

# Experimental Study of Wave Spectrum Type Impact on Inner Chamber Fluctuation, Pressure and Reflection of OWC Device

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## ABSTRACT

Increasing problems due to supplying energy demand conveyed researchers to find a solution in renewable energy resources and consequently marine engineers drew attentions towards wave energy which has the merit of higher energy density than the other resources. Oscillating Water Column (OWC) is one of the most propitious devices for capturing wave energy. Researchers have studied the device under different wave height and period conditions and they investigated various geometric parameters such as front wall draft and the chamber length. However, the effects of wave spectrum type or shape has not been investigated deeply yet. Different wave spectra have been developed for different places around the world but the focus of this study is on the two well-known spectra called JONSWAP and Pierson-Moskowitz to see how the type of the spectrum can impact on inner chamber fluctuation, pressure variation and reflection response of an offshore OWC. To achieve this goal, a 1:15 scale model of an offshore OWC was constructed in National Iranian Marine Laboratory. The results show that inner chamber free surface spectrum is affected by the type of incident wave spectrum. In another word, energy content at peak frequency was approximately 50% higher when the incident wave spectrum is of JONSWAP type. However, energy corresponding to sloshing frequency and total energy content in the chamber were almost the same for both types of the spectra. Pressure spectra inside the chamber showed a similar trend as free surface elevation. Although there was a little difference in reflection response of an OWC influenced by the type of spectra, this discrepancy was more pronounced in high frequency waves.

## 1. Introduction

Undoubtedly, environmental impacts of using fossil energy resources such as global warming and its consequent outcomes are a menace for the earth future. This was a motivation for researchers to put much more effort in harnessing renewable energy resources in recent years. Among new sustainable approaches of generating energy, one that particularly stands out is marine renewable energy. Marine renewable energy can be classified as offshore wind, thermal, tidal and wave power. Wave farm higher energy density (2-3)  $\text{kw/m}^2$  rather than solar (0.1-0.2)  $\text{kw/m}^2$  and wind farms (0.4-0.6)  $\text{kw/m}^2$  is its advantage over other marine renewable energy resources [1]. Of all different technologies developed for wave energy conversion, Oscillating Water Columns (OWC) seems to be the most propitious device even reached to full scale prototype [2]. OWCs are recognized by their common

rectangular compartment which are partially submerged. The structure is open to sea at the bottom allowing the incoming waves to be transferred in to the structure. Subsequently, wave induced fluctuation inside the chamber or compartment causes the trapped air to drive the turbine which is built in at the top of the chamber. Then using a generator, turbine movement can be converted to electricity.

Research on offshore located OWCs are much more limited rather than those which are positioned at shore or nearshore. Although offshore OWCs may suffer from higher funding for development, they are exposed to higher amount of energy rather than onshore ones. They can be integrated with floating breakwaters to reduce the construction cost and can be a good choice for the small islands or offshore construction sites to help them supply their needed energy [3]. An offshore OWC was developed by Masuda for the first time [4].

Lots of studies can be found in the context of OWCs including numerical and experimental approaches. Evans [5] was a pioneer researcher who introduced rigid piston model for free surface fluctuation inside the chamber. His model was developed by [6-9]. They tried to consider free surface crookedness through applying a periodic pressure distributed over the surface. Later, researchers who were involved with numerical procedure used boundary element methods [10-11] or utilized CFD capabilities to solve fully nonlinear interaction in the chamber based on Navier-Stokes equation [12-16]. The latter approach has the merit of taking nonlinear interactions into account; such as wave breaking and sloshing.

Apart from the aforementioned numerical investigations, valuable experimental studies can be found in the literature. Some of them focused on shore-based OWCs such as those studies conducted by Morris-Thomas et al. [17] and Vyzikas et al. [18] who worked on shape of the front wall and OWC geometry, respectively. Viviano et al. [19] built a 1:5-1:9 scale model and evaluated wave loading and wave reflection for irregular wave impingement. Ning et al. [20] did an experimental research on shore based OWCs and studied free surface oscillation in the chamber.

Contrary to shore-based experimental studies, research on detached floating or fixed OWCs are relatively limited. Sheng et al. [21] carried out experiments on floating cylindrical shaped OWCs and found that the ratio of orifice area to water column area plays an important role and a value of 1.7% to 2.28% leads to optimum efficiency for the device. Crema et al. [22], also did an experimental research on an OWC joining a floating structure, namely a breakwater. They evaluated geometric parameters and wave condition to determine OWC performance. Very recently, Elhanafi et al. [23-25] carried out experimental tests and used their data to validate their numerical model for further analyze on OWC performance. The 1:50 scale model of offshore stationary model was constructed and its performance was evaluated against regular wave attack.

