LABORATORY EXPERIMENTS ON OSCILLATING WATER COLUMN WAVE ENERGY CONVERTERS

Ilaria Crema[1], Lorenzo Cappietti[2] and Hocine Oumeraci[3]

Abstract: This paper presents first results coming from an ongoing research project aiming at the conceptual design of a Very Large Floating Structure equipped with Oscillating Water Column Wave Energy Converters. The assessment of the hydraulic efficiency of the OWCs is evaluated by means of small-scale laboratory experiments. The study has been performed by varying some design parameter such as the size of the OWC chamber, the lip drought and the simulated turbine damping.

INTRODUCTION

The increasing population density and the industrial expansion will have a relevant impact on the limited availability of land. In this context, Very Large Floating Structures (VLFS) may represent an advanced solution, because of their possible multipurpose use, such as storage or aquaculture facilities, strategic emergency bases, offshore industrial plant, etc.

At the same time, the shortage of fossil fuels and the pollution problems is stimulating the use of renewable energies such as offshore energies from wind and waves. The Oscillating Water Column is a well know concept for harvesting the wave energy but it is also counted in the literature as a possible device that may control the VLFS hydro-elastic behaviour.

It is hence motivated the development of a VLFS equipped with OWC devices for harvesting of the wave energy and attenuate the motion of the floating structure.

An assessment of the wave energy potential in the offshore of the Mediterranean sea as well as the siting for possible installation of the VLFS-OWC system has been already

1 Department of Civil and Environmental Engineering, University of Florence, (Italy). Email: ilaria.crema@dicea.unifi.it

2 Department of Civil and Environmental Engineering, University of Florence, (Italy). Email: lorenzo.cappietti@unifi.it

3 Leichtweiß-Institut für Wasserbau, Dept. of Hydromechanics and Coastal Engineering, TU Braunschweig, (Germany). Email: h.oumeraci@tu-braunschweig.de

conducted by Vannucchi & Cappietti (2013), while experimental and numerical studies are ongoing.

The experimental data are used to preliminary prototype the VLFS-OWC system and to calibrate and validate a CFD numerical model aimed to further optimization Simonetti et al. (2013). First results arising from experimental tests on a two dimensional OWC model in fixed conditions are presented.

To date, experimental studies on two dimensional fixed OWCs has been conducted. Sarmento (1992) carried out experiments to support a parametric study on scaled model in order to find the optimal geometry and dimensions for the maximum efficiency of the device. More recently, Morris-Tomas et al (2007) studied the effect of the front wall configuration upon the hydrodynamic efficiency while Ram et al. (2010) studied the air flow in the chamber. This has helped to improve the knowledge of the working principle by identifying the processes causing major energy losses and trying to reduce them by modifying the device geometry.

EXPERIMENTAL METHODOLOGY

The proposed VLFS-OWC system and motivations

The OWC device was conceived to equip a modular VLFS to be installed in the Mediterranean Sea, in order to: i) operate as anti-motion devices, attenuating the hydro-elastic response, ii) absorb part of the incident wave-energy thus protecting the VLFS from the wave loads and, iii) convert the wave energy in a usable form.

The OWCs are integrated along the perimeter of the VLFS, in order to reduce the dependence of the system energy conversion efficiency upon the wave direction (Fig.1).

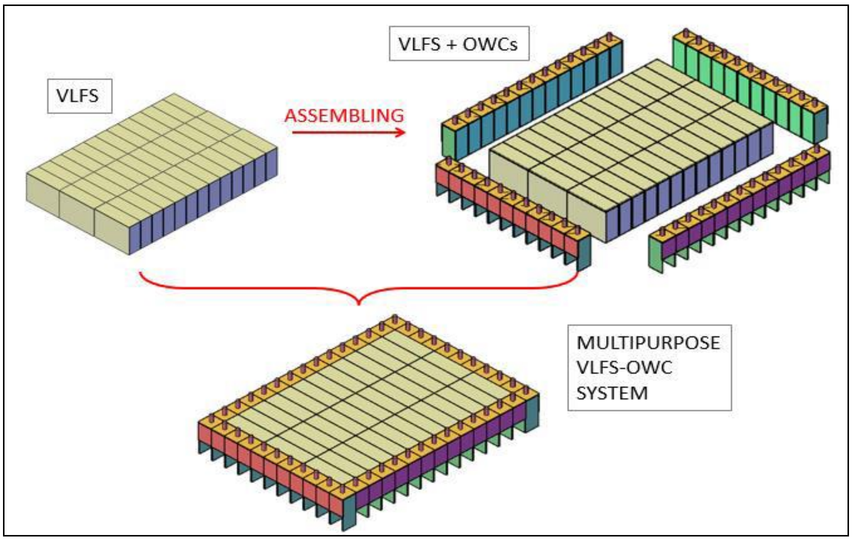

Fig. 1. 3D view of the conceptual VLFS-OWC system.

