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Design of the Point Absorber Wave Energy Converter for Assaluyeh Port

Mehdi Nazari, Hassan Ghassemi, Mahmoud Ghiasi and Mesbah Sayehbani

Department of Ocean Engineering, Amirkabir University of Technology, Tehran, Iran

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Abstract: The research explained in this paper was carried out to analyze and design a point absorber wave energy convertor for Assaluyeh coastal on Persian Gulf. The geographical conditions of this region have some local short waves which may be ideal to use this type of energy convertor. According to the collecting of wave data and using an optimized buoy, it is concluded that the adjustments on damping and natural frequency have more effect on average heave displacement. Therefore, by changing the shape of flat buoy to conical cylindrical, the drag coefficient that has direct effect on the damping of the buoy could be reduced. Regarding the length to diameter ratio of 1.7 for the selected buoy, changing its shape from flat cylinder to conical cylinder causes the drag coefficient to decrease by 50 %, which is followed by 20% increase in average amplitude of heave motion from 0.524-0.625m. This increase in average amplitude heave is efficacious in increase power buoy around 45 watts.

Key words: Wave energy · Assaluyeh port (Persian Gulf) · Optimized buoy · Energy convertor

INTRODUCTION

Waves are generated by the effect of wind and gale on the sea surface. In a given region, the wave parameters such as height, wavelength, period etc are functions of wind speed and fetch. The environmental effects are very low and it has very small effect on ecosystem of the region. Therefore, total cost of such power plants, are very low compared to regular power plants. Several methods have been proposed for employing this energy in the last four decades. First attempt was made by Japanese in 1965 who built lighthouses that operated on wave energy. So far, several methods have been proposed for absorbing and converting the wave energy [1]. Various buoy systems such as Ocean Power Technologies (OPT), Oscillating Water Column (OWC), the Archimedes Wave Swing (AWS), point- absorber Wave Energy Converter (WEC) and Pelamis wave energy converter are considered as successful examples which work by changes in the wave amplitude and in regions where wave power is 40 kw/m. Figure 1 shows a sample of point-absorber wave energy converter [2-3].

Fig. 1: Sample of absorber wave energy converter

The conversion principle, based on the resonant buoy point absorber, received considerable interest in the seventies due to their simple technology, stability, durability, ease of transportation and setting up in the sea and greater efficiency. The importance of optimum design of the buoy has risen due to increasing use of the point energy convertors, as the efficiency of these convertors depends on the amount of energy absorbed by the buoys [4]. To extract maximum energy, the natural frequency of the point absorbers should match the frequency of the incident waves. The problem with this frequency adjustment is twofold; first, point absorbers have dimensions that are small compared

Corresponding Author: Hassan Ghassemi, Department of Ocean Engineering, Amirkabir University of Technology, Tehran, Iran. Fax: +98-21-66412495, E-mail: gasemi@aut.ac.ir

Fig. 2: Assaluyeh port at Southwest of Iran

to the incident wavelength. Therefore the capture bandwidth of these types of absorbers is narrow, requires control of the natural frequency of the WEC. Several other researchers have studied the optimum control of the WECs including the work of Vantorre *et al.* [5], Nolan *et al.* [6], Fleming *et al.* [7].

Iran has around 2700 km coastal line on the Persian Gulf, where average power of waves is 4 to 12 kW per unit length of the crest of the wave. Uniformity of speed and direction of the wind, low fetch and small topographical changes of the sea bed of the Persian Gulf, are reasons for short waves in this region. These conditions are the main reasons for production of waves with constant frequency.

In this research, feasibility of using properly designed buoy in the regions with uniform wave frequency is studied. Based on the wave characteristics of the Assaluyeh coastal area, a point absorber wave energy convertor is designed. The geometrical parameters are optimized using simulations in order to absorb maximum energy, reduce damping and slamming effects and increase the chance of heave resonance [8].

