Performance of an OWC device placed over stepped bottom in random waves environment

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Abstract: The performance of an OWC device placed over stepped bottom is analyzed in random waves environment. To model the random local wave climate, the Pierson-Moskowitz spectrum along with two different sea states are considered. The effect of front wall draft, wall thickness, device chamber length and turbine damping coefficient on the efficiency of the device are discussed in details. It is observed that the local wave climate plays a vital role on the performance and efficiency of the OWC device along with the variation in device parameters.

1. INTRODUCTION

The demand for renewable energy has increased due to their non-polluting nature, and the concern of environmental issues like global warming and climate change arise due to the combustion and superfluous use of mineral fuels. In this aspect, renewable energy will play a vital role in the upcoming future. Among various renewable energy sources, wave energy has an immense potential to become the utmost source of energy and convert the same into electricity. Out of various wave power generation technology, the concept of an oscillating water column device (OWC-WEC) is well established and has a variety of features over other technologies. The mathematical modeling of these OWC devices started since 1980 by several researchers across the world. [1] Used panel method to investigate the performance of an OWC-WEC and it was reported that the geometrical configuration of the device plays a significant role to enhance the efficiency of the device. [2] Used a Galerkin approximation to study the hydrodynamics of fully submerged front wall OWC-WEC. It was concluded that as the submergence depth increases, the second resonance mechanism becomes more prominent. [3] Analyzed the working mechanism of an OWC-WEC using Fluinco. In this research, the following conclusions were obtained (i) the draft of the front wall is directly proportional to the period of the optimal efficiency and (ii) the height of the OWC chamber is inversely proportional to the efficiency of an OWC-WEC. [4] Studied the performance of an OWC-WEC placed on the sloping bottom using the HOBE. It was reported that in the long-wave regime, the efficiency of an OWC-WEC increases with an increase in chamber length, and a reverse pattern is observed in the short-wave regime. [5] Used CFD technique to analyze the performance of a single and dual chamber OWC-WEC. Recently, [6] studied the effect of geometrical configurations on the efficiency of an OWC-WEC using the BEM, and the following conclusions were obtained: (i) the existence of bottom steps in front of the OWC device diminishes the hydrodynamic performance of an OWC device, (ii) the thickness of the front barrier is inversely proportional to the bandwidth of the efficiency curve. [7] used the Eigen function expansion-BEM method to analyse the performance of an OWC-WEC placed over the undulated bottom topography. It was found that in the long wave regime, the ripple amplitude of the bottom bed significantly increases the efficiency of an OWC-WEC. In all the
aforementioned works, the OWC-WEC worked under the action of regular incident wave. Nevertheless, in the real sea environment, ocean waves are highly irregular in nature. Consequently, the analysis of the performances of the OWC devices under irregular incident waves is pivotal. [8] Developed the stochastic modeling of an OWC-WEC under the action of irregular incoming waves. It was noticed that the effect of the wave climate is negligible on the optimal rotational speed control algorithm. [9] Analyzed the mechanism of an OWC-WEC under the action of irregular incoming waves using the BEM. [10] Used a fully nonlinear NWT approach to investigate the performance of an OWC-WEC. It was reported that the air-compressed and viscous effects significantly enhance the efficiency of an OWCEWE. [11] Developed a technique to optimize the geometrical configurations of a floating OWC-WEC under the action of regular and irregular incoming waves. It was concluded that the gap between the floater bottom and the top of the large thick tube part is the key parameter to enhance the performance of an OWC-WEC. [12] Analyzed the performance of an OWC-WEC placed over the stepped bottom experimentally and numerically under the action of irregular incoming waves. It was concluded that the effect of the incident wave frequency and the damping coefficient of the turbine are more prominent to enhance the efficiency of an OWC device compared to the incident wave height. [13] Analyzed the performance of an L-shaped OWC device experimentally under the action of irregular incoming waves. It was reported that the amplification factor and the hydrodynamic efficiency of an OWC-WEC strongly depend on the submergence depth of the OWCEWE. [14] Investigated the performance of an OWC-WEC experimentally under the irregular incoming waves. It was found that the shape of spectrum inside the device chamber is influenced by the incident wave spectrum. In the present study, the performance of an OWC device placed over stepped bottom is analyzed in random waves environment. The paper is structured as follows. Firstly, the mathematical formulation is provided. Hereafter, the expressions of the key parameters associated with the OWC device performance are given. Finally, the results and conclusions are provided.