Despite all researchers' efforts, the industry needs much more confidence to invest on these devices and this issue necessitates more investigation on the OWC performance to bridge the gap between commercializing and research. Moreover, reviewing the literature shows that firstly, experimental tests on offshore OWCs are much less despite the fact that offshore OWCs are exposed to higher wave energy. Secondly, to the best knowledge of the authors there is no similar study addressing wave spectrum type impacts on OWC performance. Different spectrum types are developed for different marine environments; however, the two most familiar ones, that is to say JONSWAP and Pierson-Moskowitz (hereafter called P-M) are evaluated here. It is worth mentioning that evaluation of the device efficiency influenced by

spectrum type is presented by the authors in a separated paper [26]. Hence, the aim of this paper is only to investigate the free surface fluctuation and pressure variation inside the chamber affected by spectrum type. In addition, in this paper, reflection from OWC device is studied under the impact of wave spectrum type.

Regardless of OWC device geometry, wave-OWC nonlinear interactions such as sloshing and wave reflection have impacts on both OWC hydrodynamic performance and structural design. Concerning hydrodynamic interactions, which is the focus of this paper, it should be mentioned that the less sloshing occurs, the more energy can be extracted. This is due to low pressure variation at sloshing frequencies. Moreover, reflection is highly affected by the OWC device geometry and the ratio of water depth to wave length. The latter parameter is examined in this study. The rest of the paper can be summarized as follows; section 2 is dedicated to a brief explanation of experiments where the reader can find the test conditions. Section 3 presents the results of chamber free surface fluctuation, pressure variation and reflection affected by spectrum type. Section 4 which is the last section of this paper presents concluding remarks.

## 2. Experimental Tests

Experiments were done at National Iranian Marine Laboratory (NIMALA), Tehran, Iran. Actually, the Laboratory is a large towing tank with 400 m length, 6 m width and 4 m depth. It is possible to set the wave maker to generate regular or irregular waves. Wave height in irregular wave generation is limited to 40 cm and wave peak period is limited to 3s. However, instruction given by the laboratory technicians restricted the wave height and wave period to 30 cm and 2.5 s, respectively. Such a restriction was due to the fact that wave may flow out of tank end wall for extremely long waves. It should be mentioned that a sloped beach is constructed at far end of the tank to prevent coming back of transmitted waves. To control the wave induced movements of the OWC model and to make it fix in its location, a huge steel frame was built. Cables were also used to ensure no movement occurs. The steel frame is shown in Figure 1.

A 1:15 scale model of an OWC which was built using plexiglass is shown in Figure 2. Dimensions of the physical model are specified in Figure 2. Slot shape opening in the OWC roof was to take damping effect in to account. As applied by [3] and [18], there are several ways to consider Power Take Off effect including slot shape opening and orifice one. Slot shape approach was used in this paper. In these test series evaluating spectrum type impact, slot size was kept constant during the test at 1 cm which is equivalent to aperture ratio of 1.28%. It is worth mentioning that aperture ratio is defined as the ratio of slot size to the net chamber length (0.78m). Instrumentation along the

tank and inside the chamber is shown in Figure 3 and Figure 4 . As can be seen three Wave Gauges (WG) were used outside the OWC to separate incident and reflected waves. Two also were used inside the chamber for tracking free surface fluctuation. Pressure Sensors (PS) were also utilized to measure the pressure variation inside the chamber. Measurement frequency was 50 hz for all instruments. A data acquisition system was used to convert the voltage outputs of the WGs and PS to readable surface elevation and pressure data according to centimeter and pascal units, respectively (Figure 5).