Assaluyeh Wave Evaluation: Assaluyeh port is located at the eastern part of Persian Gulf as it is shown in Figure 2. The sea parameter measurement buoy of the ports and maritime organization of Iran is located at a location 25 meters deep with a longitude of 52.5 °E and latitude of 25.5°N along with establishment of wave recorder buoys in the region. Ports and maritime organization of Iran started a project in 2002. This project was successfully performed by national oceanography center in collaboration with hydraulics research institute of Denmark (DHI). The wave data that used in this work is related to one year portion of the ISWM project [9].

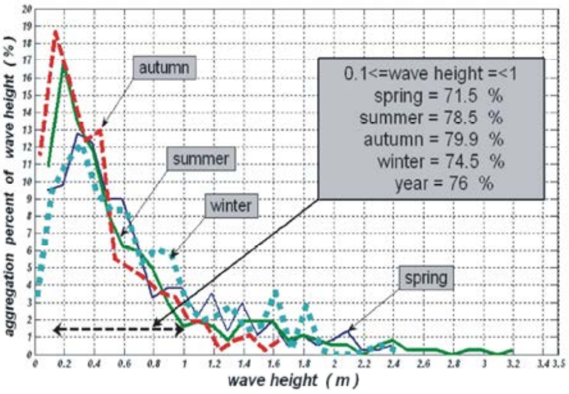

Fig. 3: Cumulative percentage of wave height at different seasons in Assaluyeh

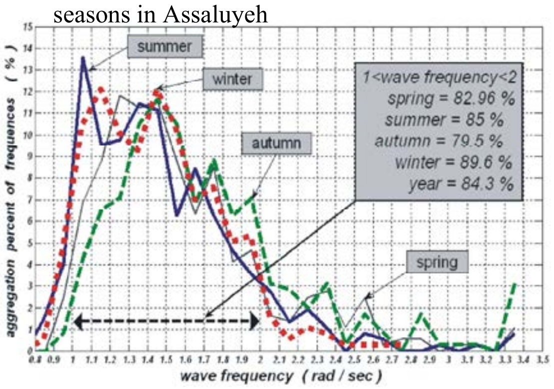

Fig. 4: Cumulative percentage of frequency in different seasons in Assaluyeh

Figures 3 and 4 show the comparison between the measured and modeled specific's height and frequency of the waves, respectively. Considering the wave data in different seasons, it could be concluded that majority of the waves have a height of less than 80 cm and only 16% of them are more than 1m in height. This is due to short fetch and geographical situation of the region. The frequency of the waves in the region was studied and it was found that it is ranged between 1 to 2r/sec in more than 84.3 % of the time of the year.

Design of the Resonant Wave Energy Absorber Buoy: In order to identify the design parameters of the buoy such as shape, dimensions, weight, natural frequency, additional mass, drag force, etc.; the governing equations were determined and applied forces on the buoy were calculated based on the wave's conditions. The factors that affect the above parameters were determined and using resonance phenomenon and reducing damping

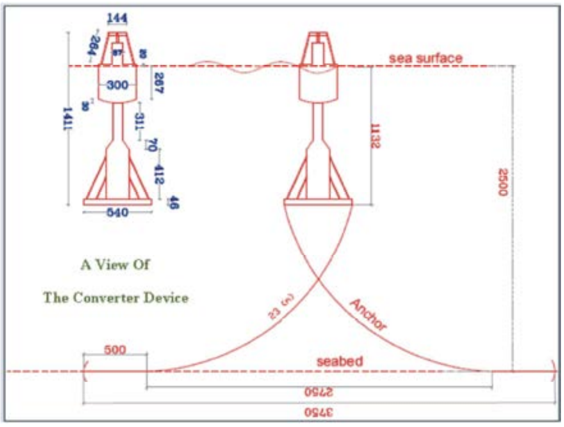

Fig. 5: Schematic of designed buoy wave energy convertor in detail full scale data.

