HYBRID STRUCTURE COMBINING A WAVE ENERGY CONVERTER AND A FLOATING BREAKWATER

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ABSTRACT

This experimental study investigates on an hybrid structure consisting in an "active" floating breakwater (FB), coupled with a new type of wave energy converter, named ShoWED. The hybrid structure achieves the double purpose of generating electrical energy and of protecting marinas. The specific objective of the tests is to evaluate the performance of the ShoWED when installed in front of a FB and the effects of the wave energy device on the performance of the FB.

Physical model tests were carried out at two different scales: 1) in scale 1:10, necessary to evaluate the performance and dynamics of the FB in the absence of the ShoWED. 2) in scale 1:1, in order to evaluate the efficiency of the ShoWED, at different distances from a rear reflective vertical wall, simulating the presence of the FB. A peculiarity of these latter tests is that the real PTO was tested, allowing to measure the produced electrical energy, as a function of the real external electrical impedance.

It is concluded that the ShoWED is able to harvest electrical energy if the incident wave height is larger than 0.05 m, a limit possibly given by some friction theshold in the PTO, and if the wave has a period longer than 1.0 s, a limit possibly caused by the finite width of the floater, 70 cm, not negligible compared to the wavelength associated to periods smaller than 1 s.

Maximum excursion of the floater are achieved when the floater location takes advantage of the total reflection of the rear wall: for T=2 s, a 22% efficiency was obtained (measured with a "wave to wire" approach), so that a 10 cm wave height produced 7 W in the laboratory. The reflection and transmission characteristics of the hybrid structures were evaluated indirectly, and the benefits compared to a traditional FB should be appreciable especially for long waves.

KEY WORDS: Wave Energy Converter. Floating Breakwater. Power Take Off, Wave flume, ShoWED, Physical model tests.

INTRODUCTION

This paper is part of a research focusing on the development of a new type of Floating Breakwater (FB), achieving the purpose of protecting marinas even under wave conditions that would typically be outside the range of application of traditional FBs.

The idea is to install on the FB a mechanism designed for Wave Energy Converters (WECs), able to effectively harvest - or at least dissipate - wave energy. The desired result is that the structure drains some of the incident energy, especially for longer waves, and the FB transmission performance is larger in conditions where the typical efficiency is rather low.

The possibility of using floating structures for protecting harbours, while exploiting the "ocean of energy" thanks to the presence of a WEC is an innovative idea, although there have been some old studies where the essence of the proposed concept is present. The effectiveness of a WEC in reducing wave transmission was probably first pointed out in connection with the first Japanese floating device, named Mighty Whale. This device is a very large floating structure combined to an OWC. A numerical simulation of an array of Mighty Whale (Masuda et al., 2001), showed that this device behaviour, in terms of wave absorption (and, as a consequence, in terms of wave transmission), performs better than the conventional floating breakwaters. The same conclusion was reached by studying the floating breakwaters. Kim and Iwata (1991) and Cheung et al (2000) describe the dynamic response a pneumatic floating platform. The latter paper concludes that a properly tuned pneumatic platform will be an attractive design concept for wave-energy absorption devices. Note that the air chamber is in every respect similar to the OWCs used for Wave Energy conversion. Similarly, Ruol (1984), Atzeni (1996) and Diamantoulaki (2007) proved experimentally and numerically that the presence of intermediate chambers between floating breakwaters can increase the overall efficiency.

This experimental research focuses on the possible application of a new type of WEC named ShoWED, to be installed on the FB. The ShoWED characteristics is to address a small amount of energy, of the order of 1 kWp (kW peak) at prototype conditions, and it is therefore a low cost device. It resembles the typical WEC activated by a floating buoy. According to Salters (Cruz, 2008), "many inventors start with heaving floats". In fact it is quite easy to understand that a device can harvest energy if some generator is attached to a floater moved by the wave. An example of a large device based on this concept is the WaveStar (www.wavestar.com).

The patent of the ShoWED covers the Power Take Off (PTO) system, that is expected to perform better for waves of very limited height and period, i.e. Hs from 0.3 to 2.0 m and Tp from 1.5 to 5 s.