2. MATHEMATICAL FORMULATION

The current study yields the mathematical modeling of an OWC-WEC placed over the stepped bottom. For the sake of modeling, 2D Cartesian coordinate system is used. The alignment of the axes is shown in Fig. 1. The OWC-WEC constitutes a rigid and impenetrable thick seaside wall of uniform thickness d and stood at x = L − b. Here, b denotes the chamber length and the draft of the front wall of the OWC-WEC are a₁ and a₂ respectively. Moreover, the backside wall of an OWC-WEC is located at x = L. The OWC-WEC is situated over the stepped bottom with the step-length b/2 at z = −h₁ for {−l < x < L − b/2} and z = −h₂ for {L − b/2 < x < L}. The two components of free surface Γ₁ and Γ₂ represent the external and internal free surface respectively. Now, to use BEM, a fictitious boundary Γ₀ is considered at x = −l. Further, Γ₀ represents the bottom foundation and Γ₁ and Γ₂ are the rigid boundaries with uniform thickness d. The fluid flow follows the potential flow theory and the motion is assumed to be harmonic in time. The expression for the total velocity potential is represented as \( \chi(x, z, t) = 9 \Re(\chi(x, z, t)e^{-i\omega t}) \). With this background, the governing equation is given by

\[
\nabla^2 \chi(x, z) = 0 \quad (1)
\]

\( \chi \) contains the \( \chi^S \) and \( \chi^R \) (see [21] for details). Now, \( \chi^S \) and \( \chi^R \) satisfy the bc at \( z = 0 \) and is provided as,

\[
\frac{\partial \chi^{S,R}}{\partial n} - K \chi^{S,R} = \begin{cases} \mathcal{N}, & \text{on } \Gamma_4, \\ 0, & \text{on } \Gamma_6. \end{cases} \quad (2)
\]

Here, we choose \( \mathcal{N} = 0 \) for \( \chi^S \) and \( \mathcal{N} = 1 \) for \( \chi^R \) respectively, and \( K = \omega^2/g \). Derivative in the normal direction is represented by \( \partial/\partial n \). Now, the boundary conditions on the impenetrable boundaries \( \Gamma_b \cup \Gamma_{d1} \cup \Gamma_{d2} \) is given by

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\[
\frac{\partial \chi_{S,R}}{\partial n} = 0, \text{ on } \phi_b \cup \phi_{d1} \cup \phi_{d2}
\]  

(3)

Now, the radiation boundary condition on auxiliary boundary \( \Gamma_1 \) is given by

\[
\frac{\partial \chi_{S,R}}{\partial n} - i k_0 \chi_{S,R} = \gamma \left( \frac{\partial \chi_I}{\partial n} - i k_0 \chi_{S,R} \right), \text{ on } \Gamma_1
\]

(4)

Here, \( k_0 \) satisfies \( \omega^2 = g k \tanh(kh) \) and the expression for \( \chi' \) is given as \( \chi'(x,z) = \left( \frac{-i g H}{2 \omega} \right) \cosh(k_0(h+z)) e^{ik_0x} \) and \( H \) is termed as incident wave height. In Eq. (4), for \( k = 1 \) for \( \chi^S \) and \( k = 0 \) for \( \chi^R \) respectively. The solution methodology for the above-mentioned BVP is discussed using the BEM. In this method, firstly, a system of Fredholm integral equations (FIE) involving the \( \chi^S \) and \( \chi^R \) are derived. The Green's function \( G(x,z;r,s) \) is given as

\[
G(x,z;r,s) = -4\pi i \frac{\cosh k_0(h+s) \cosh k_0(h+z)}{2k_0 h + \sinh 2k_0 h} e^{ik_0|x-r|} - 4\pi \sum_{n=1}^{\infty} \frac{\cos k_n(h+s) \cos k_n(h+z)}{2k_n h + \sin 2k_n h} e^{-k_n|x-r|}
\]