To share the manufacturing costs with the floating platform and to ensure an easy reliability in the available Mediterranean dockyards, the OWC devices and the platform units, are proposed to be manufactured as watertight retaining concreate-made caissons.

The OWC caisson is characterized by a pneumatic chamber with rectangular cross-section and a large opening at the bottom, placed below the water level. The compression and decompression of the air volume, trapped above the inner water surface, due to the wave-induced water oscillation inside the chamber, produces an airflow through a duct, which drives a self-rectifying turbine, located at the top of the device, (Dizadji & Sajadian, 2005).

The tested model

The laboratory tests are going on in the wave-flume of the Laboratory of Maritime Engineering (www.labima.unifi.it) of the Civil and Environmental Engineering Department of Florence University.

Considering the use of a wave flume, the modelling approach is bi-dimensional and so only the central segment of the whole VLFS-OWC system has been reproduced and tested (Fig.2). The tested segment is made of six OWC caissons, positioned respectively: three to the front and three to the backside of the platform. The central OWC is instrumented, in order to collect data less affected by boundary effects.

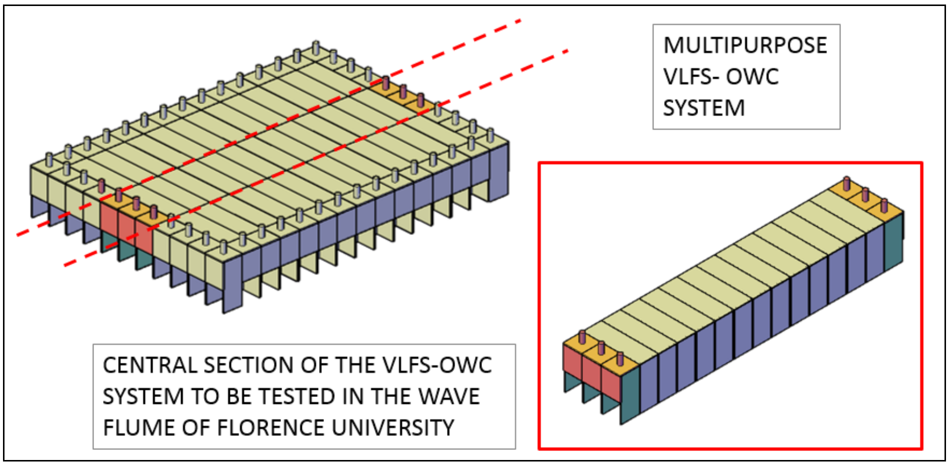

Fig. 2. 3D view of the central section of the VLFS-OWCs tested.

The physical model is performefd according to the Froude similarity, adopting a geometrical length scale of 1:50. The following three main studies are under conduction:

- Fixed OWC system, to study the OWC performances;
- VLFS without the OWC devices, to study the characteristic hydro-elasticity behaviour of the structure;
- VLFS-OWC system, to evaluate the influence of the OWC devices on the hydro-elasticity attenuation of the platform as well as to study the influence of the platform motions on the hydraulic efficiency of the OWC.

In this paper a description of the first experimental study, as well as, a preliminary analysis on the hydraulic efficiency of the fixed OWC case is presented. The investigations were conducted on the three OWC devices located at the frontal edge of the platform segment, in fixed conditions. Some design parameters were fixed while other design parameters were varied from test to test.

Starting from the study of Vannucchi & Cappietti (2013), a hypothetical installation site for the VLFS-OWC system was selected. The wave climate used as a reference for the design includes waves having significant height between 0.5 and 4.5m and mean spectral period between 3 and 8s. The target location characteristics were considered when selecting the values and/or the range of variation of design parameters.