FBs are used to protect marinas when the wave climate has similar characteristics (Hs < 1.5 m and Tp < 4 s.) and therefore it is natural to

try to install such type of WEC on FBs. In particular, when the FB is moored with piles, the same piles may be used (and designed) to support the ShoWED, providing also the essential low cost conditions for support (and deployment) of the device, that justifies its application. Furthermore, the location of FBs is well suited to host the WEC in general, since they are usually located sufficiently far from the shore to minimize the impact (e.g. noise) but still very easy to reach for maintenance purposes.
The produced energy should be sufficient to power a headlight or flashing lamp, monitoring instruments for the marina, etc: for instance for Hs=0.6 m, Tp=2 s, the incident energy flux is 500 W/m.
The objective of this work is to evaluate the performance of the ShoWED when installed in front of a FB installed on piles, and to check the disturbance of the device on the wave pattern.
For this purpose, two experimental investigations were carried out at the maritime department of the University of Padova (IT):
1) Physical model tests on a scaled FB, aiming at measuring the FB dynamics (heave, roll), the wave reflection and wave transmission. As the wave period increases, reflection reduces and transmission increases.
2) Physical model tests on the real ShoWED, in scale 1:1, aiming at evaluating the conversion efficiency and the reflection and transmission characteristics of the device. It was found that the transmission characteristics are also affected by the actual efficiency of the WEC (function of the load applied to the generator).
Unfortunately, it was impossible to reproduce the ShoWED at the same scale of the FB (and vice-versa) and therefore it was decided to separate the tests and investigate on the effects of the ShoWED on the wave pattern using a fake FB (a vertical wall).
It is expected that the ShoWED induces a larger disturbance on reflection rather than on transmission, and therefore the focus of the research is directed also toward wave reflection.

PHYSICAL MODEL TESTS ON THE FB

A large prefabricated FB of the Π-type was tested in scale 1:20 (Fig.1) using the same experimental and analysis procedures described in Ruol et al, (2013). The FB is 150 tons, 20 m long, 8 m wide. Water depth was 50 cm. Incident and reflected waves were measured by two arrays of wave gauges as in Fig 2. Logging frequency was 20 Hz.

Figure 1. Tested floating breakwater (FB).

In order to evaluate the structure dynamics, the natural period of oscillations was investigated. Fig. 3 shows the heave response to an impulse (heave oscillations vs time): the heave natural period of oscillation (dotted line) fitting the observed movements resulted 0.96 s (4.3 s at prototype scale). A significant damping is observed, the damping coefficient being 0.15. The structure is therefore suited to host a ShoWED since it is designed for mild wave climates, i.e maximum periods of the order of the natural period of oscillation (Ruol et al., 2013).

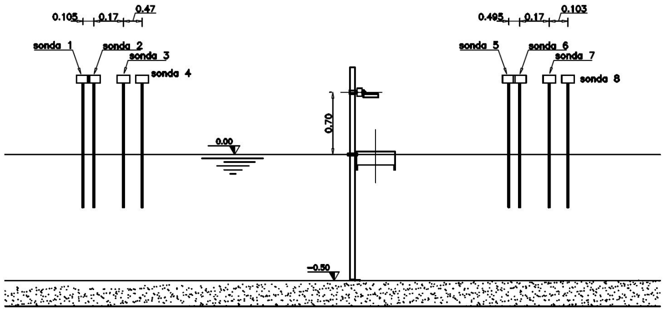

Figure 2. Setup of the FB experiments.

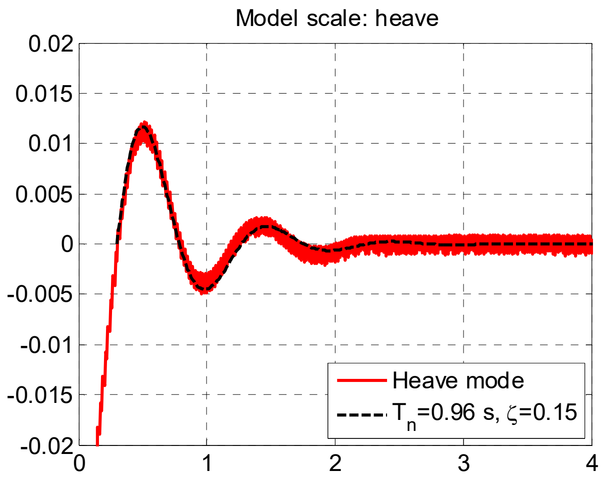

Figure 3. Natural heave oscillation of the FB.