(5)

Using Green’s identity on \( \chi^R, S \) and \( G(x,z;r,s) \) and using the bcs (2)-(4), the following FIE are obtained as

\[
-\frac{1}{2} \chi^S + \int_{\phi_1} \chi^S \frac{\partial G}{\partial n} - i k_0 G \, d \phi + \int_{\phi_b + \phi_{d1} + \phi_{d2}} \chi^S \frac{\partial G}{\partial n} d \phi + \int_{\phi_{t2}} \chi^S \frac{\partial G}{\partial n} - KG \, d \phi
\]

\[
+ \int_{\phi_1} \chi^S \frac{\partial G}{\partial n} - KG \, d \phi
\]

\[
= \int_{\phi_1} G \left( \frac{\partial \chi_I}{\partial n} - i k_0 \chi_I \right) d \phi
\]

(6)
\[-\frac{1}{2} \chi^R + \int_{\psi_{1}} \chi^R \left( \frac{\partial G}{\partial n} - i k_0 G \right) d \phi + \int_{\psi_{b} + \psi_{d1} + \psi_{d2}} \chi^R \frac{\partial G}{\partial n} d \phi + \int_{\psi_{f2}} \chi^R \left( \frac{\partial G}{\partial n} - KG \right) d \phi + \int_{\psi_{f1}} \chi^R \left( \frac{\partial G}{\partial n} - KG \right) d \phi = \int G d \phi \]  

(7)

Now, Eqs. (6) - (7) are transformed into a number of algebraic equations using the BEM method and solved of \( \chi \) and \( \partial \chi / \partial n \). The details are available in [7].

3. RANDOM WAVES ENVIRONMENT

Random ocean waves are represented using the concept of wave spectrum and associated sea-states. Here, the Pierson-Moskowitz spectrum [15] is used, and the form is given by

\[ S_{\text{inc}}(\omega) = 263 H_s^2 T_e^{-4} \omega^{-5} \exp(-1054 T_e^{-4} \omega^{-4}) \]  

(8)

The standard deviation \( \beta_p \) of the chamber pressure is given by (see [15] for details)

\[ \beta_p^2 = \int_0^\infty S_{\text{inc}}(\omega) \left[ \frac{\text{Pr}(\omega)}{\text{amp}(\omega)} \right]^2 d\omega, \]  

(9)

where \( \text{amp}(\omega) = \sqrt{2 S_{\text{inc}}(\bar{\omega}) \delta \omega} \) is the incident wave amplitude for individual regular wave component. Here, \( S_{\text{inc}} \) represents the incident wave spectrum. Now, the average efficiency of an OWC device is given by

\[ \zeta_A = \frac{W_A}{P_A}. \]  

(10)

where \( W_A \) and \( P_A \) are termed as average available power to the Wells turbine and the incident wave energy flux respectively and given by

\[ P_A = \rho g w \int_0^\infty S_{\text{inc}}(\omega) C_g(\omega) d\omega, \]  

(11)

\[ W_A = \tau \beta_p^2. \]  

(12)

Here, \( w \) and \( C_g \) are the width of the chamber and the group velocity of the incoming waves. Further, \( \tau \) is the turbine damping coefficient.

