ISBN: 978-92-990075-2-5

6th EnvImeko - IMEKO TC19
Symposium on Environmental Instrumentation and Measurements
June 24-25, 2016, Reggio Calabria, Italy

PULSATING FLOW DISCHARGE MEASUREMENTS INSIDE A WAVE ENERGY CONVERTER AT SEA

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Abstract: This paper describes an original technique adopted for measuring the water discharge flowing inside a Wave Energy Converter (WEC) device. The investigated system represents a small scale model of a plant belonging to the family of Oscillating Water Columns (OWCs). Measuring the pulsating water discharge through the plant is necessary for calculating the absorbed wave energy. Conventional measurements techniques are not applicable to this case, due to the large size of WEC conduits and the harsh operational environment.

The technique adopted to measure the pulsating water discharge inside the WEC is based on the estimation of particle acceleration inside the water column, starting from simultaneous pressure measurements along the streamline. The effectiveness of the method is checked by measuring the instantaneous position of the air-water interface inside the plenum.

Keywords: alternating flow, OWC, water discharge, in field measurements.

1. INTRODUCTION

REWECs are caisson breakwaters embodying a wave energy absorber. They were introduced by Boccotti [1, 2] and deeply investigated both theoretically ([3, 4]) and experimentally ([5, 6]). A 1:10 scale model of an ocean OWC breakwater was realised and put at the sea off the beach of Reggio Calabria (Italy). The breakwater (about 16 m long and 3.5 m height) was placed on a 2.1 m bottom depth, and embodied a release of REWEC conceived for port defence. Aim of the experiment is to test the energy absorption capabilities of the system and to analyse the waves-absorber interaction mechanism. Achieving this objective involved some measurements made critical because of the harsh environment, the high variability of randomly oscillating flows and unavoidable scale effects. In the next Sections of the paper, it is shown how these operational difficulties were overcome by developing " ad hoc" measurements techniques.

In particular, this paper is focused on a critical measurement: the water discharge through the plant, necessary to estimate the absorbed power. Discharge measurements of pressurized fluids flowing inside closed conduits is never a trivial task, because the discharge is a measure intrinsically extensive by definition. Well established devices for the measurement of steady flow include differential pressure flow meters, electro-magnetic and ultrasonic flow meters, vortex shedding flow meters, hot wire anemometers, etc. The exact, time resolved measurement of pulsating flow, on the other hand, still poses great problems. Hot wire anemometers can provide accurate results for pulsating flow up to extremely high frequencies [7], but their use is limited to clean flow. The use of orifice plates for the measurement of unsteady flow is often discouraged. Nevertheless, some effort has been made by various authors to investigate and establish the use of orifice plates for the measurement of pulsating flow. A review of work done in this field and the outline of limits of applicability of existing theories was made by [8].

Measurements carried out in the REWEC conduits were carried out by using two different techniques, in order to make them robust. In fact, Water discharge were calculated by integrating the particle acceleration of the water column, by recording the pressure simultaneously in different point along the streamline. This punctual measurement was compared with measurements carried out by an ultrasonic probe located on the roof of the plenum chamber. Because of the width of the sound beam, this measurement is space averaged.

2. THE EXPERIMENT AT SEA

2.1 Description of absorber breakwater

The breakwater put off the beach of Reggio Calabria was 16.3 m long, and it was realized by nine caissons close, one to each other (Fig. 1). Each caisson consists of three interconnected cells, in that air can flow from one cell to another of the same caisson (the air flows through holes H in Figure 2). The central caisson is equipped with a small scale prototype of Wells turbine without guide "ad hoc" designed to be coupled with the breakwater. The blades were manufactured in composite material reinforced by carbon fibre and were attached to the hub with a stagger angle of 90 deg.

The permanent magnet DC motor joined to the shaft of the turbine had a double function: it was operated as a power generator when pneumatic power of the air flow was high enough to allow the turbine to produce energy, and behaved as a motor when it was necessary to start the turbine (this is

ISBN: 978-92-990075-2-5

not to able to self start) and when it was necessary to support it because the pneumatic power was not sufficient to ensure the rotation speed set-up.