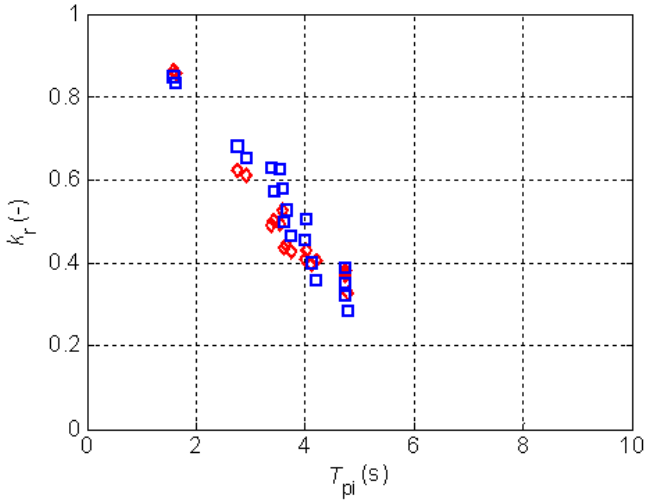

Figure 4. Reflection characteristics of the FB.

The test programme investigated irregular waves with period ranging from 1.5 s to 5 s and heights from 0.5 m to 2 m (prototype scale).
The transmission coefficient k_t, i.e. the ratio between transmitted and

incident wave height, was found to depend almost only on the peak wave period T_p. It was approximately zero for $T_p <= 1.5$ s and almost proportional to the period for T_p in the range 3 to 5 s, where k_t varied from 15 % to 60 %.
In order to further reduce the transmission, it is desired that the ShoWED placed in front of the FB drains part of the incident wave.
Fig. 4 shows the reflection coefficient, i.e. the ratio between reflected and incident wave heights: it may be observed that the reflection is quite large, of order 80% for wave periods of 2 s. In conclusion, for small wave of limited period the FB reflection characteristics are very similar to a vertical wall. For this reason, it was replaced by a vertical wall in the next set of experiments.

PHYSICAL MODEL TESTS ON THE SHOWED

The tested model is a preliminary version of a device under development named ShoWED. A similar version was deployed in the Venetian lagoon (along the Giudecca Canal) for some time, under the name of Giant-Giem.
The tested floater is 1 m long, and has an ellipsoidal form, with axes of 75 cm x 45 cm. Draft at equilibrium is approximately 11 cm.
Such low cost device is suited to areas with small incident energy, and the patented power take off is designed for average power of the order of 1 kWp.
The tested device (and the PTO) is at full scale, and cannot be reduced 20 times (as it was for the FB). However, the lab facility does not allow a reproduction of the depth at full scale, of order 10 m (canal depth is 1.3 m) nor the real FB. Actually, water level was set to 0.5 m, due to other existing constraints. The experimental study was therefore subject to strong approximations: in fact the depth influences the shape of the wave and the celerity of propagation, so that results measured at depth of 0.5 m will have to be carefully interpreted for possible application at depth of 10 m. Furthermore, being impossible to observe the details of the interactions between the ShoWED and the FB at the same scale, the tests of the ShoWED were carried out separately from the previous ones. Fig. 4 shows that at the periods of interest (approx. 2 s) the FB reflects almost completely the incident wave, similarly to a vertical wall. Therefore the FB was substituted by a vertical wall, located at different positions.
More precisely, three configurations were tested:
1) device with no rear wall (Fig. 5)
2) device with a fixed rear wall located at 110 cm (Fig. 6)
3) device with a fixed rear wall located at 220 cm (Figs. 7, 8)
In the first configuration (Fig. 5) the ShoWED floater was hanging from the top of the flume. This case was tested to observe the transmission and reflection characteristics of the device.
The second and third configurations included the presence of a rear wall. These cases allowed to measure the reflection characteristics of the device for two different distances of the device from the hypothetical FB located behind the ShoWED: for T=2s, the floater is placed respectively at the node and at the antinode of the standing wave induced by the rear wall.