4. RESULTS

The parameters associated with the OWC device and the incoming waves are the following: \( h = 10 m, \rho = 1025 \text{ kg/m}^3, g = 9.81 \text{ m/s}^2, L = 3 h, b = h, d = 0.05 h, c = 0.5 h, a = 0.5 h \) unless mentioned explicitly. The characteristics of two different most occurrence sea states for the incoming wave spectrum as in Eq. (8) are the following (see [15] for details): the significant wave heights \( H_s = 1.88 \text{m}, 3.18 \text{m} \) and the corresponding energy periods \( T_e = 6.33 \text{s}, 9.93 \text{s} \).
Figs. 2(a) and 2(b) illustrate the variation of free surface elevation $\zeta$ for variety of (a) chamber length $b/h_1$ and (b) submergence depth $a_1/h_1$ respectively. It is observed that the amplitude of $\zeta$ decreases with an increase in $b/h_1$. Further, certain phase change in $\zeta$ is observed for various $b/h_1$. On the contrary, the amplitude of $\zeta$ increases in the open water region with an increase in $a_1/h_1$ and reverse trend is seen inside the device chamber. Moreover, a phase change in $\zeta$ occurs for various $a_1/h_1$.

Figs. 3(a) and 3(b) illustrate the variation of $\zeta$ for variety of (a) $a_2/h_1$ and (b) $d/h_1$ respectively. Both the figures show that the $\zeta$ does not alter much with the variation in $a_2/h_1$ and $d/h_1$. The reason is that the energy of the ocean waves is mostly concentrated near the free surface and therefore, the effect of bottom protrusion on $\zeta$ is less.

In Figs. 4(a) and 4(b), the average efficiency $\zeta_A$ vs turbine damping coefficient $\tau$ is plotted for various $b/h_1$ for first and second sea states. It is seen that for first sea state, efficiency $\zeta_A$ decreases as $b/h_1$ increases. On the contrary, $\zeta_A$ increases as $b/h_1$ increases for second sea state. This indicates that the efficiency of the OWC-WEC significantly depends on the sea states, i.e., on the local wave climate.

Figs. 5(a) and 5(b) show $\zeta_A$ vs $\tau$ for various $a_1/h_1$ for first and second sea states. For both sea states, efficiency $\zeta_A$ decreases as $a_1/h_1$ increases. The reason behind this is that as draft of the front wall becomes higher, wave energy gets reflected by the front wall. As a consequence, less wave energy enters into the chamber.
Fig. 4. $\zeta_A$ vs $\tau$ for various $b/h_1$ with (a) $H_s = 1.88, T_e = 6.33$ and (b) $H_s = 3.18, T_e = 7.97$

Fig. 5. $\zeta_A$ vs $\tau$ for various $a/h$ (a) $H_s = 1.18, T_e = 6.50$ and (b) $H_s = 1.96, T_e = 7.97$

Fig. 6. $\zeta_A$ vs $\tau$ for various $a_2/h_1$ (a) $H_s = 1.18, T_e = 6.50$ and (b) $H_s = 1.96, T_e = 7.97$

Figs. 6(a) and 6(b) depict $\zeta_A$ vs $\tau$ for various $a_2/h_1$ for first and second sea states. For both the cases, efficiency $\zeta_A$ decreases as $a_2/h_1$ increases. The reason behind this is already explained in the previous figures.
Figs. 7(a) and 7(b) display $\zeta_A$ vs $\tau$ for various $d/h_1$ for first and second sea states. For both the cases, efficiency $\zeta_A$ decreases as $d/h_1$ increases. The reason behind this is already explained in the previous figures. A comparison between Figs. 7(a) and 7(b) demonstrates that the efficiency $\zeta_A$ is much higher for second sea state as compare to first sea state. The reason is that the wave height is higher in second sea state and so contains more wave energy.

5. CONCLUSIONS

In this study, the average efficiency of an OWC device placed over stepped bottom is analyzed in random waves environment. To model the irregular local wave climate, Pierson-Moskowitz spectrum along with two different sea states are considered. It is seen that the efficiency of OWC-WEC decreases as the front wall draft and thickness increases. For the first sea state, efficiency decreases as chamber length increases and opposite results are observed for the second sea state. Moreover, the amplitude of surface elevation increases in the open water region with an increase in front wall draft and reverse trend is seen inside the device chamber. Further, phase change occurs in the free surface elevation for various front wall draft and chamber length.

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