Figure 2. Dimension of the physical model (meter)

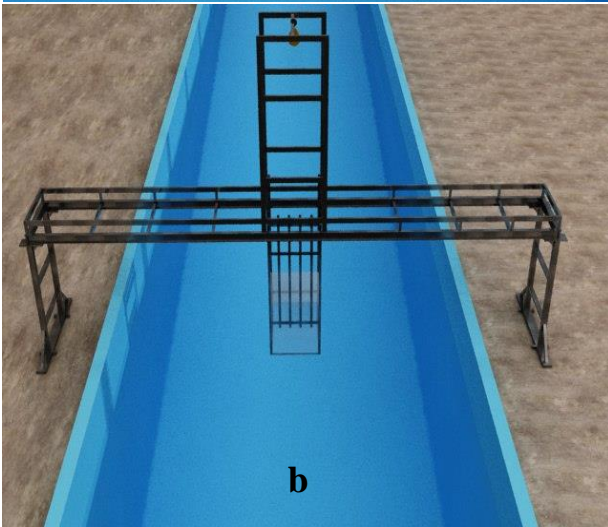
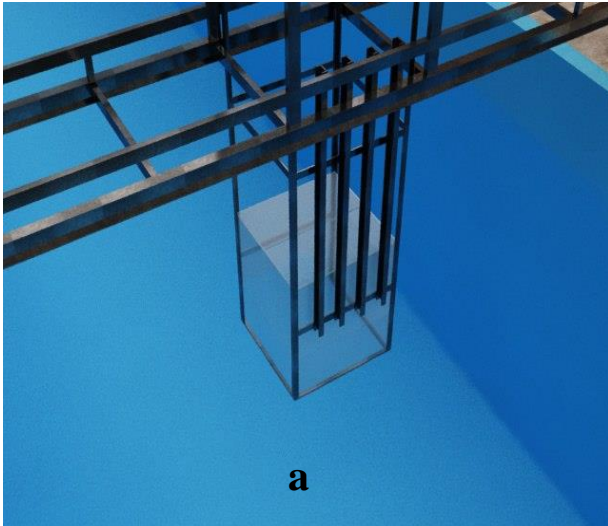


Figure 1. 3D view of holding frame for keeping OWC in its position, (a): back view of OWC (using U section beams at the back of the OWC structure, (b); Front view

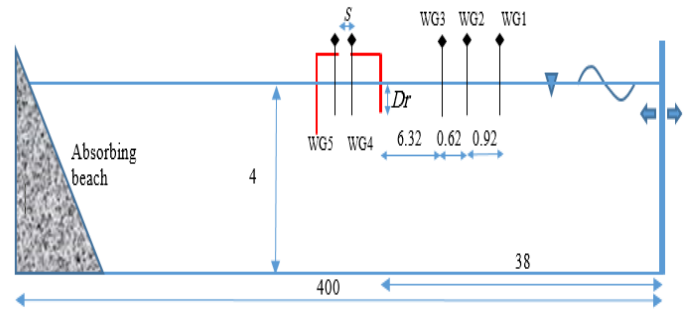


Figure 3. Location of the wave gauges and pressure sensors, in meter (Not to scale) [26]

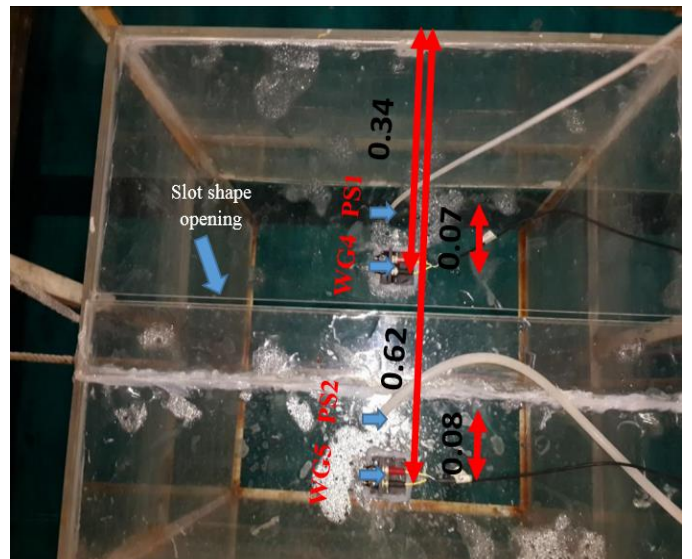


Figure 4. Top view of the OWC chamber, PS and WGs location, in meter



Figure 5. Data acquisition system

JONSWAP and P-M spectra were used in this paper. The following equations account for JONSWAP and P-M spectra.

$$S(f) = \frac{\alpha g^2}{f^5} \exp\left[-\frac{5}{4} \left(\frac{f_p}{f}\right)^4\right] \gamma^r \quad (1)$$

where

$$r = \exp\left[-\frac{(f - f_p)^2}{2\sigma^2 f_p^2}\right] \quad (2)$$

$$\alpha \approx \frac{0.0624}{0.230 + 0.0336\gamma - (0.185 / (1.9 + \gamma))} \quad (3)$$

and  $\sigma \approx 0.07$  if  $f \leq f_p$ , and  $\sigma \approx 0.09$  if  $f > f_p$ .

