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Wave forces on an Oscillating Water Column Device

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Abstract

The Oscillating Water Column (OWC) is one of the wave energy device working on the principle of rise and fall of free surface water oscillation due to continuous impingement of waves that penetrates into a semi submerged chamber. It is one of the successful device that has been proved up to pilot stage in the field. There have been many studies on optimizing various parameters of the OWC device through laboratory modeling. In order to quantify the horizontal and vertical wave forces on a 1:12 OWC model, a series of experiments has been conducted in a wave flume, 72.5 m long, 2 m wide and 2.5 m deep. The chamber with dimensions of 1910 mm wide (w) (parallel to the wave crest) and 300 mm length (b) (along the wave direction) was made of 20 mm thick acrylic sheet. The total height of the chamber is 900 mm and the water depth (d) in front of the chamber is 500 mm. The bottom opening (o) in the front lip wall is 300 mm. An air vent of 0.68 % of the plan area of the device was maintained. Custom made strain gauge based force transducer has been mounted to measure two force components namely vertical and horizontal. The test set-up was located at a distance of 45 m from the wave maker. The strain gauges in the load cell were placed in such a manner to nullify the effect due to moment in the measurement. The experiments were conducted for regular waves with the wave characteristics defined by Froude model scale law. The wave frequencies range between 0.42 Hz and 1.25 Hz with the wave steepness, H/L in the range of 0.0107 to 0.0524 and relative water depth, d/L in the range of 0.09 to 0.30 have been considered in the present study. It is observed that at natural frequency of system, the force on the structure is less due to high-energy absorption by the OWC.

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Keywords: Oscillating Water Column; Wave energy; Wave force; Force transducers;

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1. Introduction

Among the renewable energy resources, Ocean energy is the one, in abundance around the globe. The Ocean wave energy in the form of surface gravity waves, are formed due to the imbalance between gravitational force and shear due to wind. As the waves travel from deep to shallower water region, certain amount of energy (potential energy + kinetic energy) dissipates, particularly in the breaking zone. The level of dissipation as well as an increase in its amount depends on several parameters, of which, the most important being the seabed friction, bathymetry, and presence of obstructions. Nevertheless, the wave power available in the near shore is quite enough to produce electricity and it is directly proportional to the square of the amplitude of the wave and its wavelength.

Takahashi et al., (1988) defined the development of wave energy extracting caisson breakwater in Japan. The wave energy extracting device is combined in the form of air chamber attached with an ordinary caisson. The dynamic pressure excited on the sloped front wall well compared with the theory of Goda (1985). The sliding tests on the caisson breakwater proved that sloped front wall have a higher stability than the other caisson types tested. It was inferred by Malmo and Reitan (1985) that the natural frequency of an OWC system primarily depends on its front lip depth. McIver and Evans (1988) observed that the reaction of OWC system depends on the extent of the dynamic pressure and its excitation period, whereas, Zheng et al., (1989) proved that flared harbour walls in an OWC enhanced its efficiency compared to the one with rectangular walls. Muller and Whittaker (1993) tested a 1:36 physical model of the Isle of Islay to obtain the wave-induced pressures on the lip wall. It was observed that the suggestions given by the Coastal Engineering Research Center (CERC 1984) for the estimation of design pressures were conservative. Jayakumar (1994) conducted experimental study on OWC caisson model and found that the wave forces on OWC caisson model were less than the conventional rectangular caisson when air damping inside the OWC model maintained is less.

Evans and Porter (1995) considered the air chamber length (b), water depth (d) and the submergence of lip wall (s) to be the main parameters dictating the efficiency of an OWC. It was interfered that for lower values of the ratio, b/d, the behavior of fluid is like a rigid body inside the OWC chamber. It was also reported that for higher values of s/d, the frequency band of efficiency was becoming narrow. In this study, the thickness of lip wall was not considered. Through a detailed experimental study on OWC, Thiruvenkatasamy and Neelamani (1997) found that an increase in wave steepness causes a decrease in its performance in terms of its efficiency and for a/A (ratio of air hole area (a) to plan area (A)) larger than 0.81 %, a considerable reduction in energy absorption capability of the device was reported. Tseng et al., (2000) reported that the experimental investigation on multi-resonant oscillating water column yields only 28.5 % of efficiency because of high-energy loss. Wang et al. (2002) studied analytically and experimentally the change in bottom slope in front of the shoreline mounted OWC model and observed that an increase in the slope of the bottom leads to a shift in the capture-width ratio at lower frequencies. The thickness of the front wall did not have any influence on energy conversion capacity of the device as is claimed by Thomas et al. (2007) through an experimental study.