The following design parameters were fixed once selected according to a detailed literature review (Fig. 3):

1) OWC width (W=9.20m), conceived to minimize the formation of standing waves within the air chamber, ensuring a wave sloshing period below 5s, which is the natural period of oscillation of applied OWC devices (The Carbon Trust 2005).
2) Freeboard (Fc=+8.00m S.W.L.), calculated taking into account tolerable limits for the overtopping volumes (EurOtop manual, 2007).
3) Back wall length and side walls length (B=22.5m), to maximize the wave reflection, thus amplifying the water column oscillation (Suroso, 2005).
4) Vertical Frontal wall, to minimize the wave run up and maximize the wave reflection, producing an amplification of the water column oscillations.
5) Thickness of the frontal, back and top cover walls (th_{fbt}=0.50m), Thickness of the side walls (th_s=0.40m) selected according to the current state of the art of reinforced concrete cellular caisson design for marine structures.

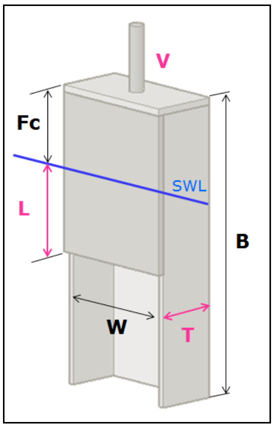

Fig. 3. Schematic view of the OWC prototype.

The analysis on the wave-to-pneumatic power conversion, was instead performed by varying the following parameters:

1) The *Thickness of the chamber* (T), because of its relevant influence on:
- resonance frequency of the OWC (Evans, 1978);
- air volume and spring, implying multiple resonance peaks (Lovas, 2010);
- wave sloshing period within the chamber (The Carbon Trust, 2005 and Sheng et al. 2012).

During the physical tests, the effect of the thickness on the OWC performances was investigated reproducing three different amplitudes (T1, T2 and T3, respectively of 5m, 10m and 15m).

2) The *Lip draught (L)*, because of its significant influence on:
- resonance frequency of the OWC (Evans, 1978);
- formation of inlet broaching, that implies PTO losses (The Carbon Trust, 2005);
- wave sloshing period within the air chamber (Sheng et al., 2012).

The effect of the lip draught on the air pressure fluctuations was reproduced, for each length of the chamber, modifying the frontal wall of the OWC (L1, L2 and L3, respectively of -3.5m, -9m and -14.5m S.W.L.).

3) The *turbine damping (V)*, in order to investigate the pressure drop due to the installation of the air turbine.

Since, to reproduce the Power Take-Off System (PTO) in a small-scale physical model is not a possible option, the effect of different pressure drops were simulated by vents on the centre of the top cover of the OWC, with the following opening surface rates (Sheng et al., 2013): 0.5%, 1% and 2% of the top cover surface. Each vent was equipped by a duct of equal length for each test, so as to canalize the airflow.

Experimental set-up

The wave-current flume of Florence University is a structure completely made of steel and glass side walls, with a total length of 37.0m and 0.80m wide and high.

The piston type wave maker is installed at one end of the flume and it has a stroke equal to 1500mm driven by an electromechanical system with an absolute encoder of 0.1mm accuracy in position. The wave generation algorithm is based on the so called Deterministic Spectral Amplitude and Random Phase Method. The wave maker can generate random sea waves with a given target spectrum and maximum significant wave height Hs 0.30m for Tp 1.5-2.0s on a water depth up to 0.60m.

For the present work, the water depth was set equal to 0.50m on a horizontal flume bottom representing the offshore conditions corresponding to 25m for the prototype scale, as identified by previous studies (Vannucchi & Cappietti, 2013).

The OWC models were placed 22m far from the wave maker. The test duration and the model positioning in the flume have been selected in order to avoid re-reflection problems without the need of using an active absorption system. The post-processing of the collected measurements has proved that the re-reflection in the analysing time window was totally absent. The time-history of the wave motion in front of, inside and on the back of the model was measured (Fig.4).