$\gamma$  is known as shape factor which is considered to be 3.3 and 1 for JONSWAP and P-M spectra, respectively. The wave condition applied in this paper are mentioned in Table 1. Three test series including six tests were performed here. To isolate wave spectrum type effect, wave height and period was kept constant during each series. Moreover, wave steepness defined as  $H_{m0}/L_p$  was kept constant during the test at 0.026. It is notable that water depth was 4m in all tests.

Table 1. Tests Condition

Test no.	Incident Wave Characteristics			OWC Geometry	
	Spectrum Type	Wave Height ( $H_{m0}$ ) [cm]	$kd$	Slot size [cm]	Front wall Draft [cm]
1	JONSWAP	10	6.45	1	20
2	P-M	10	6.45	1	20
3	JONSWAP	15	4.28	1	20
4	P-M	15	4.28	1	20
5	JONSWAP	25	2.60	1	20
6	P-M	25	2.60	1	20

### 3. Results and Discussion

#### 3.1. Spectrum Type Impact on Free Surface Fluctuation inside the Chamber

Previously, it was found by the authors that for shorter period waves ( $kd=6.45$  and  $4.28$ ), efficiency of the device is higher when the incident wave spectrum is of

JONSWAP type while for longer wavelengths ( $kd=2.6$ ) P-M spectrum causes more energy capture. This was attributed to the wider distribution of the inner chamber spectrum caused by incident P-M spectrum at  $kd=2.6$  [26]. The aforementioned results are not repeated in this paper for abridgement. As an extension to the previous paper [26], this paper studies the effect of spectrum type on inner chamber free surface fluctuation with the focus on sloshing in the chamber. According to [27], sloshing may occur in closed chambers. When sloshing happens, the pressure variation in the chamber would be nearly zero and thus no energy could be extracted by the device. Hence, it is of great importance to be evaluated in designing procedure. Given  $B$  as chamber length, sloshing can be observed at different modes according to  $kB = n\pi$ . Replacing  $B$  by 0.78 (net length of the OWC chamber) it is likely to see first mode at 1 hz and second mode at 1.4 hz in this study.

Figure 6 to Figure 8 show spectrum density calculated for WG5 influenced by wave spectrum type. As it is clear, in all Figures, the inner chamber spectra are influenced by the incident wave type. In fact, when the incident wave type is of JONSWAP type, greater values of energy content was observed at incident wave peak frequency. For example, in Figure 6, peak energy content in the chamber corresponding to JONSWAP type spectrum is approximately 50% more than the energy content calculated for P-M spectrum. For the rest of the domain frequencies, P-M spectrum may yields higher energy content; especially at  $kd=2.6$  for  $0.5 < f < 0.7$ .

However, spectral analysis shows that total energy content in the system due to water fluctuation is the same for the two spectra which have been applied. Table 2 shows the result of spectrum analysis for both spectra. As can be seen, there is negligible difference between wave heights values calculated in the chamber showing that the amount of energy content inside the chamber caused by water fluctuation is almost equal for both spectra.

