Modeling and Simulation of Buoy Heave Response Under Electric Generator Load Using Simulink

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Abstract. According to the different links of energy transmission, the oscillating buoy wave energy converter is divided into mechanical mode and hydraulic mode. For the oscillating buoy wave energy converter with mechanical transmission, it’s requisite to consider the influence of electric generator and different transmission ratio on the heave response of buoy in its design process. Consequently, the Simulink toolbox is used to establish the simulation model of the buoy heave response under the electric generator load, and the heave response of the buoys with different diameters under the electric generator and transmission ratio is analysed. The results show that as the buoy diameter increases linearly, the heave displacement, heave velocity and generating power curve amplitude do not increase linearly which shows that the increment of amplitude becomes smaller. Therefore, buoys with different diameters have different load capacity.

1. Introduction

Wave energy converter is composed of wave energy capture link, energy transfer link and power generation link [1]. According to the operating principle of wave energy converter, wave energy converter is divided into oscillating water column, oscillating bodies and overtopping [2]. According to the different links of energy transmission, the oscillating buoy wave energy converter is divided into mechanical mode and hydraulic mode. In mechanical mode, the heave motion of the buoy is transformed into rotary motion by mechanical transmission device such as gear and rack, and then the mechanical energy of rotary motion is transformed into electric energy by electric generator in the power generation link [3].

A lot of researches have been carried out on the oscillating buoy wave energy converter at present. Martins et al. study the hydrodynamic performance of the oscillating buoy wave energy converter [4]. Felipe et al. design and manufacture a two-body wave energy device and carried out relevant experiments [5]. Liang et al. study a two-body wave energy converter oscillating in heave [6]. Xu et al. carry out experiments and numerical studies on the hydrodynamics of a two-body floating-point absorber wave energy converter under both extreme and operational wave conditions [7]. Ossama et al. study the control of a small two-body heaving wave energy converters for ocean measurement applications [8].

For the oscillating buoy wave energy converter with mechanical transmission, it’s requisite to consider the influence of electric generator and different transmission ratio on the heave response of buoy in its design process. Consequently, the Simulink toolbox is used to establish the simulation model of the buoy heave response under the electric generator load, and the heave response of the buoy under the electric generator and different transmission ratio is analysed.
2. Buoy heave response model under electric generator load

2.1. Buoy free heave model

When the cylindrical buoy is in free heave motion, it is subjected to the damping force and the hydrostatic restoring force from the wave. Assuming that the fluid is incompressible and the buoy heaves under the action of small amplitude wave theory, its response model can be simplified as a damped forced vibration system, and the forcing force is wave force [9]. As shown in Figure 1, the x-z coordinate system is established, the x-axis is the static water surface, the z-axis is the heave direction of the buoy centroid, and the origin of coordinate axis is the buoy centroid. The coordinate system is absolute and does not move with the buoy.

![Figure 1. Schematic diagram of buoy heave motion](image)

According to Newton’s second law:

\[(m + m_a) \ddot{z} + C_w \dot{z} + K_w z = \rho g A_a [A \sin(\omega t) - z] \]  

(1)

By sorting out the formula (1), we can get the following results:

\[(m + m_a) \ddot{z} + C_w \dot{z} + K_w z = F_w \]  

(2)

\[K_w = \rho g A_a \]  

(3)

\[F_w = K_w \cdot A \sin(\omega t) \]  

(4)

where \(m\) is the buoy quality; \(m_a\) is the additional quality of buoy; \(C_w\) is the buoy damping coefficient; \(K_w\) is the coefficient of hydrostatic restoring force; \(F_w\) is the wave force; \(\rho\) is the water density; \(g\) is the acceleration of gravity; \(A\) is the wave amplitude; \(A_a\) is the draft cross-section of float; \(\omega\) is the wave circle frequency; \(z\) is the heave displacement of the buoy centroid; \(t\) is the time.

Using the Laplace transform and sorting out the formula (2), the result is obtained:

\[
\frac{z(s)}{F_w(s)} = \frac{1}{(m + m_a)s^2 + C_w s + K_w} 
\]

(5)

Buoy free heave response simulation model based on Simulink is shown in Figure 2.

![Figure 2. The simulation model of buoy free heave response](image)

2.2. Electric generator load model

DC motor is selected as the electric generator in power generation, the armature circuit diagram is shown in Figure 3. The M (rotor) rotates to produce \(I_a\) (armature current) and \(E_a\) (counter electromotive force) in the armature circuit [10].
According to the circuit theory, the voltage balance equation of armature circuit is listed:

\[ E_a = L_a \frac{dI_a}{dt} + I_a \cdot R_a \]  

(6)

The induction potential equation of the DC motor is:

\[ E_a = K_e \cdot \omega_m \]  

(7)

The basic equation of electromagnetic torque is:

\[ T_F = K_t \cdot I_a \]  

(8)

where \( E_a \) is the counter electromotive force; \( L_a \) is the armature current; \( R_a \) is the armature inductance; \( R_a \) is the armature resistance; \( K_e \) is the counter electromotive force coefficient; \( \omega_m \) is the rotor angular velocity; \( K_t \) is the torque coefficient; \( T_F \) is the electromagnetic torque.