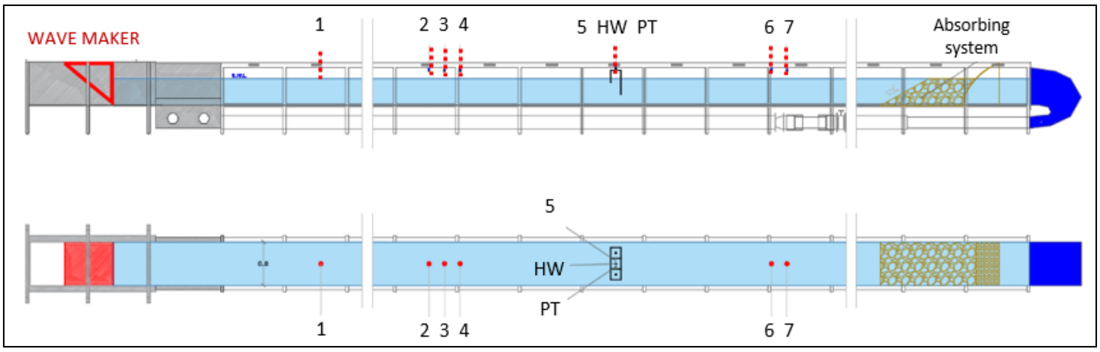

Fig. 4 Location of the instruments and the OWC model in the wave-current flume.

Seven ultrasonic distance sensors (WG), characterized by a declared repeatability of 1mm, were positioned as follows:

- One wave gauge (WG1) was located 4m far from the wave maker, in order to measure the generated waves.
- An array of three wave gauges (WG2, WG3 and WG4), was placed in front of the OWC model at a distance of 3.6m (about 18.4m far from the wave maker). The distance between these gauges was of 0.30m, in order to measure the incident and the reflected waves, by means of Goda & Suzuky method [16].
- The WG5 was installed on the roof of the OWC to measure the internal free surface oscillations (Fig.5).
- Two wave gauges (WG6 and WG7) where placed on the back of the model, at a distance of 3m to measure the transmitted wave.

The OWC model was instrumented with a pressure transducer (full scale range 100mbar and accuracy of ± 0.1% FS) to measure the internal pressure variations. A hot wire anemometer (HW), located in the duct connecting the vent, was used in order to measure the airflow rate (Fig.5).

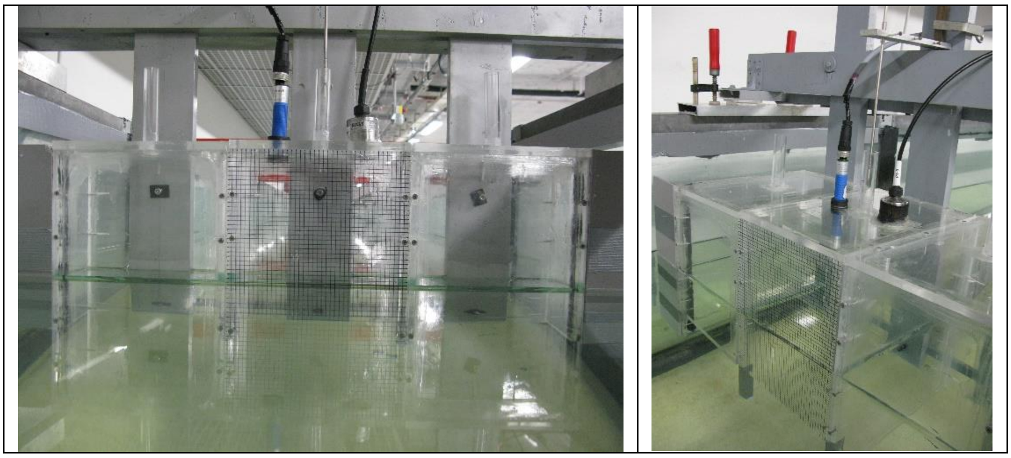

Fig. 5 Model setup in the wave flume during the investigation on the fixed OWC case.

HW is a constant temperature anemometer (CTA), characterized by a platinum plated tungsten wire with a diameter of 5μm and a length of 1.25mm. It was calibrated ad hoc in the interval range of 0-15m/s.

The sea states simulated during the experimental tests were selected as representative of the installation of the hypothetical Multipurpose VLFS-OWC System in an Italian Mediterranean area. In particular, this site is located in the Central Tuscany, in the south of Livorno and it is characterized by a mean annual wave power of 2.8kW/m (Vannucchi & Cappietti, 2013).