2.2 Measurement of the mean energy flux absorbed by the plant

The mean effective energy flux absorbed by a single cell was obtained from

$$\Phi_p = \left(\Delta p + \rho \frac{Q_p^2}{2b^2 s'^2} \right) Q_p \tag{1}$$

where Δp is the pressure fluctuation at the mouth of the vertical duct and Q_p is the volumetric flow rate entering in the cell (assumed positive when entering the plant)

$$Q_p = -bs'' \frac{d\xi}{dt} . \tag{2}$$

The mean energy flux absorbed by one cell may be re-written in the form

$$\overline{\Phi}_p = \frac{1}{T} bs'' \left[\Delta p(0)\xi(0) - \Delta p(T)\xi(T) + \int_0^T \xi(t) \frac{d\Delta p_w}{dt} dt \right] \tag{3}$$

where Δp_w is the wave pressure fluctuation on the outer opening of the vertical duct, obtained by means of a pressure transducer at the centre of this opening.

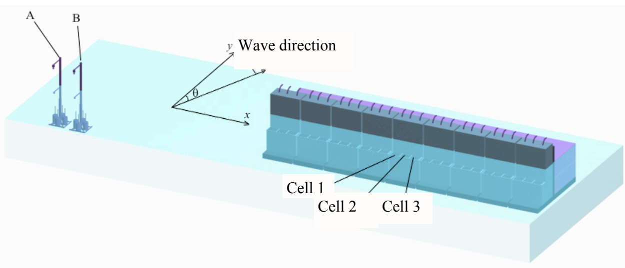

Figure 1 - Experimental apparatus. Piles A and B supports gauges or measuring the wave energy flux in the undisturbed field. Cells 1, 2 and 3, belongs to the central caisson of he breakwater and are instrumented for measuring the absorbed energy.

For obtaining $\zeta(t)$ we used three pressure transducers (see Fig. 3). Two transducers A and B were placed inside the oscillating water column, the third one (transducer C) was in the air pocket. The actual height ζ of the water column proceeds from acceleration $a = (p_A - p_B - \rho g h)/(\rho h)$ calculated from the pressure difference between point A and point B and the pressure difference between point A (or B) and point C:

$$\zeta = \zeta_1 - \frac{p_A - p_C}{\rho(g + a)} \tag{4}$$

For checking the results, in cell 2 (the central one) we had a direct measurement made by a ultrasonic probe, and in cell 3 we had a fourth pressure transducer (D) so that we obtained ζ by means of two triplet: A,B,C and B,D,C.

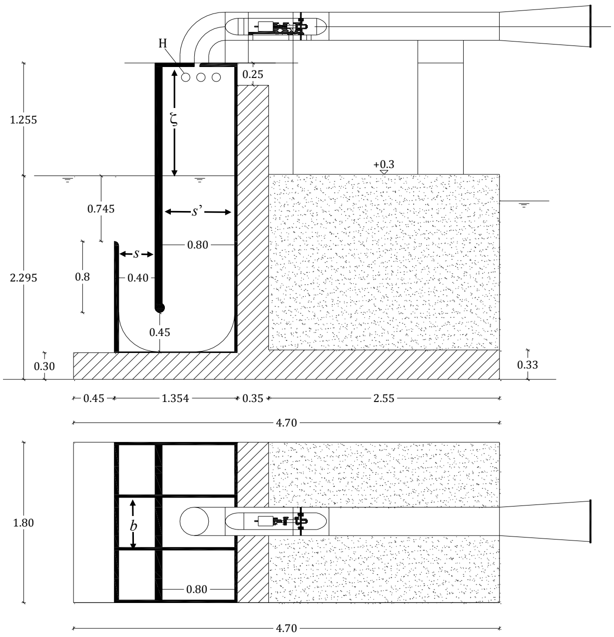

Figure 2 -The central caisson of the absorber breakwater where was installed the turbine. [measures are in meters and referred to the m.w.l.]

2.2 Measurement of the available pneumatic power

The pneumatic power P_p generated by the air flow rate Q is related to the pressure drop Δp_0 across the turbine

$$P_p = Q\Delta p_0 . \tag{5}$$

During the experiment on the REWEC system, the Wells turbine was operated under the action of the highly irregular air flow produced by the oscillating water level inside the chamber of the REWEC. Neglecting the effects of the compressibility of the air, the volumetric air flow rate Q crossing the turbine was assumed equal to the sum of the flow rates Q_p estimated from the fluctuations of the water level inside the three cells, as described in the previous sub-section.