Measurement istruments

Waves were measured by two arrays of wage gauges. For tests without wall (Config. 1), the wave gauges were located in front an behind the structure. For tests with the wall, both arrays were obviously located in front of the structure. Distance among the gauges were 0.10 m, 0.16 m, 0.4 m (first array, closer to the wave paddle), and 0.39 m, 0.17 m, 0.10 m (second array).
The vertical oscillations of the buoy were recorded by a wire displacement meter (max length 50 cm). The wire applies a constant load of 7 N, i.e. a negligible load for the floater. The produced electrical output is "dissipated" by a resistance R in parallel to a capacitor. The DC tension $V(t)$ produced by the ShoWED was measured in parallel to the resistance and the capacitor, after being reduced 200 times (due to the limitations of the maximum tension in the data logger).

Figure 5. ShoWED located over the canal, in config. 1 (no rear wall).

Figure 6. ShoWED in configuration 2 (rear wall at 110 cm).

Figure 7. Floater on the crest of the wave (configuration 3, rear wall at 220 cm).

Figure 8. Floater on the trough of the wave (configuration 3, rear wall at 220 cm).

Since the value of the selected resistance is known, the total measured power was:

$$P(t) = V(t)^{2} / R \qquad (1)$$

Where $V(t)$ was amplified 200 times to account for the applied reduction. Waves were logged at 20 Hz, tension and displacement at 100 Hz.

Test programme

The test programme included regular waves with height in the range 0.05-0.18 cm, periods from 1 to 5 s. Eight different values of the resistance R were tested (ranging from 16 Ω to 1.5 kΩ) and three different values of the capacitor C (0 μF, 940 μF and 9900 μF).

Results

For each tests, results are relative to the wave pattern and to the power production.

Waves were analyzed the Zelt and Skjelbreia (1992) procedure, in order to obtain the incident and reflected components at both arrays. For incident wave H_i, the value at the first array is given. Standard downcrossing time domain and spectral analysis were carried out.

For configuration 1, the transmission and reflection coefficient were evaluated as the ratio between the (rms) wave incident the second array (transmitted wave) and the (rms) wave incident the first array (incident wave). The reflection coefficient is computed at the first array (located in front of the structure).

In configuration 2, two reflection coefficients were evaluated, one for each array, and they resulted in agreement.

Fig. 9 shows the wave transmission coefficient k_t, measured while the structure is producing energy (R=230 Ω, C=940 μF), function of the wave period T.

For short periods, the WEC does not convert energy and oscillations are small. The transmitted energy is of order 40%, since reflection is large. However the 8 m wide FB tested in the previous experiments is much more effective, the transmission being negligible.

For long periods (in the range 2 s to 5 s), the WEC converts some energy and oscillations are significant. The transmission coefficient is approximately 85%. The energy reduction for long periods is very important in the overall behavior of the hybrid structure, since the FB is not efficient when the period exceeds 4 s.

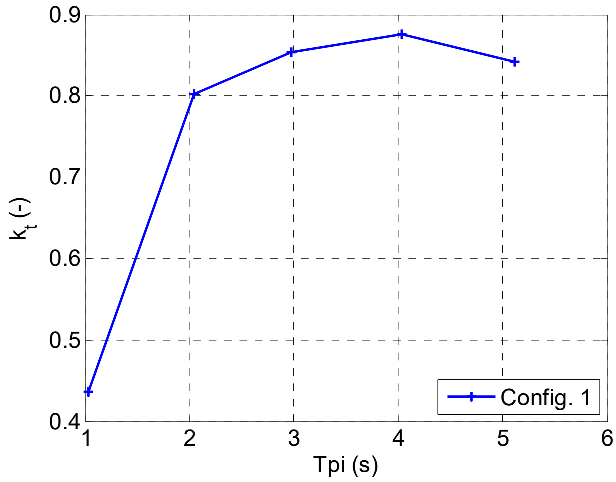

Figure 9. Transmission coefficient – ShoWED, configuration 1, with PTO absorbing energy.