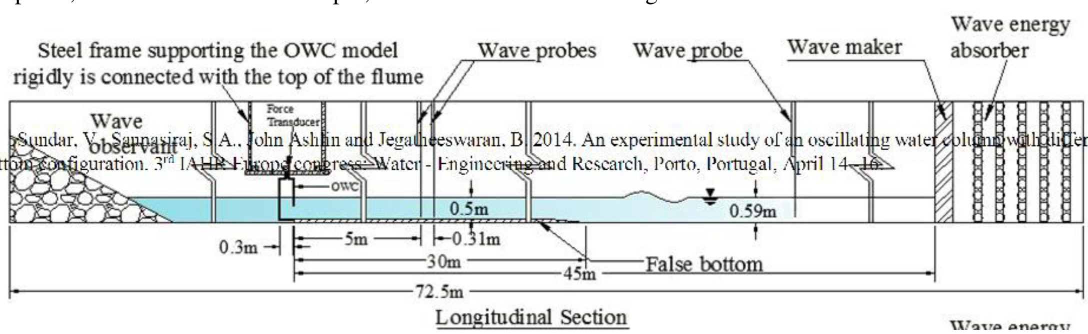
Sundar et al. (2010) presented a comprehensive review on the possible approaches that can make use of the OWC as part of breakwaters and coastal defense systems for the harbour formation. The concept of integration of OWC with breakwaters that can reduce the total cost significantly to bring forth economic security in project planning was highlighted. Zhang et al. (2012) observed that the efficiency of OWC centred on a resonant frequency. This clearly shows the importance of phase lag between the dynamic excitation pressure and the corresponding air pressure being developed. Wilbert et al., (2013) have considered the parameters such as water depth inside the wave energy converter (d) and opening in the bottom of the wave energy converter (o) and, found that effective energy conversion capacity of OWC was found to be increasing with an increase in its bottom opening, o/d. It reached a maximum efficiency of 94 % closer to the natural frequency for o/d = 0.80. However, at the same time, the peak efficiency was found to shift towards the higher frequency with an increase in opening depth. Recently, the chamber bottom profile configuration (i.e., Flat, Circular curve, Slope 1 in 1 and Slope 1 in 5 bottom profiles) has been optimized by Sundar et al. (2014)[1]. It was concluded that the circular curve bottom profile is more efficient in terms its hydrodynamic performance, i.e. wave amplification factor inside the chamber, hydrodynamic efficiency and front wall outside pressure compare to other bottom profiles tested. For designing the components of an optimized circular curve bottom profile OWC device, the magnitude of wave loads dictates the design criteria. The unavailability of well-defined empirical methods to find the wave force estimation on OWC is forcing to find the wave force through experimental study. Hence, in the present study, an attempt is made to estimate the wave forces on a circular curve bottom profile OWC through experimental study which will be useful in designing its components. The details of the dimensions of the OWC model, experimental model set-up, wave characteristics, experimental procedure, results and discussion are reported in this paper.

2. Experimental setup

In this paper, an experimental study on Circular curve bottom profile OWC exposed to the action of regular waves has been carried out in a wave flume of 72.5 m length, 2 m width and 2.5 m depth is discussed. The flume is equipped with a wave maker capable of operating in piston and hinged mode in order to generate both shallow and deep water waves. A parabolic perforated beach on the other end is capable of absorbing energy in the generated waves up to about 90 %. The models were kept at 45 m away from the wave maker. The models were made-up of acrylic sheets of 20 mm thickness. An inner-to-inner dimension of a chamber was 1.91 m x 0.3 m and the height of the model was about 0.9 m with a front lip wall of 0.6 m depth and 0.3 m water inlet to a chamber from the bottom of a chamber. The custom made two component (vertical and horizontal) force transducers were used to measure the wave force acting on the structure. The two (vertical and horizontal) full bridged strain gauges were placed on each force transducer in such a manner to nullify the effect due to moment in the measurement.