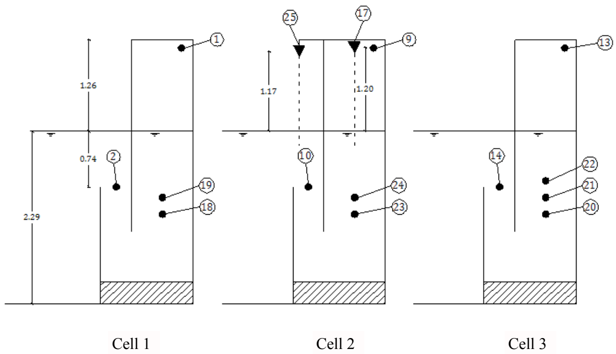

Figure 3 – The three cells of the central caisson equipped with gauges (indicated with numbers) for measuring the absorbed energy.

Since we had three interconnected chambers (only the central one being connected to the air duct of the turbine), we evaluated the volumetric flow rate as

$$Q = \sum_{i=1}^{3} Q_i = \sum_{i=1}^{3} A_i \frac{d\zeta_i}{dt} \qquad (6)$$

where A_i and ζ_i are the surface area and level of the water, respectively. Since the transfer of air from the lateral chambers to the central one is obtained through ports of known area and air pressure was recorded in all the chambers, it was possible to check the air flow rate Q_i (i=1, 3) from the lateral caissons to the central one from

$$Q_i = \pm C_D A_{p,i} \sqrt{2\frac{|p_i - p_c|}{\rho_a}} \qquad (7)$$

where $A_{p,i}$ is the geometric area of the port, C_D is the discharge coefficient, p_i-p_c is the pressure difference between the lateral caisson and the central one and, finally, ρ_a is the air density. Sign + in Eq.(7), is used if $p_i > p_c$ (air leaving the lateral caisson), while the sign – is used when $p_i < p_c$ (air entering the lateral caisson).

During the experiment, we recorded 261 sea states (each lasting five minutes); 73 records of wind waves, 61 records of wind waves superimposed on swells, a sequence of 95 records of swells of average T_p about 4 s, and a sequence of 32 records of swells of average T_p about 7.5 s.

Figure 4 shows the time plots of the flow rates obtained through the two above explained methods: it appears a very good agreement between the two records, confirming the reliability of the method adopted for evaluating the discharge.

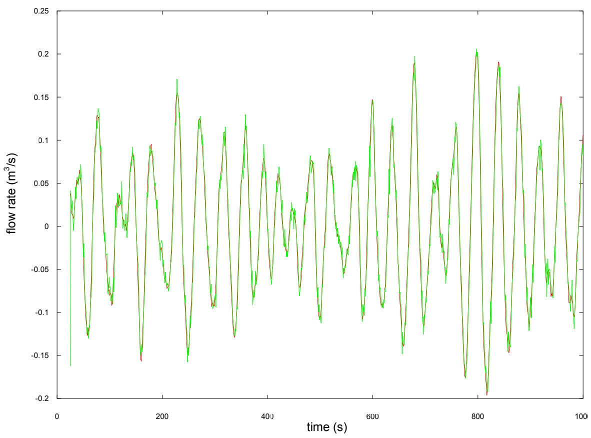

Figure 4 – Measurements of air flow rate from water level (red line) and pressure measurements (green line).

Figure 5 shows time records of pressure in the three connected cells. It appears that the simultaneous values of pressure are about equal one to each other. A small pressure drop from the lateral chambers to the central one is observed when the pressure reaches the positive peaks while, vice versa, a drop from the central chamber to the lateral ones when the pressure reaches the negative peaks: such pressure drop is due to the pressure losses caused by the air flowing through the ports connecting the three chambers. The very small pressure drop between the connected chambers confirms that the assumptions that the compressibility effects are negligible is absolutely acceptable.

It is worth noting also that, otherwise what happens in the conventional OWC [9], there are not significantly differences in shape and amplitude of the fluctuations between the time in which the air is pumped out of the chamber and the time the air is aspired.

Figure 6 shows the time plots of the air flow for the three chambers during the same time interval considered in Figure . It appears that the simultaneous values of flow rate are about the same in the three cells.

The time plot of the pneumatic power produced in the time interval is given in Figure 7. It appears that the frequency of the power oscillations is doubled with respect to the frequency of oscillation of pressure and flow and peaks of power reaches the value of hundreds of watts while the average power is much lower.