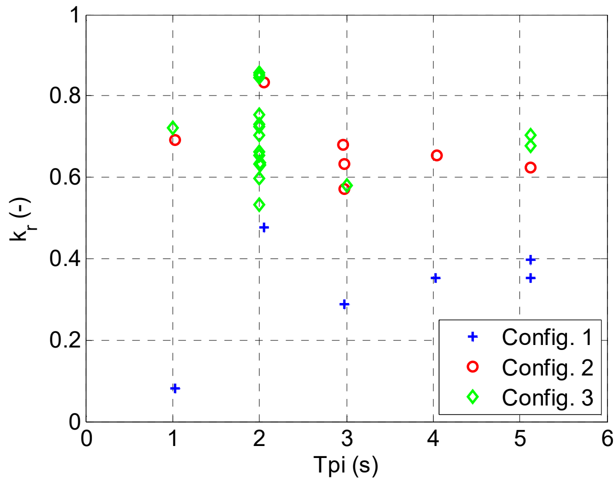

Figure 10. Reflection coefficient – ShoWED, all configurations.

Fig. 10 shows the measured wave reflection. Different points are relative to different configurations of the PTO resistance and capacitor: it can be observed that reflection is smaller than expected. This is due to the presence of a system that drains the energy with different efficiency. In particular, a higher peak is observed in configuration 2, i.e. when the floater is located in correspondence of the node of the standing wave induced by the vertical wall. In configuration 3, the reflection is large when the device is not properly tuned, but reaches a very low value when the system is properly tuned: in order to observe the effect of the PTO settings, the vertical displacement of the floater and the output tension should be observed. They are obviously quite affected by the settings of the resistance R and capacitor C, since these variables modify the current and power production and therefore the force applied to the floater.

Figure 11 shows the vertical oscillation of the ShoWED floater, in configuration 1, when the incident wave is 0.10 m, period 5 s (energy flux = 28 W). The buoy is seen to oscillate vertically 0.10 m. Basically, the wave is long enough to raise the floater reaching the crest in quasi-static conditions. The tension (also plotted in figure 10) grows during the phase in which the floater rises, and the capacitor stores energy in this initial phase until it is fully loaded. After one half of the period, the floater "freely" falls (without any energy generation) and in this phase

the capacitor continues to release part of the stored electrical energy. The tension is the consequence of the value of the resistance R. The produced power is the tension multiplied by the current flowing through the resistance (Eq. 1), and is shown in Fig. 12.
The produced power has an oscillating behavior, with average given in the legend (2.9 W).

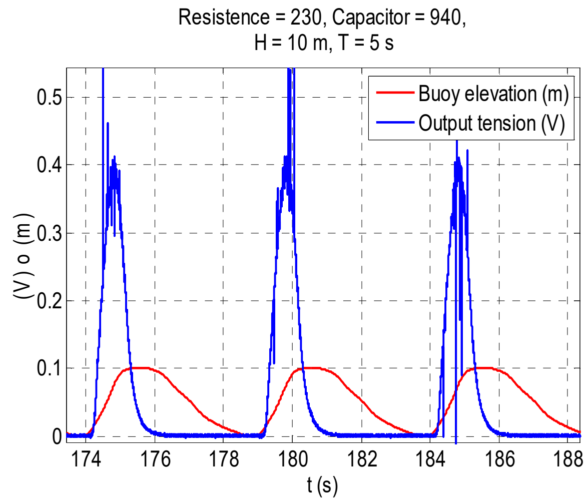

Figure 11. Example of record of the tension and of the floater vertical oscillation (average power for this case is 3W).

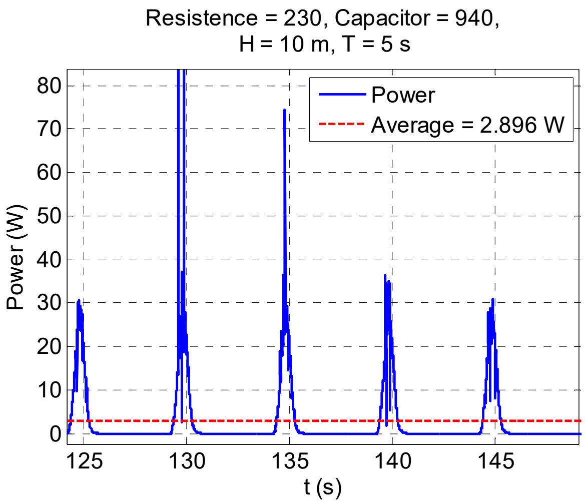

Figure 12. Example of record of the produced power.