The OWC model was fixed rigidly with the two force transducers connected at 1/3 and 2/3 of width of the flume and model was rigidly supported on a steel frame arrangement to capture the true wave force acting on the structure. To avoid transferring of wave forces to the wave flume walls, a clearance between OWC model and side walls of 25 mm and between the bottom of the OWC model to the wave flume bottom surface of 70 mm were maintained. There was a false bottom surface of thickness 90 mm provided in front of the OWC model for a length of 30 m from the OWC model towards wave maker to avoid direct wave penetration under the OWC model due to clearance provided of 70 mm between OWC model and wave flume bottom surface within an addition of 20 mm given for thickness of the model. The experimental model setup inside the wave flume is shown in Fig. 1a. The force transducer arrangements fixed to the OWC model is shown in Fig. 1b.

The details of the OWC model in plan and sectional elevation with circular curve bottom of radius 300 mm are shown in Fig. 2. The experiments were carried out with an air vent as 0.68 % of plan area of the air chamber. Three wave probes, one at a distance of 7 m from the wave maker (η_1) and the other two at 5 m (η_2) and 5.31m (η_3) from the model were used to measure the wave elevations. Five run-up (R_u) probes were used to measure the sloshing node, water level rise and fall inside the chamber. Four Pressure transducers facing the waves (P_{out}) fixed at various level were used to register the pressure variations on the front wall. On the rear side (P_{in}) of OWC model, two pressure transducers were fixed to measure the pressure variation inside the chamber. The air pressure inside the chamber of OWC model was measured with a pressure sensor on top (P_{air}). In essence, seven pressure signals, five run-up signals, incident water wave elevation, two wave probes for to measure reflection from the model and four strain measurements (two load cell), thus in total 19 channels of signatures were simultaneously acquired with a sampling interval of 0.02 s for further processing of the signals from the measurements. In this paper, the effect of wave steepness, H/L and relative water depth, d/L on the wave force acting on the OWC model are studied.



[1] Sundar, V., Sannasiraj, S.A., John Ashlin and Jegatheeswaran, B. 2014. An experimental study of an oscillating water column with different bottom configuration. 3rd IAHR Europe congress- Water - Engineering and Research, Porto, Portugal, April 14–16.

Fig. 1a. The experimental model setup inside the wave flume.

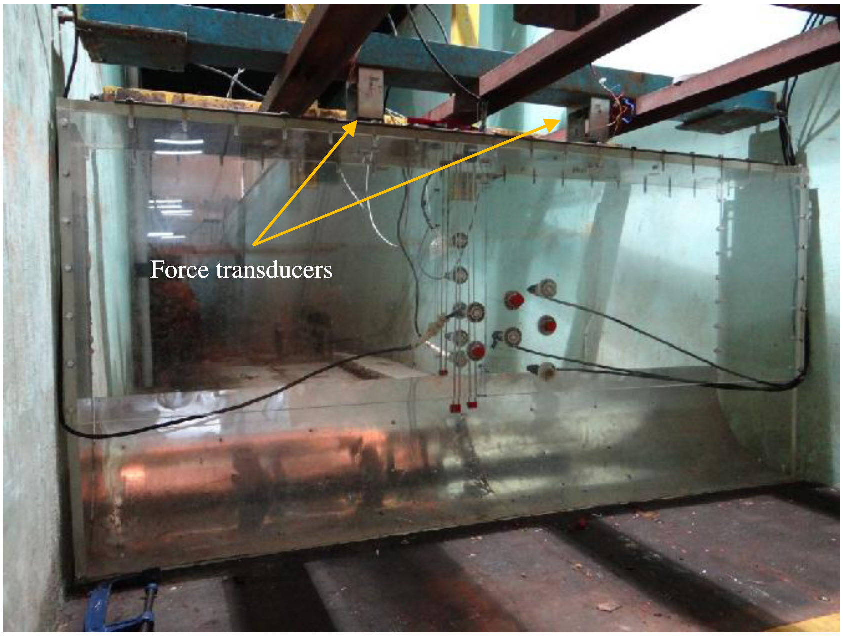


Fig. 1b. The force transducer arrangement details.