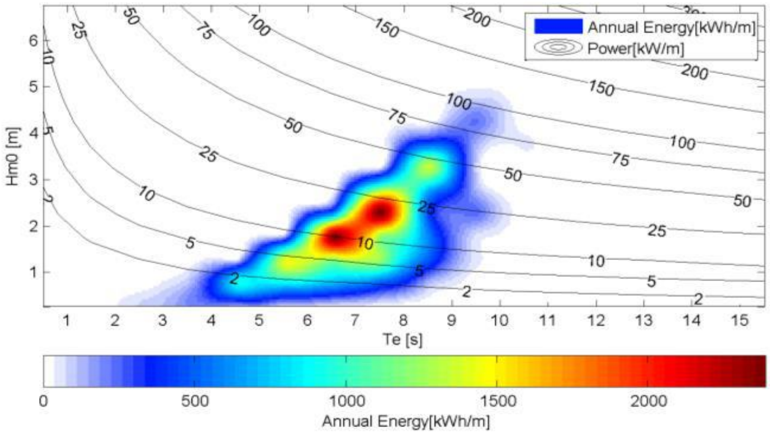

Fig. 6. Annual Energy for the Central Tuscany area (Vannucchi & Cappietti, 2013).

In Figure 6, it is possible to note that the highest annual energy for a give measured sea state (characterized in terms of the couple significant wave height and mean wave period) is approximately 2.4MWh/m. This value is obtained with an occurrence frequency of 4.2%, for sea states in the range $1.5m \leq Hm0 \leq 2.5m$ and $6.5s \leq Te \leq 8.0s$ (in which Hm0 is the significant wave height and Te is the energetic wave period).

The mean annual energy value, above 1MWh/m, is related to a sea state with an occurrence frequency of 16% and characterized by wave height and periods in the range: $1.0m \leq Hm0 \leq 3.0m$ and $5.0s \leq Te \leq 8.0s$.

The 8 different sea states that were simulated in the wave flume are shown in the Table 1. They are selected from the annual mean energy results obtained in the chosen sites at a water depth of 25m.

Table 1. Target wave parameters of the selected wave attacks

WAVE TYPE	WAVE CODE	Prototype scale H [m]	Prototype scale T [s]
Regular	H01	2	6.0
Regular	H02	2	7.0
Regular	H03	2	10.0
WAVE TYPE	WAVE CODE	Prototype scale Hm0 [m]	Prototype scale Te [s]
Irregular	H1	1	6.5
Irregular	H2	1	7.0
Irregular	H3	2	7.0
Irregular	H4	2	8.0
Irregular	H5	3	8.0

RESULTS

For the simulated OWC configurations, time-histories of incident wave, $\eta_{inc}(t)$, OWC inner water surface oscillation, $\eta_{OWC}(t)$, air velocity at the center of the top cover pipe, $U_{max}(t)$, and air pressure inside the OWC chamber, p(t), were collected at a sample frequency of 20Hz.

Figure 7 shows an example of such time-history for one of the tested OWC configurations, for regular and irregular incident waves, respectively.

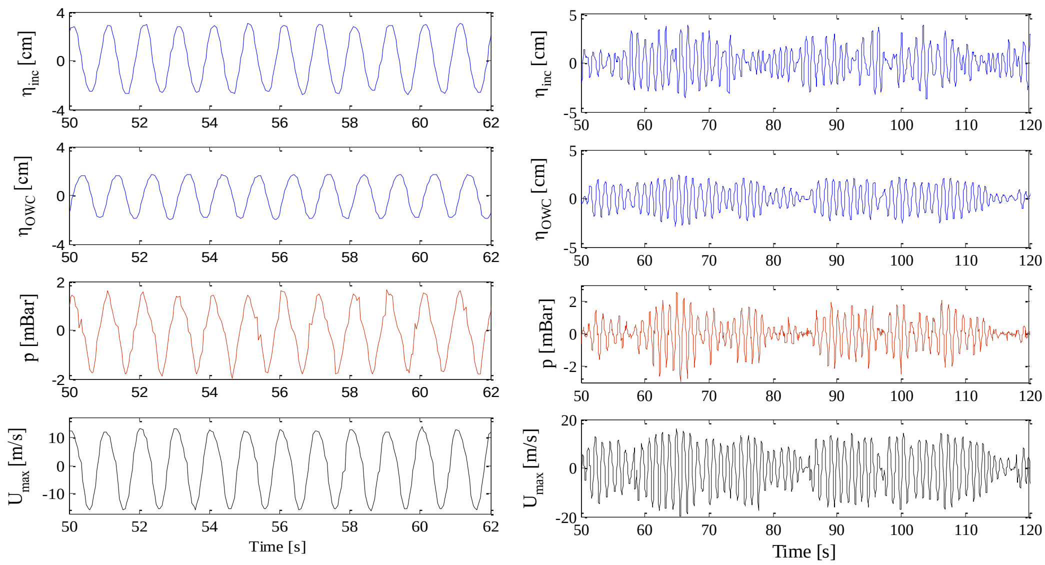

Fig. 7 Time series: inner surface oscillation, η_{OWC} (top), air chamber pressure p (centre) and velocity at the pipe centre U_{max} (bottom). Data are related to the OWC configuration T1L2V2 and incident wave H02 (regular wave with H=4cm and T=1s and wave H5 (irregular wave with H_{m0} = 6cm and $T_{m-1,0}$ = 1.1s).