Figure 13 shows the floater oscillation and the tension for a different value of the capacitor compared to Fig. 10 and 11, namely 9900 µF. Obviously, since during the floater movements the load differs from the previous case, and lasts quite longer, the dynamic of the floater is also different. In particular, the maximum oscillation is only approximately 0.085 m, differently from the quasi-static behavior previously observed. The produced power is much more steady but lower in average (2 W only, compared to the 28 W incident the buoy).

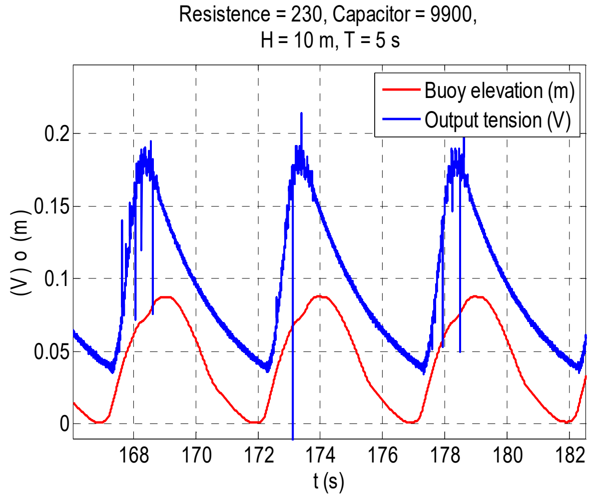

Figure 13. Example of record of the tension and of the floater vertical oscillation (average power for this case is 2W).

ShoWED efficiency

The best efficiency of the device is found in configuration 3 and for T=2 s, since the floater is placed on the antinode of the standing wave induced by the rear wall.
Efficiency is measured as the ratio between the transformed average power and the incident average energy flux. The incident energy flux is computed, for regular and irregular waves respectively, as:

$$F = \langle (\rho \, g \, H_i^{\,2} / 8) \, c_g \, B \rangle \qquad (2)$$

or

$$F = \langle (\rho \, g \, H_{si}^{\,2} / 16) \, c_g \, B \rangle \qquad (3)$$

where B=1 m is the device width, H_i or H_{si} the regular or significant incident wave height, < > is the averaging operator and c_g is the group celerity, always equal to 2.2 m/s in the tested shallow water conditions, independently from wave period.

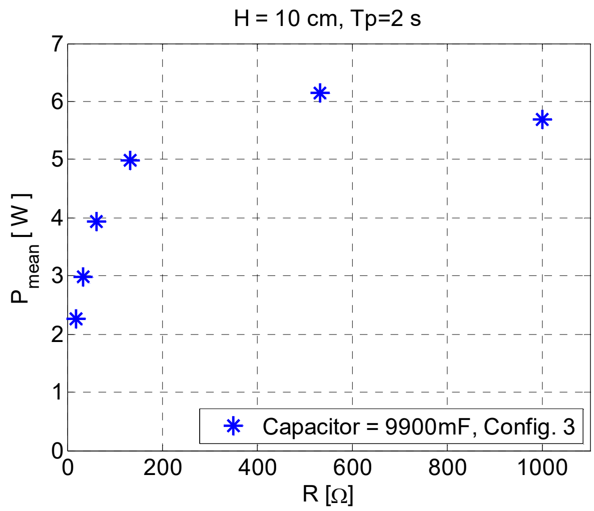

Figure 14. Produced power (input power is 28 W).

Fig. 14 shows the effect of a change on the resistance of the PTO, for a given value of the capacitor (9900 µF). A maximum is found for R=500 Ω, and for H_i = 0.1 m, the obtained power is 6.15 W, corresponding to an efficiency η= 6.15 W / 28 W=22%.