3. Results and Discussion

The measured peak wave forces on the OWC model are normalized by dividing by $\rho g w d * (H/2)$ and is defined as F^{p}_{*} which is given below,

$$F^{p}_{*} = F^{p}_{V} \text{ or } F^{p}_{H} / \left(\rho g w d * (H/2)\right) \tag{1}$$

Wherein, '*' denotes horizontal peak wave force, F_H or vertical peak wave force, F_V, ρ: mass density of fluid, g: gravitational acceleration, w: width of the OWC model, d: water depth inside the OWC chamber, H: wave height. The normalized force coefficients were used to study the effect of different wave steepness range on wave force which acting on the OWC model.

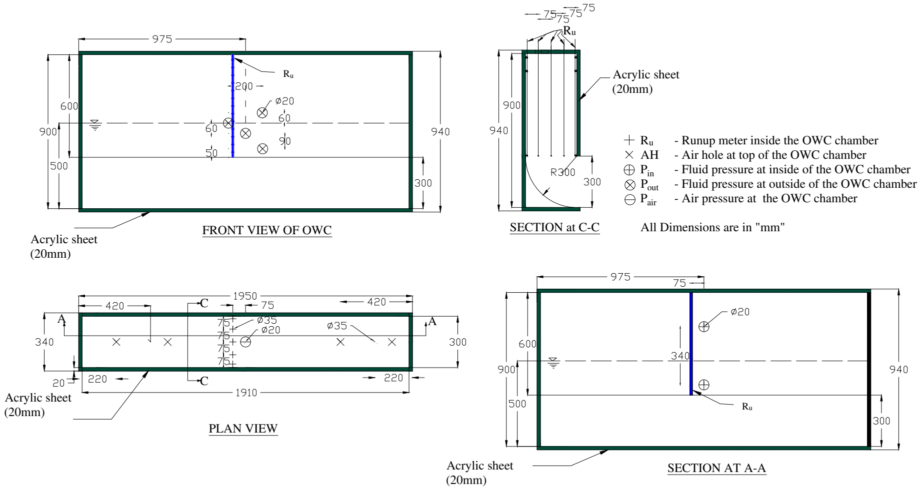


Fig. 2. Dimensional details of OWC

Typical time histories of wave surface elevations (η_1, η_2 and η_3), vertical wave force (F_V) and horizontal wave force (F_H) measured in the OWC with the circular curve bottom subjected to regular waves of H/L=0.0302 and d/L=0.5018 are projected in Fig. 3. It is clearly seen that the horizontal wave force acting on the OWC structure is more than twice that of vertical wave force acting on the structure.