In the overall simulations performed, measurements of $U_{max}(t)$ and $p(t)$ show maximum values of around 15m/s and 2.5mBar, respectively. The pneumatic conversion efficiency of the device was estimated using these measurements.

Energy conversion efficiency of the OWC device

To evaluate preliminarily the device conversion potential, the mean absorbed pneumatic power was evaluated, for both regular and irregular incident waves.

For regular incident waves, the period averaged incident wave power per unit width [W/m], for a generic water depth h, was computed as

$$\overline{P_{w,reg}} = \frac{1}{16}\rho g H^2 \frac{\omega}{k}\left(1+\frac{2kh}{\sinh(2kh)}\right) \tag{1}$$

where ρ is the water density, H is the regular wave height, ω is wave frequency and k is wave number.

For irregular incident waves, instead, the period average deep water incident wave power per unit width was computed as follows

$$\overline{P_{w,irr}} = \frac{1}{64}\frac{g^2}{\pi}\rho H_{m0}^2 T_{m-1,0} \tag{2}$$

where H_{m0} is the significant wave height and $T_{m-1,0}$ is the mean spectral wave period.

The mean absorbed pneumatic power [W], was estimated by integrating over the duration of records, Ttest, the product of air pressure measurements in the OWC chamber, $p(t)$, and air flow rate, $Q(t)$, (Goda & Suzuky, 1976).

$$\overline{P_{abs}} = \frac{1}{T_{test}} \int_0^{T_{test}} Q(t)\, p(t) dt \tag{3}$$

where, the air flow rate *Q(t)* was derived from the time series of air velocity sampled at the centre of the top cover pipe $U_{max}(t)$. For this purpose, the average velocity along the pipe cross section $U_{average}(t)$ was calculated based on the value of Reynolds number *Re*.

For the cases with $Re < 2400$, a fully developed laminar pipe flow is assumed, hence $U_{average}(t)$ is calculated as half of $U_{max}(t)$. When $Re > 2400$, instead, the flow inside the pipe is assumed to be turbulent and a one-seventh power law (Eq. 4) is used to compute $U_{average}(t)$ from the velocity profile *U(x)* along the pipe radius *R*.

$$\frac{U(x)}{U\,max} = \left(1 - \frac{x}{R}\right)^{\frac{1}{7}} \tag{4}$$

where, *x* denotes the distance from the pipe center.

The OWC averaged pneumatic efficiency is then defined as:

$$\varepsilon = \frac{\overline{P_{abs}}}{\overline{P_W} \cdot W} \tag{5}$$

where, *W* is the OWC width, corresponding to 0.2m in the test model analysed here, and respectively $\overline{P_W}$ denotes $\overline{P_{w,reg}}$ (for regular waves) or $\overline{P_{w,irr}}$ (for irregular waves).

The results obtained for the OWC pneumatic efficiency for the tested OWC geometrical configurations, for regular and irregular waves are documented in Table 2.

Table 2. Pneumatic Efficiency [%] of some OWC geometry tested

WAVE CODE	**Simulated OWC geometry**			
	T1L2V2	**T1L2V3**	**T2L1V2**	**T2L1V3**
H01	11	4	26	15
H02	37	33	67	68
H03	16	5	24	11
H1	34	21	66	49
H2	43	30	74	60
H3	31	25	59	49
H4	34	30	60	49
H5	27	25	37	46

In the regular wave cases (Table 2, wave attacks H01 to H03), the OWC pneumatic efficiency reaches a maximum value of ≈68%, corresponding to the configurations T2L1V2 and T2L1V3 for the incident wave H02. Generally, the four simulated OWC geometries show maximum conversion efficiency for the incident wave H02, which corresponds to a wave period T = 1.1 s. For both lower (which is the case of wave H01) and higher (as for H03) wave periods, the pneumatic efficiency decreases in all the tested configurations.

For fixed values of the front wall draught and the chamber length, decreasing the turbine applied damping from V2 to V3, results in a decrease of the pneumatic efficiency for almost all the considered incident waves (hence, over all the considered range of frequencies).