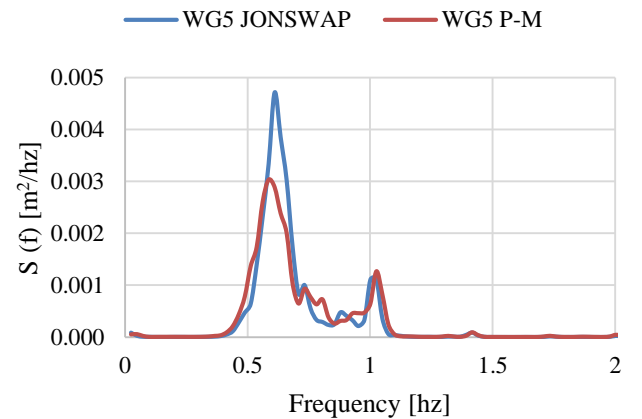
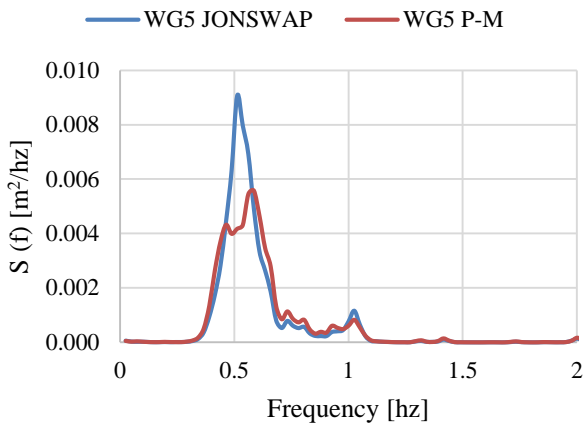
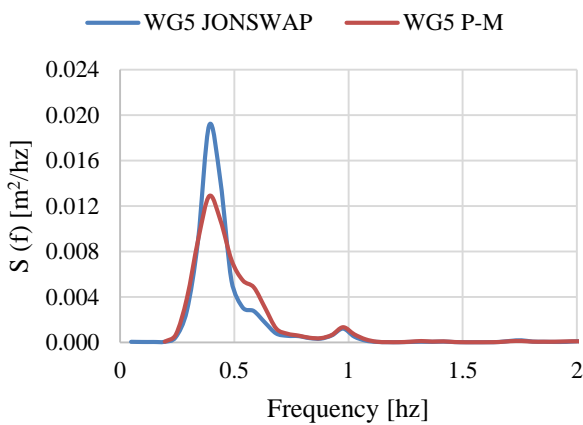


Figure 6. Spectrum of WG5 under the impact of JONSWAP and P-M spectra as incident waves,  $H_{m0}=10$  cm  $kd=6.45$



**Figure 7. Spectrum of WG5 under the impact of JONSWAP and P-M spectra as incident waves,  $H_{m0}=15$  cm  $kd=4.28$**



**Figure 8. Spectrum of WG5 under the impact of JONSWAP and P-M spectra as incident waves,  $H_{m0}=25$  cm  $kd=2.60$**

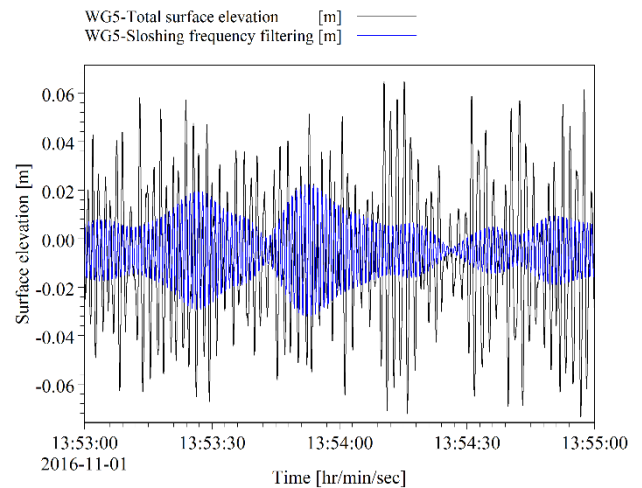
**Table 2. Spectral analysis for the conducted tests, results of WG5**

Incident Wave Characteristics				Inner Chamber Spectral Analysis
Test no.	Spectrum Type	Incident Wave Height ( $H_{m0}$ ) [cm]	$kd$	Inner Wave Height ( $H_{m0}$ ) [cm]
1	JONSWAP	10	6.45	10.89
2	P-M	10	6.45	10.57
3	JONSWAP	15	4.28	15.79
4	P-M	15	4.28	15.29
5	JONSWAP	25	2.6	22.51
6	P-M	25	2.6	22.59

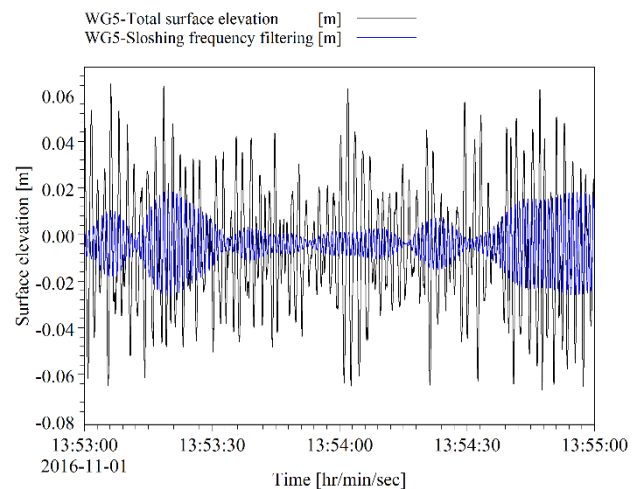
Another important point is energy content related to higher frequencies. Although the energy content for higher frequencies are much less than energy content corresponding to peak frequency, it is of great importance as it is associated with sloshing energy content. It should be mentioned that sloshing has destructive effects both on structural strength and device energy conversion efficiency.