Fig. 15 shows that a constant efficiency of the order of 20% was measured for all the regular waves in the range 7 to 18 cm, whereas for waves smaller than 4 cm no energy was produced (not in figure). Possibly due to this non-linear effect, an efficiency of 10% and 12% was measured for irregular waves with H_{si} of 8 and 12 cm. The positive correlation between H_{si} and η may be a consequence of the non-linear behavior, and for larger H_{si} , e.g. H_{si} = 0.5 m, an average efficiency tending to 20% is expected.

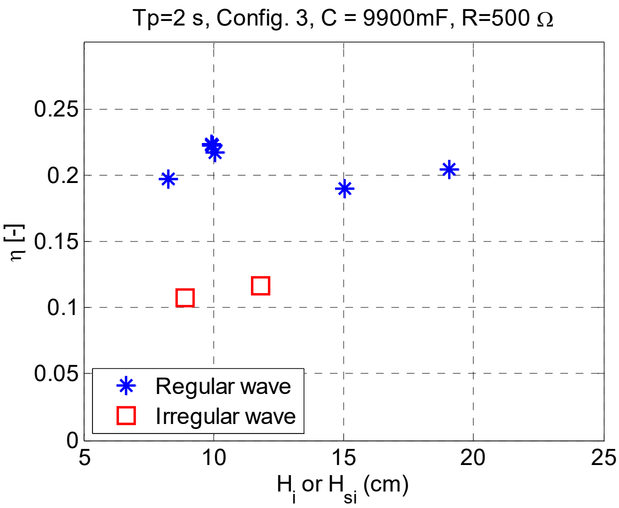

Figure 15. Efficiency for different incident wave heights (Config. 3).

Fig. 16 shows the effect of the type of configuration. The efficiency power is much lower than optimal in the figure, probably due to a wrong choice of the resistor (cfr Fig. 14).

However the comparison between the tests shows that:

- in all configurations the produced power is very low for T=1 s, possibly due to the small dimensions of the floater compared to the wavelength for this case.
- in general the efficiency grows with the wave period, with the exception of the response for T=2 s: in configuration 2 and 3 the floater is respectively at the node and antinode of the standing wave induced by the rear wall. Consequently, the efficiency tends to zero in the first case and tends to be doubled in the second.

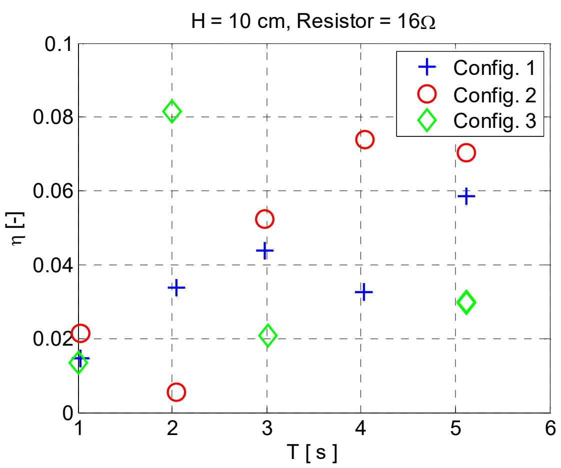

Figure 16. ShoWED in different configurations. (unfortunately the production is very low, due to a wrong choice of the Resistor value).

CONCLUSIONS

This experimental research, focuses on the development of a hybrid structure, formed by a new type of WEC named ShoWED, installed on a FB. Conclusions are subject to strong approximation, caused by the limitation of the experimental facility and the necessity to test the WEC at full scale.

According to the interpreted results, in the proposed ideal installation a FB of width 8 m, is moored on piles, on a water depth of 10 m. The most frequent incident wave is Hs=0.7 m, Tp=2 s. In these conditions, the FB is completely stable and wave transmission almost zero. The incident wave flux is 480 W/m, and the ShoWED converts 20% of this amount, i.e. approximately 95 W DC, sufficient to power a powerful led lamp.

For a design wave of Hs=1.5 m, Tp=4 s, incident wave flux is 1000 W/m, the efficiency is lower, of order 10%, and the amount of converted energy is not much larger. Transmission of the hybrid structure is of order 50%, slightly better than for the FB alone.

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