A WAVE-2-WIRE EXPERIMENTAL INVESTIGATION OF THE NEW "SEABREATH" WAVE ENERGY CONVERTER: THE HYDRAULIC RESPONSE

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In view of a potential design of a 2 kW small scale prototype of a wave energy converter named Seabreath, the dimensioning of the power take off, generator and relative electrical equipment is under investigation. This note presents an innovative research focusing on a holistic description of the behaviour of this device. Within a Marinet application (FP7 Research Infrastructure Action) named "Multi-chamber oscillating water column device for harvesting Ocean Renewable Energy" (MORE), electrical experiments have been carried out in the "hardware in the loop" test bench in Tecnalia laboratory, Bilbao, in order to test different control strategies. For these experiments, the Electrical and hydrodynamic response need to be fully coupled. The note describes how the available hydrodynamic model of the Seabreath has been modified to be coupled to the new electric experiments. Since the electrical tests are being used to calibrate an electrical numerical model, the procedure depicts an innovative and complete type of wave-2-wire model of a wave energy converter.

Keywords: Hardware in the loop; Seabreath; Wave 2 wire model; Wave Energy Converters

INTRODUCTION

A floating wave energy converter (WEC) is formed by several components: the power take off, the electrical system, the mooring system and the structure itself.

The research and development of new WEC devices requires the optimization of each single component in order to maximize the overall efficiency. Clearly, a more correct approach aims at optimizing each component through a holistic approach, in order to optimize the overall performance of the wave energy device (i.e. accounting for all the above mentioned components and for the interactions among them).

Since the eighties, Budal and Falnes (1980) showed that phase control by latching may enhance the wave energy absorption of oscillating bodies, pointing out the importance of a holistic methodology in the study of WECs. In fact, recent projects and scientific works often focus on dynamic interactions, including those between moorings and power take off (PTO). The models based on this approach are called wave-2-wire (e.g. Brito-Melo 2002; Nielsen et al., 2014), in analogy with similar ones regarding wind turbines, named wind-2-wire. A review of these models is given by Kramer and Nielsen (2014).

A W2W model is a numerical tool that can typically offer the following outputs under operating wave conditions:

- time series of the power output;
- fatigue loads on structural components which are exposed to high cyclic loading (mainly on mooring system);
- dynamic prediction of the response of a wave energy converter.

The model is quite suited to compare different Power Take Off (PTO) systems, different control strategies, and the effects of PTO on structure motions and mooring line forces.

Sometime the model extend its capabilities to simulates the device response also under extreme waves, e.g. determining the optimal management of the PTO under such non-operational conditions.

This study focuses on the interaction between the hydraulic and the power-take off responses of a new floating multi-chamber oscillating water column device (M-OWC) called Seabreath (www.seabrteath.it). The scope of the research, started in 2013, is to:

- develop a small scale Seabreath device (2.4 x 6m, formed by 2 chambers) to be placed in fixed conditions (like a jetty)
- choose turbine (around 2 kW)
- choose control strategy

The specific aim of this paper is to investigate on the electrical response of the system in order to establish the best strategy for the generator, in the long term.

The method used to achieve the result consists of a W2W model calibrated on 2 different experiments, hydraulic and electric.

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In particular, this note presents the interface between the hydraulic model and the electrical new experiments (Fig. 1)

The new experiments are focused on the power electronics, acting as interface between the electric generator, the turbine and the grid. The generator and the power electronics are characterized by many controllable parameters, such as the speed, the efficiency, the duty, the generation capacity, the temperature, the output power level and the power quality, so the control strategies can be different. The control may act directly on the power electronics or others components (e.g. controlled valves) of the pneumatic subsystem. The behavior of others parts, such as the turbo-generator and the hydrodynamic.

This note first presents the Seabreath WEC device, with a short description of the working principle. Then, the implementation of the available hydrodynamic model to suite the electrical experiments in a W2W perspective is given. Finally, after a brief description of such experiments, the obtained results are presented. Details of the electrical experiments are not given, assuming the Costal Engineer is not interested, and may be found in Delmonte et al., 2014.

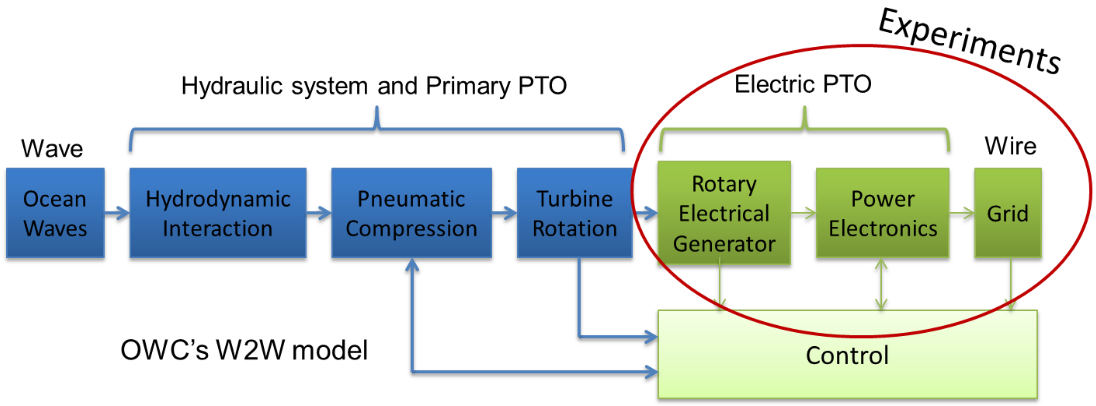

Figure 1 – W2W model.