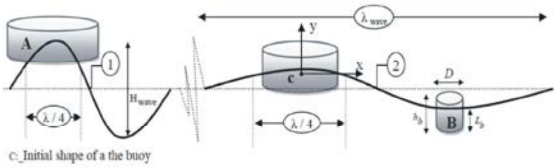

Fig. 6: Effect of the buoy diameter and absorption maximum energy.

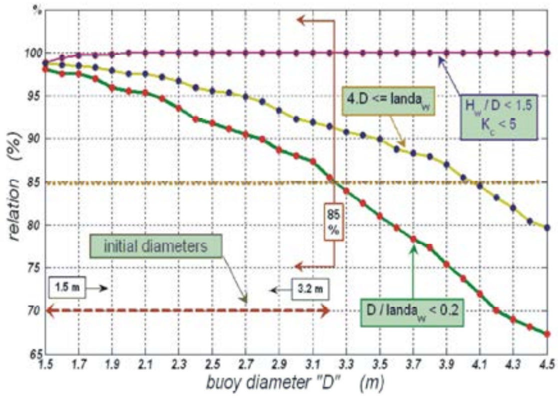

Fig. 7: Effect of the buoy diameter and wavelength.

effects, the optimum dimension of the buoy to absorb maximum wave energy were determined in MATLAB software environment. Figure 5 shows the practical designed point absorber wave energy convertor in detail full scale for the Assaluyeh coastal wave data and buoy absorbed wave energy.

To reduce the effects of the reflection and refraction and for the uniformity of waves reaching the buoy, a cylindrical buoy was selected. Since the force exerted on the buoy is the product of the effective area of the buoy and the pressure of the wave, the diameter was selected such that the wave pressure is uniformly applied on the surface of the buoy. Figure 6 shows the effect of the diameter of the buoy on uniformity of the pressure exerted on the bottom surface of the buoy and maximum energy absorption. A buoy with large diameter (buoy A) is not capable of absorbing maximum energy in case of short wave wavelengths (wave no. 1) and buoys with small diameter (buoy B) also, absorbed minimum energy in case of long wave wavelengths (wave no. 2).

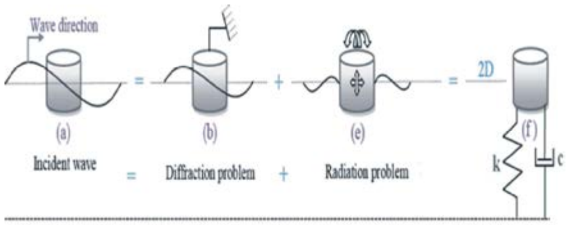

Fig. 8: Interaction of the buoy and wave.

For maximum energy absorption of the buoy in each wave crossing, it is required to assume some geometry and physical coefficients in order to eliminate dispersion effects (reducing the effects of reflection and radiation), which occurs when the wave crosses the cylindrical absorbent buoy.

The effect of applying these limits on the assumed initial diameter is shown in Figure 7. According to this figure, the initial diameter was selected to lie between 1.5-3.2 m. In this region, the limits are satisfied more than 85% of the time of the year.

Assuming that the linear wave theory is satisfied in the above conditions, the interaction of the cylindrical buoy with the fluid was divided into two problems using superposition principle. The system was modeled in two-dimension (Figure 8).

Since only maximum absorption of energy in heave direction is of interest and the buoy is allowed to move only in y-direction (heave), the governing equation and its coefficients are defined as:

$$(m+m_{33})\ddot{y}+B_{33}\dot{y}+C_{33}y=F_3(t) \tag{1}$$

Where added mass, m_{33}, dumping coefficient, B_{33} and restoring coefficient, C_{33} are given as follows:

$$\begin{cases} m_{33}=0.167\rho D^3, \\ B_{33}=\dfrac{8}{3\pi}\left(\frac{\Delta y}{0.5T}\right)\left(0.5\rho C_D L_b D\right), \\ C_{33}=\rho g A_c. \end{cases} \tag{2}$$

Where, all parameters are defined as follows:

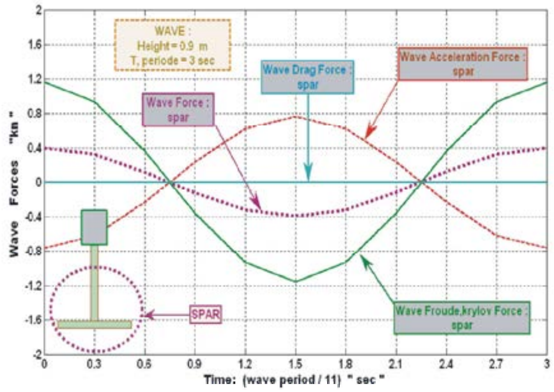

Fig. 9: Wave forces acted on the spar in y-direction.

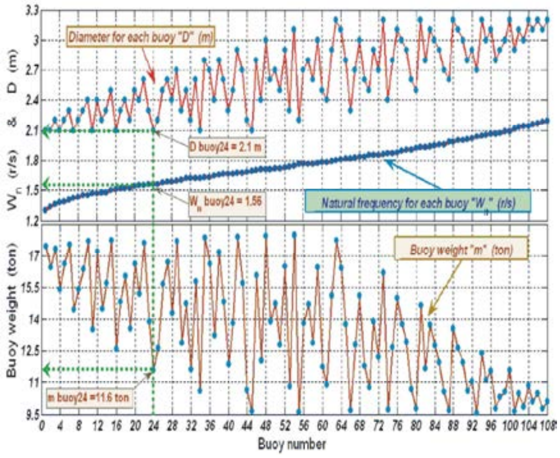

Fig. 10: Parameters of the 108 buoys with highest probability of resonance

$$\begin{cases} \Delta y = \dfrac{F_y / C_{33}}{\sqrt{[1 - \Omega^2]^2 + [2\eta\Omega]^2}}, \quad \Omega = \dfrac{\omega}{\omega_n}. \\ \omega_n = \sqrt{\dfrac{C_{33}}{m + m_{33}}}, \quad \omega_d \quad \omega_n\sqrt{(1 \pm \quad \eta^2)} \qquad - \\ \eta = \dfrac{0.5B_{33}}{(m+m_{33})\omega_n} \end{cases} \tag{3}$$

For the linearized regular wave, the dynamic pressure (P_c) and acceleration ($\dot{U}_y$) are expressed as

$$\begin{cases} P_c = 0.5\rho g H_W e^{ky} \cos(kx \quad \omega t) \qquad - \\ \dot{U}_y = \quad 0.5 H_W \omega^2 e^{ky} \cos(kx \quad \omega t) \end{cases} \tag{4}$$

Therefore, the vertical force exerted on the buoy from the wave can be obtained as follows:

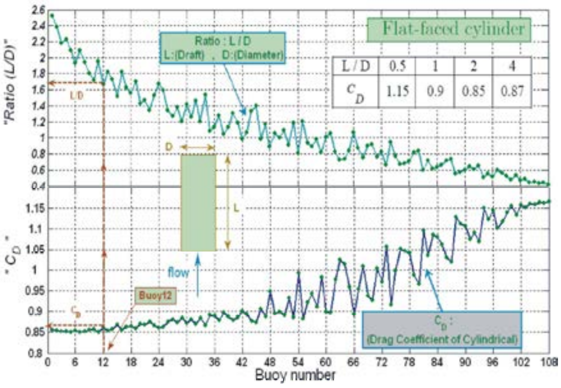

Fig. 11: Drag coefficient (C_D) of the all buoys

$$F_y = F_{fy} + F_{ay} = P_c A_c + m_{33}\dot{U}_y \tag{5}$$

For the surge motion, the same formulae as given in heave motion, the exerted horizontal force is calculated by:

$$F_x = m_{11} H_W \omega^2 \frac{1}{k}(1 - e^{-L_b tk})\sin(kx - \omega t) \tag{6}$$

$$where:\ m_{11} = 0.765\rho D^2 L_b$$

All parameters are defined in appendix.