It is clearly visible that sloshing energy content occurs at all the cases which have been tested but it is more pronounced at incident waves with higher peak frequency because the ratio of sloshing energy to total energy inside the chamber is higher for short period waves. On the other hand, there is no significant difference in sloshing energy for the two spectra, as regardless of the spectrum type, the tests showed almost equal sloshing energy. This trend was seen in all the tests.

For a better understanding of sloshing contribution on free surface fluctuation inside the chamber, sloshing frequency is filtered and plotted during the test. The results of total free surface fluctuation inside the chamber are presented beside the sloshing-only surface elevation for a better comparison. Figure 9 shows the case when the incident wave is of JONSWAP type and Figure 10 is related to the case of P-M spectrum as incident wave. As it is clear, the maximum amount of sloshing fluctuation is the same for both spectra and it is around 4 cm.



**Figure 9. Comparing surface fluctuation due to sloshing and total free surface fluctuation measured at WG5 for incident wave of JONSWAP type; Test no.1**

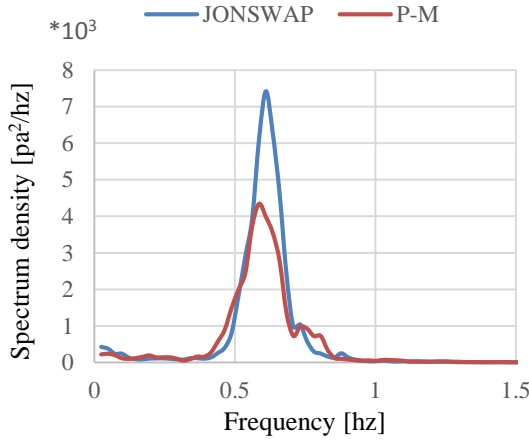


**Figure 10. Comparing surface fluctuation due to sloshing and total free surface fluctuation measured at WG5 for incident wave of P-M type; Test no.2**

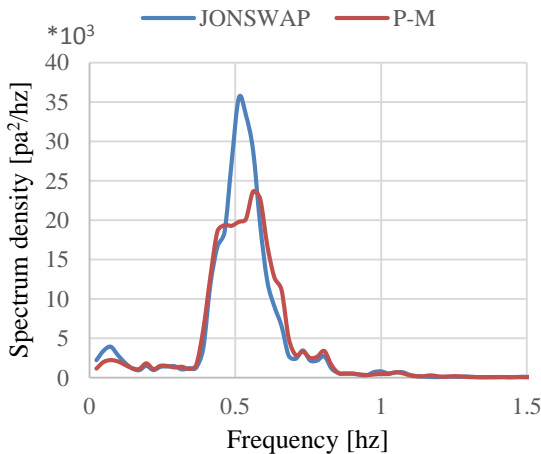
### 3.2. Spectrum Type Impact on Chamber Pressure Variation

Apart from the fact that longer incident periods caused higher pressure values, the focus of this part was on chamber pressure variation due to spectrum type for the same wave condition. The results show that air pressure inside the OWC is completely affected by the incident spectrum type. Figure 11 to 13 shows pressure spectra inside the chamber. The shape of the obtained spectra are influenced by the shape of the incident wave spectrum. In other words, JONSWAP spectrum caused higher pressure in peak frequency but this was not the case for  $f > fp$ . In fact for frequencies other than peak frequency, the pressure spectra were overlapped.

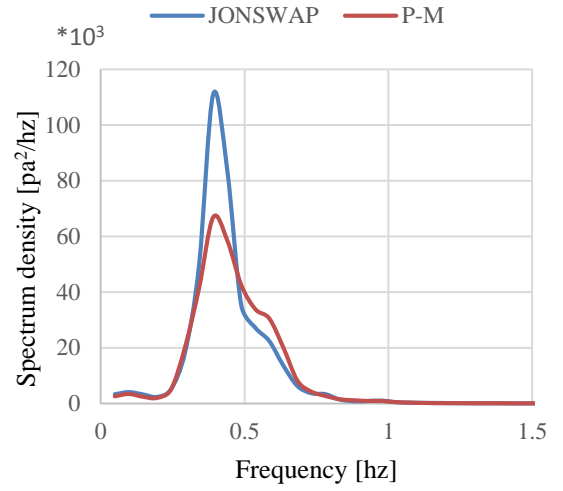
It is worth mentioning that according Figure 11 to 13 pressure values corresponding to  $f=1$  hz (sloshing frequency) is almost zero.