THE SEABREATH

The Seabreath device, patented by Luigi Rubino, is described in detail in Martinelli et al. (2013). The concept may be easily grasped observing Fig. 2.

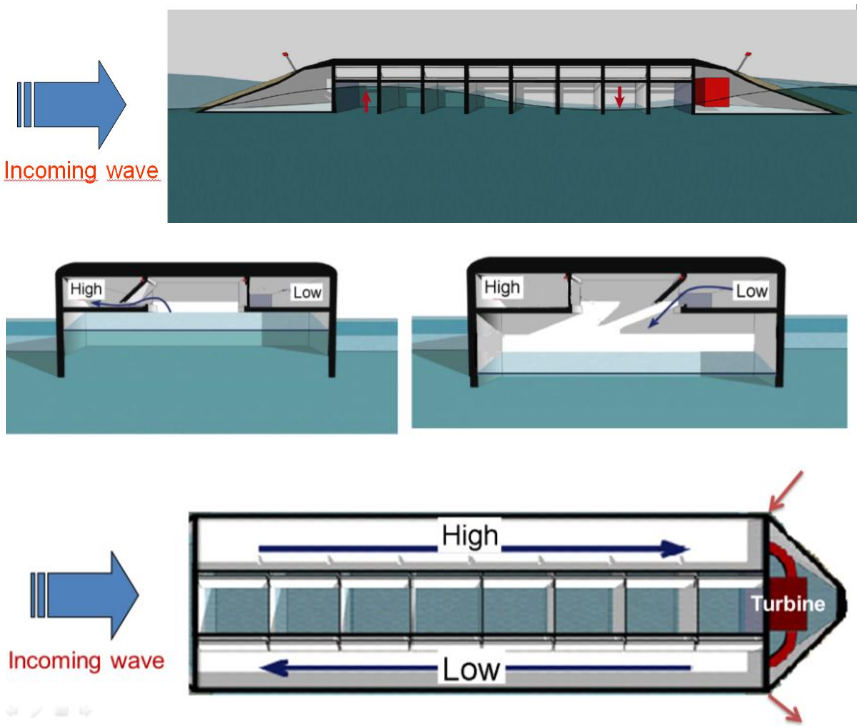

Figure 2 – The Seabreath concept: longitudinal section (top), plan view (middle), cross section (bottom).

Fig.2, top view, shows the longitudinal section of the device. Waves approach from the left and, as they propagate, induce a compression in some of the cells, where the water level tends to increase, and decompression in others, where water level decreases. In the chambers where the water level is high, air is directed by non-return valves into a high pressure duct. Where the water level is low, air is sucked from low pressure duct. Fig. 2, bottom, shows through a the plan view that air flows from the high pressure to the low pressure ducts through a turbine.

The drawings are just rearrangements of the first images present in the website few years ago, and several details are missing, as usually happens in the first stage of the design.

The research carried out in the past two years focuses on the definition of all the missing "details", i.e. the generator (placed behind the turbine) delivering electricity through a power umbilical that follows one of the lines of the mooring system.

THE HYDRAULIC MODEL

The proposed hydraulic model is an application of the numerical model described in Martinelli et al. (2013), specifically formulated to describe the air flow within a Seabreath of any geometry. The numerical approach was developed and calibrated on the basis of physical model tests carried out in the Wave Flume of ICEA Department, Padova University, on a 1:60 reproduction of a Seabreath with 4 chambers.

The basic hypotheses are:

- Quasi-stationary conditions;
- Constant density of air;
- Evaluation of losses and transfer function $\tau(\omega)$ based on small scale tests.
- Fixed structure with 2 chambers;
- Given relation between discharge and pressure drop at the turbine.

An experimental transfer function was derived between the incident wave and the hydraulic head within each of the 4 chambers of the tested device. More specifically, the head is:

$$h=\eta + p/\rho g \qquad (1)$$

$$\tau(\omega) = h(\omega) / H_{inc}(\omega) \qquad (2)$$

Where h = hydraulic head, η = water elevation, p = pressure, H_{inc} = incident wave, ω = wave frequency, τ = experimental transfer function given in Fig. 3.

It was found that the experimental transfer function could allow to predict the hydraulic head in the chambers in two extreme conditions: when the chambers are fully open above and when there is no or little flow out of the chambers (close chambers). In fact in these two cases, the incident wave oscillations are transformed into elevation (h) or pressure oscillations ($p/\rho g$), respectively (cfr. Eq. 1).

