plate is nonlinear, so it is difficult to find its analytical solution. To analyze its motion clearly, the numerical solution can be obtained by modeling and simulation.
4.2. Simulation Model

4.2.1. AWQA® Frequency domain simulation. The process is shown in Figure 6. The simulation results showed that when wave period $T = 2.5$ s, the wave height $H = 0.2$ m, the amplitude of exciting moment is $M_e = 4.721$ N.m. Additional moment of inertia $I_w = 0.0292$ kg.m, damping coefficient $C_w = 4.1557 \times 10^{-4}$ N.m/(°/s), stiffness factor $K_w = 0.2231$ N.m/°. Then the exciting moment $M_{ry}$ can be expressed as

$$M_{ry} = 4.721 \sin\left(\frac{2\pi}{2.5}t\right)$$

4.2.2. Single pendulum generator simulation by SIMULINK®. Due to the existence of two unidirectional bearings, the device will drive different motors when the pendulum plate rotates in two different directions, as described in equation (1), equation (4), and equation (5).

The output voltage of the two generators can be obtained as shown in figure 4 and figure 5 below. Under the influence of unidirectional bearing, it can be seen that the voltage value does not decay directly to 0.

4.2.3. Pendulum and Fan by SIMULINK® Simulation.

![Figure 6. Single pendulum generator simulation](image6)

![Figure 7. Fan rectification and stabilization](image7)
The voltage value obtained directly through the pendulum device and the fan device is not stable, and the stable voltage value can be obtained by rectifying and filtering the circuit to charge the battery equipment. The voltage can be stabilized in the waveform through the three-phase rectifier bridge, and the voltage fluctuates between +15V and +25V. The procedure is displayed in Figure 7 and the output is in Figure 9.

While the pendulum device reduces the wave to the fan platform, the pendulum circuit is connected in series to the fan circuit to charge the storage equipment and its voltage value can be stabilized at about +25V. The procedure is presented in Figure 8 and the output is in Figure 10.

5. conclusion
The most obvious finding to emerge from this study is that the integrated wind-wave generator works effectively with the pendulum component resisting wave against the main column. Other than that, the circuit simulation revealed that stable output of voltage can successfully transmit to the chargeable battery. The findings reported here shed new light on the possibility of applying a pendulum generator on the existing fan generator to lengthen its service life by eliminating wave impulses while generating more power. Thus, provisions of this integrated wind-wave generator will significantly enhance the energetic utilization of marine energy and reduce carbon emission from fossil fuel plants.

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