Figure 9 shows the forces acting on the spar in y-direction.

In order to optimize the diameter-depth ratio, 108 buoys are selected. Every buoy has to be floated and stable in all conditions. Therefore, the weight of each buoy was selected to be equal to its buoyant force. For continual stability of the system, the weight of the upper portion of the buoy which is the place for energy absorbers assembly should be limited in order to avoid high reversal torques in surge and roll vibrations and to obviate the need for increasing the stiffness of the controlling torques. As a result, the diameter was limited between 2.1-3.2m. A limit of 9 to 18 tons for the weight and 1-2 r/sec for the natural frequency of the buoy were applied. Parameters of the 108 buoys with highest probability of resonance are shown in Figure 10. Also, drag coefficient (C_D) is presented in Figure 11 for 108 buoys. These were the optimized wave energy absorber buoys with respect to the probability of occurrence of the resonance. The most important thing is to determine the natural and dumping frequencies. Figure 12 shows those frequencies for all buoys.

Heave Motion and Genarated Power of Optimized Buoy: Analyzing the output of each buoy, it was found that

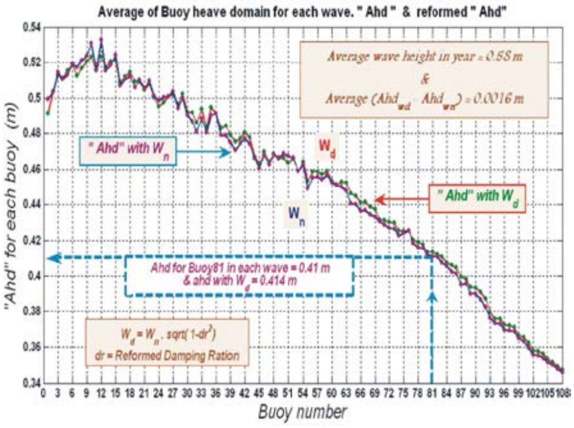

Fig. 12: Natural frequency of the buoy with and without damping.

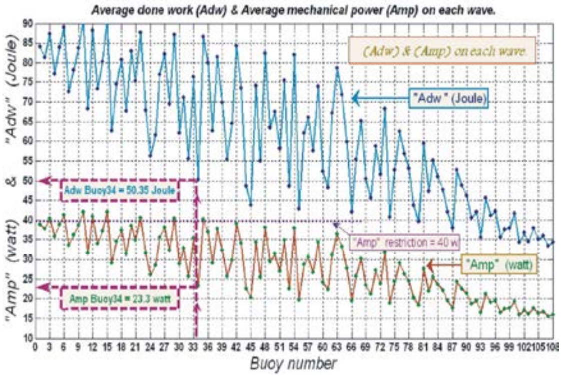

Fig. 13: Average heave displacement for each buoy

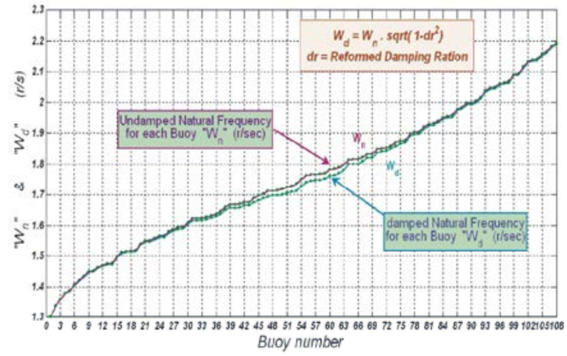

Fig. 14: Average work done and average mechanical power for each buoy in the year.

by adjusting the natural frequency of the buoy close to the frequency of the waves, the amplitude of the heave motion could highly increase. Figure 13 shows the average heave displacement (*Ahd*) for each buoy when a wave passes. After analyzing the performance of the buoy number 1 with ω_d = 1.3r/sec to buoy number 108 with ω_d = 2.2r/sec, it was found that since the wave frequency lies between 1.3-1.6 r/sec, the resonance occurs and the heave amplitude of the buoy increases by 51% from 0.35m (buoy no. 108) to 0.524 (buoy no. 12). It is determined that the difference between the *Ahd* with and without dumping frequencies is 0.0016 m.