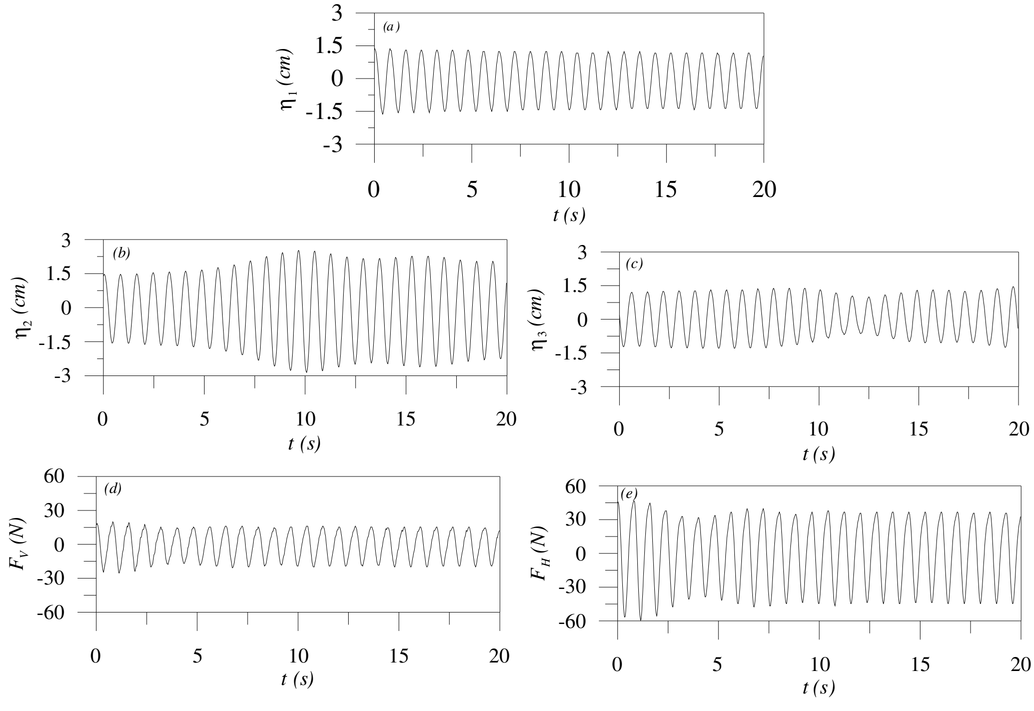


Fig. 3. Typical time histories of (a) η_1, (b) η_2, (c) η_3, (d) F_V, (e) F_H circular curve bottom OWC. (H/L=0.0302 and d/L=0.5018)

The OWC caisson model is not symmetrical about its transverse axis and hence, the force acting towards the shore (positive force) different from this likely to be from that acting towards the sea (negative force). As one would expect the seaward force to be more, the results only for positive peaks of both the horizontal and vertical force components alone are reported.

The variation of $F^p{}_V$ on the OWC model for the different range of H/L is shown in Fig. 4. From the results, clearly demonstrate that the $F^p{}_V$ increases with an increase in H/L. The trend in its variation is found similar for all three range of H/L tested.

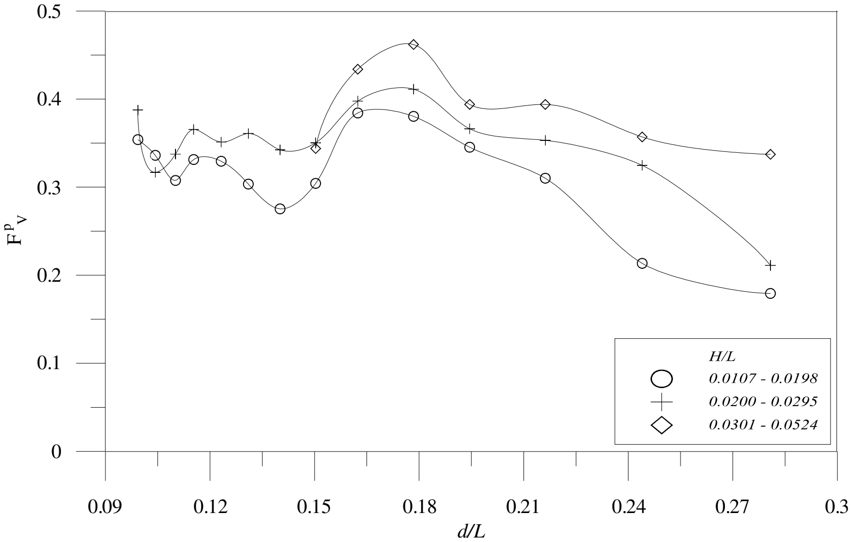


Fig. 4. Variation of normalized vertical peak wave force with d/L (for different H/L range)

$F^p{}_V$ is increases up to d/L of 0.16 for all the different ranges of H/L considered. Further, increase in d/L leads to a reduction in the force, the rate of reduction being quite high for the least H/L tested. It was reported by Sundar et al., (2014) that the maximum absorption of the incident wave energy takes place when d/L is around 0.131 and the present investigations show that around the same d/L the vertical force is found to be less. The results also indicate that effect of non-linearity on the vertical forces dominates for d/L greater than 0.16. The above said results need to be verified with numerical predictions which are in progress.

The variation of $F^p{}_H$ on OWC model for the different range of H/L is shown in Fig. 5. The results show that the trend in the variation of $F^p{}_H$ with d/L is found to be similar to the variation of $F^p{}_v$ as explained earlier. Except for d/L of about 0.19, the non-linearity in the case of horizontal force is found to be much less than that found in the variation of vertical forces. As the structure herein considered in unsymmetrical, in addition to its efficiency in absorbing incident energy which in turn is frequency dependent, the problem on the wave force prediction on such a structure becomes more complicated which is reflected in the trend of its variation with the wave characteristics.

The variation of the ratio between the horizontal and vertical peak wave forces, $F^p{}_r = F^p{}_H / F^p{}_V$ acting on the OWC model is shown in Fig. 6.