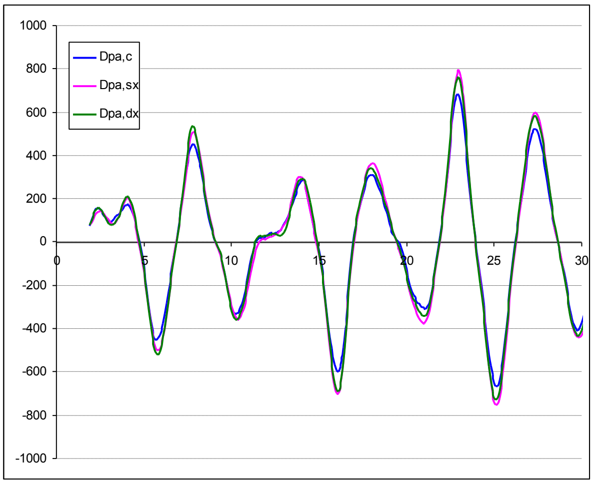

Figure 5 – Time plots of pressure inside the three chambers of the REWEC system. Pressure in mmH2O and time in seconds. (Dpa,c: central chamber; Dpa,sx: left side, Dpa,dx, right side).

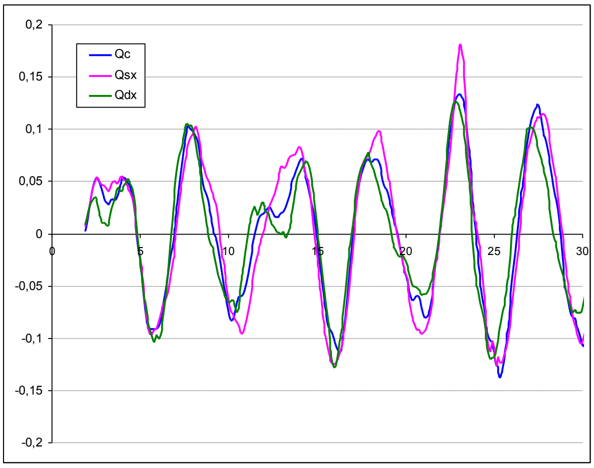

Figure 6 – Time plots of the air flow produced by the three chambers. Air flow in m^3/s and time in seconds. (Qc: central chamber; Qsx: left side, Qdx: right side).

ISBN: 978-92-990075-2-5

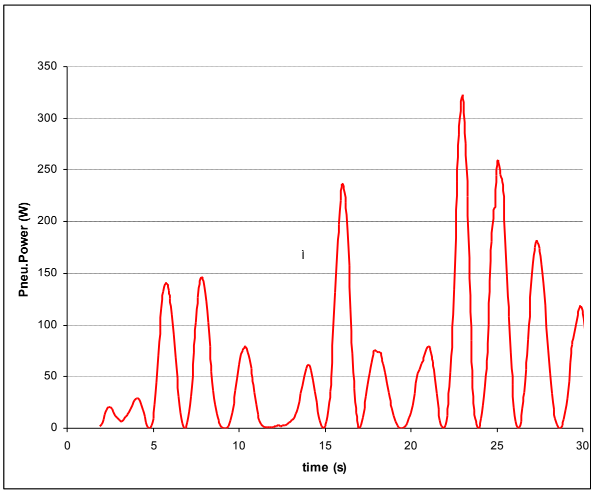

Figure 7 – Time plot of the pneumatic power.

3. CONCLUSIONS

The paper describes the methodology used for measuring the pulsating flow rate produced by waves inside an Oscillating Water Column, during an experiment carried out at sea on a small scale device. The plant was equipped with a monoplane Wells turbine without guide vanes, and the measurement technique adopted permitted to evaluate the power absorbed and to characterize the unsteady behaviour of the turbine. Conventional measurement techniques used in controlled environment with clean fluids are not suitable in a harsh environment like sea. Moreover, the flow rate inside the device pulsates with the same frequency as the incident wave period, that is between 0,125 and 0,4 Hz.

We achieve the mean velocity by integrating the acceleration of the moving column of fluid. The effectiveness of the results was checked resorting to a second measurement, based on the derivation of the instantaneous value of the water-air interface inside the chamber of the OWC.

In this paper it is shown that the measurements of flow rate based on the measurement of water level inside the chamber give very good results as shown by the comparison of the flow rate through the connecting holes.

In conclusion, the described methodology appears to be reliable and suitable to give accurate results about the unsteady behaviour of the turbine, notwithstanding the difficulties related to take measurements under real sea wave conditions.

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