Regarding Figure 13, the average work (*Adw*) and average mechanical power (*Amp*) can be determined by Eq. (7) as follows:

$$\begin{cases} Adw.(Joule) = Ahd(m) \quad w(kg.m \times s^2) \\ Amp.(watt) = Adw(Joule)/T(\sec)/2 \end{cases} \tag{7}$$

Where *Ahd* (is average heave displacement) and *w* (is the weight).

The results of work and power for each buoy are shown in Figure 14. As observed in this figure, the *Amp* is around 15-40 watt for buoys numbered from 1 to 108. The average obtained power is around 30 watt.

Selection of the optimized buoy amongst the 108 buoys could be based on basic parameters of an energy absorber buoy such as maximum heave displacement, average mechanical power effects in each wave crossing during a year.

Various buoy shapes and different diameter sizes are investigated. By changing the shape of the flat buoy to conical cylinder shape, the drag coefficient that has direct effect on the damping of the buoy could be reduced. Regarding the length to diameter ratio of 1.7 for the selected buoy, changing its shape from flat cylinder to conical cylinder causes the drag coefficient to decrease by 50%, which is followed by 20% increase in the average amplitude of heave motion from 0.524m to 0.625m. The results showed that the frequencies of the buoy had affected by changing the buoy shapes and sizes. This increase in average amplitude heave is efficacious in increasing power buoy (to around 45 watts). Also, using resonance and decreasing damping effects causes a 7% increase in the amplitude of vibration of the buoy with respect to the average wave height in the region (0.582 meter).

CONCLUSIONS

Based on the Present Research Findings, Following Results Can Be Drawn:

- The waves in the Assaluyeh coastal region have a height of less than 80 cm in over 76.6% of the time and a frequency of 1-2r/sec in over 84.3% of the time during a year. Using those wave data and analyzing the results, a point absorber buoy was designed.

- The buoy parameters were optimized using simulations in order to absorb maximum energy, to reduce damping and slamming effects and to increase the chance of heave resonance.
- Using resonance, the average heave amplitude of the buoy increases by 51% and the average achievable power rises to more than twice.
- The frequencies of the buoy are affected by changing the buoy shapes and sizes. This caused an increase in average amplitude heave and as results it increased the amount of power to around 45 watts.
- Finally, using resonance and decreasing damping effects causes a 7% increase in the amplitude of vibration of the buoy with respect to the average wave height in the region (0.582 meter)

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APPENDIX

g = Acceleration of gravity
m = Buoy mass
m_{11} = Surge added mass
m_{33} = Heave added mass
$\ddot{y}$ = Heave acceleration
$\dot{y}$ = Heave velocity
$F_3(t)$ = Excitation heave force
ρ = Density of water
D = Diameter buoy
A_c = Area with water level
P_c = Wave pressure
H_w = Wave height
k = wave number
ω = Wave frequency
ω_n = Buoy natural frequency
ω_d = Dumping natural frequency of buoy
U_m = Average of current velocity
$\dot{U}_y$ = Heave wave acceleration
F_{fx} = Surge Froude-Krylov force
F_{ax} = Surge acceleration force
F_{fy} = Heave Froude-Krylov force
F_{ax} = Heave acceleration force
F_x = Horizontal inertia force
F_y = Vertical inertia force
C_{33} = Heave restoring coefficient
B_{33} = Damping coefficient
Δy = Heave displacement
C_D = Drag coefficient of buoy
L_b = Draft of buoy
η = Damping ratio
Ω = Ratio wave frequency to buoy natural frequency
Adw = Average work done
Ahd = Average displacement
Amp = Average mechanical power
w = Buoy weight