The OWC configurations with larger chamber length along the wave propagation direction and smaller front wall draught (T2L1 code) show, for all the incident waves, an efficiency almost double than that of the configurations with smaller chamber length and higher front wall draught (T1L2 code).

In the irregular wave cases (Table 2, wave attacks H1 to H5) the pneumatic efficiency reaches a maximum value of about 74%, corresponding to the configuration T2L1V2. Similarly, to the regular wave cases, smaller applied damping (V3 code) results in a decrease of the OWC pneumatic efficiency.

For waves having similar height and periods, e.g. wave H02 and wave H3, the OWC pneumatic efficiency is higher in regular waves than in irregular waves. The relative difference between pneumatic efficiency in regular and irregular waves varies between 10 and 30%, approximately.

OWC resonant frequency estimation

The OWC device performance, in terms of energy harvesting, may be increased by tuning the device to the frequency of the incident wave associated with the highest annual energy in a particular location. The natural resonance frequency of the water column inside the OWC is a function of multiple parameters, i.e. geometry, air chamber volume, turbine damping.

The characteristic resonance frequency of each OWC device was investigated. These tests were performed in absence of the wave attacks and imposing, by means of air suctioning, a free surface level inside the OWC chamber higher than the external still water level. The air was sucked from the duct on the OWC roof then the duct was opened, allowing the water column, through its natural oscillations, to reach the equilibrium state. The measured oscillation was analysed in frequency domain in order to highlight the resonant frequency.

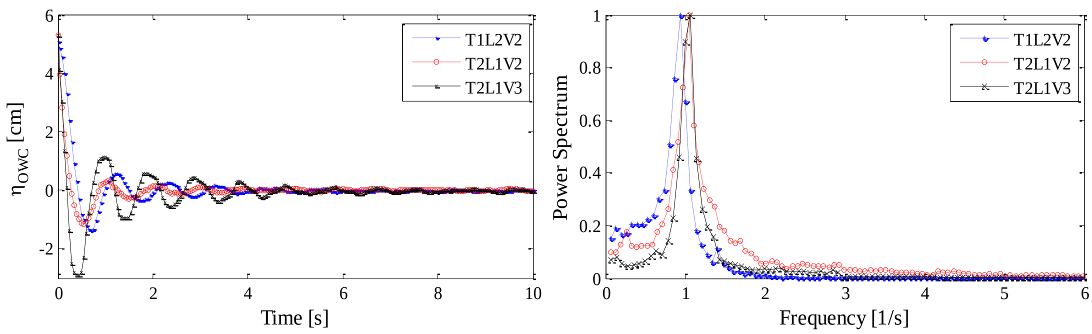

Fig. 8 Time series of water level oscillation inside the OWC chamber for resonance test and Fast Fourier transform spectra of the induced surface oscillation for the OWC configurations T1L2V2, T2L1V2 and T2L1V3

The results obtained by setting an initial inner water level 0.05m higher than the SWL are reported in Figure 8 for the OWC configurations T1L2V2, T2L1V2 and T2L1V3. A Fast Fourier Transform (FFT) is applied on surface elevation data to individuate the resonance frequency.

For the configuration T1L2V2, a resonance peak at the frequency 0.96Hz is obtained. For the configurations T2L1V2 and T2L1V3 (which only differs for the value of the applied turbine damping, bigger for the first) resonance peaks corresponding to 1.06 and 1.04 Hz are obtained, respectively. The power spectrum bandwidth is, however, remarkably narrower in the case of T2L1V3 (so, for the smaller values of the applied damping).

The resonance peaks estimated from resonance tests are in good agreement with the results concerning the OWC pneumatic efficiency: maximum values of efficiency were observed for incident wave periods T close to 1s (hence corresponding to a frequency of about 1Hz).

CONCLUSIONS

In the presented work, the experimental methodology and set-up of a laboratory test campaign to assess the wave energy conversion efficiency of OWC devices to be installed on floating platforms were presented.

Preliminary results of pneumatic conversion efficiency obtained for different configurations were presented (i.e. varying the OWC lip draught, the chamber length in wave propagation direction, and the aperture of the orifice used to mimic the PTO system damping).

Both regular and irregular waves were tested. The reference waves used in the preliminary test are representative of a Mediterranean wave climate, hence the preliminary analysis presented are the first step on a site specific optimization of the OWC device geometry.