Using the Laplace transform and sorting out the above formulas, the result is obtained:

\[ T_F = K_t \frac{K_e \cdot \omega_m}{L_a s + R_a} \]  

(9)

Due to mechanical friction, hysteresis loss and eddy current loss, \( T_f \) (resistance torque) is produced in motor. Inertia torque \( T_J \) is produced when the rotor rotates because of \( J \) (the moment of inertia of the rotor). The product of \( E_a \) and \( I_a \) is the ideal generating power. In the process of gear transmission and power generation, the total energy transfer efficiency is expressed by \( \mu_i \).

Therefore, The total load torque \( T \) is:

\[ T = T_F + T_J + T_J \]  

(10)

To sum up, the simulation model of electric generator load can be obtained, as shown in Figure 4.
2.3. Buoy heave response model under electric generator load
Considering the role of \( r \) (gear transmission ratio) in energy transmission link, the buoy heave response model under electric generator load can be obtained by synthesizing 2.1 and 2.2, which is shown in Figure 5.

The output of the simulation model of buoy free heave response is the heave displacement of buoy, which is “Displacement” in Figure 2. The product of “Displacement” and \( r \) (gear transmission ratio) is the rotation angle of motor rotor, which is “Angle” in Figure 4. The product of the total load torque \( T \) and \( r \) (gear transmission ratio) is the resistance acting on the buoy. The difference between wave force and the total load torque \( T \) is the actual force acting on the buoy.

![Figure 5. The buoy heave response model under electric generator load](image)

3. Result and discussion
The simulation parameters of the system are shown in Table 1, Table 2 and Table 3, gear transmission ratio \( r = 200 \), energy transfer efficiency \( \text{m} \text{i} \text{u} = 0.75 \).

| Sequence number | Diameter (m) | Height (m) | Draft (m) | Quality (kg) | Additional quality (kg) |
|-----------------|-------------|------------|-----------|--------------|-------------------------|
| 1               | 1.0         | 0.4        | 0.2       | 80.5         | 170.8                   |
| 2               | 1.5         | 0.4        | 0.2       | 181.1        | 576.6                   |
| 3               | 2.0         | 0.4        | 0.2       | 322.0        | 1366.7                  |

| \( H/L \) | \( k \) | \( L \) (m) | \( H \) (m) | \( A \) (m) |
|-----------|--------|------------|------------|------------|
| 0.02      | 0.23   | 27.25      | 0.56       | 0.28       |

| \( R_s \) (\( \Omega \)) | \( L_u \) (mH) | \( K_v \) (v/r·min\(^{-1}\)) | \( K_e \) (Nm/A) | \( J \) (kg·m\(^2\)×10\(^{-5}\)) | \( T_f \) (Nm) |
|-------------------------|----------------|-----------------|-----------------|-------------------------------|---------------|
| 20.82                   | 18.13          | 0.138           | 1.33            | 226                           | 0             |

Figures 6, 7 and 8 show the comparison of heave displacement, heave speed and generating power of buoys with different diameters. When the electric generator and transmission ratio remain unchanged, the heave displacement, heave speed and generating power increase with the increase of buoy diameter. Although the buoy diameter increases linearly, the heave displacement, heave velocity and generating power curve amplitude do not increase linearly which shows that the increment of amplitude becomes smaller, and the heave displacement curve of the buoy is closer to the wave curve. The reason is that when the load is constant, the larger the buoy diameter is, the easier it is to drive the load to do work, and the smaller the influence of the load on the buoy heave response is. With the increase of buoy diameter, the phase difference between buoy heave response curve and wave curve increases. The reason is that when the buoy diameter increases, the buoy quality also increases, and the larger the diameter is, the worse the wave following performance is.
4. Conclusion
This paper establishes the simulation model of the buoy heave response by the Simulink toolbox. Under the condition of determining the parameters of generator and the transmission ratio of mechanical transmission mechanism, the heave response and generating power of buoys with different diameters is studied. The results show that: as the buoy diameter increases linearly, the heave displacement, heave velocity and generating power curve amplitude do not increase linearly which shows that the increment of amplitude becomes smaller, it can be seen that the power generation capacity of the buoy with larger diameter has not been fully utilized. Therefore, buoys with different diameters have different load capacity, in order to make full use of the power generation capacity of buoys, it is necessary to match the best load for buoys with different diameters.

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