**Figure 11.** Pressure spectrum inside the chamber, under the impact of JONSWAP and P-M spectra as incident waves,  $H_{m0}=10$  cm  $kd=6.45$



**Figure 12.** Pressure spectrum inside the chamber, under the impact of JONSWAP and P-M spectra as incident waves,  $H_{m0}=15$  cm  $kd=4.28$



**Figure 13.** Pressure spectrum inside the chamber, under the impact of JONSWAP and P-M spectra as incident waves,  $H_{m0}=25$  cm  $kd=2.60$

### 3.3. Spectrum Impact on Reflection by OWC

Detailed information on separating incident and reflected waves can be found in Ref [28]; however, a brief explanation of this procedure is provided in the following paragraph. Wave surface elevation can be decomposed to linear incident and reflected wave components. In its complex form it is given as;

$$\eta = \sum_{n=-N}^N [a_{In} e^{i(\omega_n t - k_n x)} + a_{Rn} e^{i(\omega_n t + k_n x)}] \quad (4)$$

, for  $n \neq 0$

where  $a_{In}$  and  $a_{Rn}$  are complex parameters representing incident and reflected components, respectively. Their absolute values show the amplitude.  $t$  is time,  $x$  is wave propagation direction, subscript  $n$  shows  $n$ th harmonic component,  $\omega_n$  is angular frequency defined as

$$\omega_n = \frac{2\pi n}{t_{end}}$$

where  $t_{end}$  represents the total test duration;  $k_n$  is wave number. Applying Fourier transformation on each probe (assume it as  $m$ ) data, it can be written as a function of a complex parameter  $F_{n,m}$ .

$$\eta_m = \sum_{n=-N}^N F_{n,m} e^{i \omega_n t} \quad (5)$$

From Eq. (4), the following relation is acquired;

$$F_{n,m} = a_{In} e^{-ik_n x_m} + a_{Rn} e^{ik_n x_m} \quad (6)$$

where  $x_m$  shows the location of the probe  $m$ . This procedure can be repeated for each of the probes. If 3 probes were used, the method of Mansard and Funke

[29] based on least square method could be used to solve the unknowns.

As mentioned before absolute values of  $a_{In}$  and  $a_{Rn}$  are equal to incident and reflected wave amplitude for the  $n$ th harmonic, respectively. Hence, reflection function  $Cr(f)$  for each wave frequency component can be calculated as;

$$C_r(f) = \frac{|a_{Rn}|}{|a_{In}|} \tag{7}$$

and total wave reflection coefficient is given by Eq. (8);

$$C_r = \sqrt{\frac{\sum_{n=n_1}^{n_2} |a_{Rn}|^2}{\sum_{n=n_1}^{n_2} |a_{In}|^2}} \tag{8}$$

where  $n_1$  and  $n_2$  are lower and upper bounds of the spectral range within that reflection value is calculated. Figure 14 shows reflection coefficients for each test. As it is obvious, reflection increases with the increase of  $kd$  for both types of spectra. This can be attributed to the larger ratios of wave length to chamber length for low frequency waves which causes the wave to be transmitted more rather than to be reflected. Therefore, low frequency waves yield lower reflection coefficients than high frequency waves in offshore OWCs.

There is negligible difference in reflection due to wave spectrum type. For example, at  $kd=2.6$  reflection by OWC in the case of JONSWAP spectrum is around 0.18 while for P-M spectrum it is approximately 0.19. Generally, reflection coefficient is lower when the incident wave is of JONSWAP spectrum. This issue is more pronounced at high frequency waves; i.e.  $kd=6.45$ .