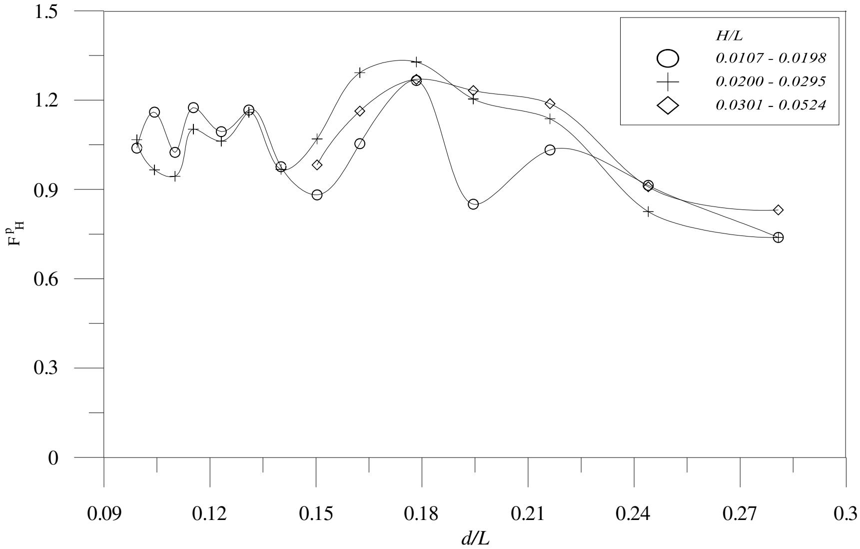


Fig. 5 Variation of normalized horizontal peak wave force with d/L (for different H/L range)

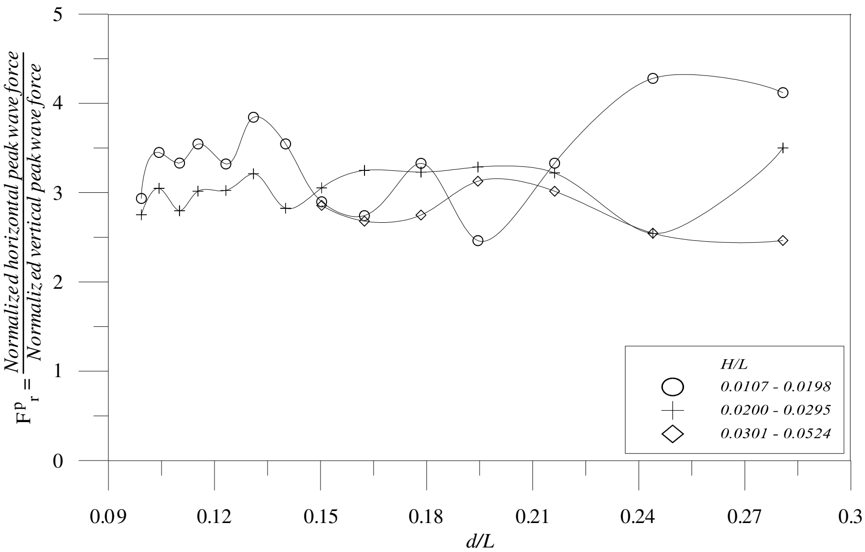


Fig. 6 Variation of normalized peak wave force ratio with d/L (for different H/L range)

4. Conclusions

A comprehensive experimental set-up to measure the total forces on an OWC model was rigged in a flume and subjected to the action of regular waves. The salient conclusions drawn from the study are presented. The peak horizontal wave force acting on the structure is more than 2.5 to 3 times the peak vertical wave force. The wave forces acting on the OWC structure increases with an increase in wave steepness. The both peak vertical and horizontal wave force components increase with an increases in d/L up to the value of 0.16, beyond which a decreasing trend is observed. The nonlinearity due to the variation in the wave steepness in the case of vertical forces is found slightly more compared to the horizontal forces

Nomenclature

d	water depth
H	wave height
L	wave length
d/L	relative water depth
H/L	wave steepness
R_u	run up
P_{out}	pressure transducer register pressure variations on front of the lip wall
P_{in}	pressure transducer register pressure variations inside the OWC chamber
P_{air}	pressure transducer register pressure variations on top of the air chamber
F_V	vertical wave force
F_H	horizontal wave force
F^p_V	normalized vertical peak wave force
F^p_H	normalized horizontal peak wave force
ρ	mass density of fluid
g	gravitational acceleration
F^p_r	ratio between the horizontal and vertical peak wave forces

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