The OWC resonant frequency was estimated performing specific resonance tests, and the indication of a natural frequency of about 1Hz was obtained for the different configurations tested.

The pneumatic efficiency of the device for regular waves reaches the maximum value at 68%, showing a strong dependency upon both the frequency of the incident wave and the geometric characteristics of the OWC. This result confirms the importance of performing site specific optimizations of the OWC device. For irregular waves, the maximum pneumatic efficiency is 74%. It has to be emphasized that the tested irregular waves have mean spectral wave periods $T_{m-1,0}$ varying in a narrower range around the OWC resonance frequency compared to the regular waves. For this reason, particularly low efficiencies were not observed in irregular waves.

The effect of the turbine damping results to be relevant as well, influencing both the system frequency response and the overall conversion efficiency. The importance of performing a combined optimization of the OWC geometry and of the turbine damping is, hence confirmed.

Although the assessment of the interaction between the OWC chambers is a relevant aspect in multi-chamber OWC devices, this is not an objective of the present work.

Air compressibility may have a relevant influence on the performance of OWC wave energy converters (e.g. air compressibility spring like effects may imply multiple resonance peaks for a given device geometry (Lovas, 2010). Froude similarity, which is applied in this study, lead to recognized bias in air compressibility scaling (Braeunig et al., 2009). Specific researches, combining both numerical simulation and physical tests, are going on to take in to account and properly evaluate these aspects.

REFERENCES

Braeunig J.-P., Brosset L., Dias F., and Ghidaglia, *Phenomenological study of liquid impacts trough 2D compressible twofluid numerical simulations*. Proceedings of 19th International Offshore and Polar Engineering Conference, June 21-26, Osaka, Japan, 2009.

Dizadji N. and Sajadian S.E., *Modeling and optimization of the chamber of OWC system*, Energy 36 – pp.2360-2366 Elsevier, 2011.

EurOtop Manual, *Wave Overtopping of Sea Defenses and Related Structures: Assessment Manual.* Die Kuste, 2007.

Evans D., *The Oscillating Water Column Wave-energy Device*. J. Inst. Maths Applies, 423-433, 1978.

Goda Y. and Suzuki Y., *Estimation of incident and reflected waves in random wave experiments*, Proceedings of 15th Conference on Costal Engineering - ASCE, 828-845, 1976

Lovas S., *Theoretical modeling of two wave-power devices*. Master Thesis, Department of Civil and Environmental Engineering MIT, 2010.

Morris-Thomas M., Irvin R. and Thiagarajan K. *An investigation into the hydrodynamic efficiency of an oscillating water column*. Journal of Offshore Mechanics and Arctic Engineering Transactions of the ASME; 129:273-278, 2007.

Ram K., Faizal M., Ahmed M. and Lee Y. H. *Experimental studies on the flow characteristics in an oscillating water column device*. Journal of Mechanical Science and Technology; 24:2043-2050, 2010.

Sarmento A., *Wave flume experiments on two-dimensional oscillating water column wave energy devices*. Experiments in Fluids; 12:286-292. 1992.

Sarmento A., *Model-Test Optimization of an OWC Wave Power Plant*, International Journal of Offshore and Polar Engineering, pp. 62-62, 1993.

Sheng W., Lewis T., Alcorn R., *On wave energy extraction of oscillating water column device*. ICOE, Dublin 2012.

Sheng W. et al., *Investigation to air compressibility of oscillating water column wave energy converters.* OMAE2013-10151. Nantes, France, 2013

Simonetti I., Cappietti L., ElSafti H., Oumeraci H.. *Numerical Modelling Of Fixed Oscillating Water Column Wave Energy Conversion Devices: Toward Geometry Hydraulic Optimization*, Proceedings of the ASME 34th International Conference on Ocean, Offshore and Arctic Engineering OMAE2015, 2015, accepted, 2015.

Suroso A., *Hydraulic Model test of Wave Energy Conversion*. Jurnal Mekanikal, No. 19, 84-94, 2005.

The Carbon Trust, M. E. *Oscillating Water Column Wave Energy Converter Evaluation*. Report. ARUP e-on 2005.

Vannucchi V., Cappietti L., *Wave Energy Estimation In Four Italian Nearshore Areas*, Proceedings of the ASME 2013, 32nd International Conference on Ocean, Offshore and Arctic Engineering OMAE2013 June 9-14, Nantes, France, 2013.