For a better understanding of reflection response of an OWC influenced by the type of incident wave spectrum, the spectral reflection coefficient for  $kd=6.45$  (caused biggest difference in reflection response) is plotted versus the ratio of chamber length to wave length for each frequency component (See Figure 15). As can be seen, some differences between the two spectra occurred at  $B/L=0.05$  to  $0.07$ ,  $0.36$  to  $0.5$  and  $0.8$  to  $0.96$  but the general trend is similar. This figure shows that regardless of the spectrum type all reflection coefficients for  $B/L=0.1$  to  $0.36$  are almost zero. Outside this range for greater  $B/L$ , spectral reflection values were greater than 1. This behavior can be attributed to energy transfer between wave frequencies. Wave energy conversion in an OWC system highly depends on water and air motion. Since irregular waves are intrinsically variable in time domain, their interaction with OWC influence on air intake and outflow. When incident wave is not in phase with air flow inside the chamber, its pressure instantly adjusts while air frequency may need to a longer time for being adjusted. Consequently, those wave frequencies which are in phase with air flow (they are close to peak frequencies) would be transformed to pneumatic energy and those which are not in phase with air motion

can't enter into the chamber. The latter wave frequencies are those frequencies which their reflection amplitude is greater than their incident amplitude; yielding spectral reflection values  $Cr(f) > 1$  [19].

It is worth mentioning that  $Cr$  values calculated by Eq. (8) always lead to a value lower than 1, because it considers the ratio between the incident and reflected energy based on conservation of energy [28]. On the other hand as spectral components characterized by  $Cr(f) > 1$  are small they have little impact on  $Cr$  calculated by Eq. (8) [28].

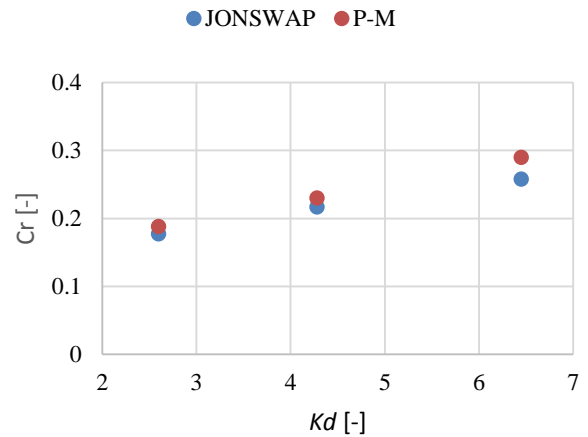


Figure 14. Reflection coefficient  $Cr$  versus  $kd$  for JONSWAP and P-M spectra

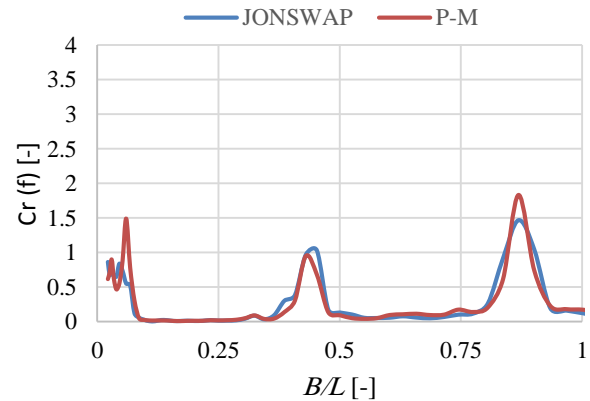


Figure 15. Spectral reflection versus  $B/L$  for each frequency component,  $kd=6.45$

#### 4. Summary and Conclusions

OWC is one of the wave energy devices which is widely studied by the researchers in the last years. However, experimental studies focusing on offshore OWCs are relatively limited. On the other hand, the previous researchers put their concentration on evaluating wave condition and chamber geometry effects in OWC efficiency. This paper addressed the wave spectrum type impacts on free surface fluctuation inside the chamber, pressure variation and reflection by OWC using a 1:15 physical scale model. The concluding remarks can be summarized as follows;

- Inner chamber free surface spectrum is affected by the type of incident wave spectrum. In another word, energy content at peak frequency was approximately 50% higher when the incident wave spectrum is of JONSWAP type. However, energy content corresponding to sloshing frequency and total energy content in the chamber were almost the same for both types of the spectra.
- JONSWAP spectrum caused higher pressure in peak frequency but this was not the case for  $f > f_p$ . In fact for frequencies other than peak frequency, the pressure spectra of different types (JONSWAP and P-M) were overlapped.
- Reflection coefficient increased by increase of  $kd$  for both types of spectra.
- There was a little difference in reflection response of an OWC influenced by the type of spectra; however, this discrepancy was more pronounced in high frequency waves.
- For  $kd=6.45$  both types of spectra applied as incident waves, showed somehow similar trend in spectral reflection.
- Regardless of the spectrum type all spectral reflection coefficients for  $B/L=0.1$  to  $0.36$  are almost zero.

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