Fig. 3 shows that the $\tau(\omega)$ complies with two expectations:

- $\tau(\omega)$ is larger with longer wave periods
- $\tau(\omega)$ is larger for the front chamber and lower for the rear one

It is well known that the PTO affects the nearby hydrodynamics. Nevertheless, the developed numerical model aimed at describing the air flux through the turbine, and did not try to describe the coupling effects between turbine and hydrodynamic response.

A second weakness of the hydraulic model lies in the oversimplification of the model of the turbine, that is assumed to work in ideal conditions, although the probability to work in such conditions is small. The actual response of the turbine is unknown, and the consequences of this uncertainty may well be anticipated: even before the description of the hydrodynamic model, it may be understood that head loss induced by the turbine is a key factor for the evaluation of the total air flux, and therefore of the produced energy.

In simple words: the overall turbine response depends on the shaft speed, which varies in time: how can we predict the output current in absence of a tool to predict the shaft speed?

In order to model the turbine response, it is necessary to model also the generator that is attached to the same shaft, together with a control strategy. In conclusion a coupling between the hydraulic and electric modeling is indispensible to try to describe the real working conditions of the wave energy converter.

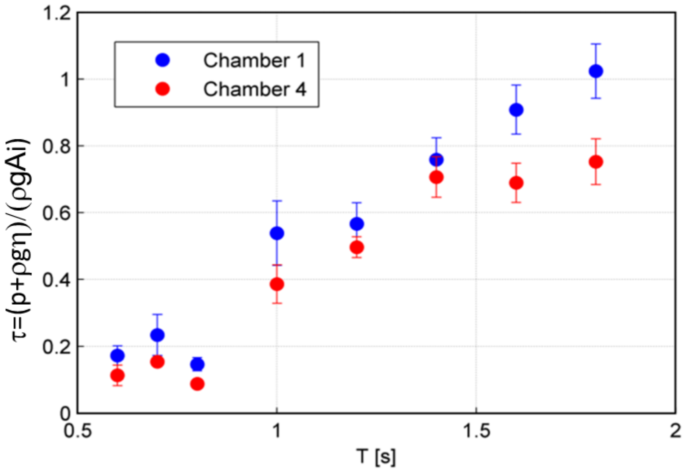

Figure 3 – The experimentally supplied transfer function τ(ω) (Martinelli et al., 2013)

The flow of air is solved a typical system of pipes (Fig. 4) where the unknowns are discharges along the pipe and pressure at the nodes. Typical equations are used: continuity, head balance (inlet) or momentum balance (outlet) in order to define the "system" curve, and a give "turbine curve" describing the head loss through the turbine. The main problem is due to the non-linearities due to the head losses and, primarily, to the presence of non-return valves, that require a special attention.

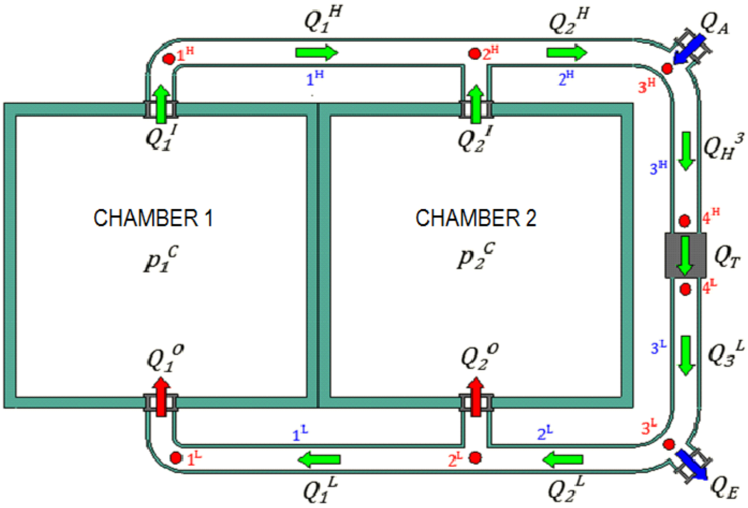

Figure 4 – Scheme of the pipe system, with unknowns used in the model

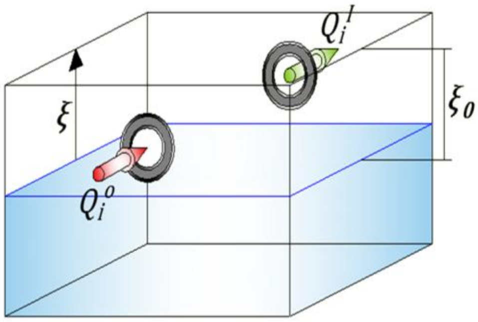

Figure 5 – Boundary condition: within each chamber, mass balance imposes a condition between discharge, pressure and water level,

Boundary conditions are given in each chamber in terms of the head *h* (as obtained by the transfer function, see Fig. 3), or more specifically in terms of the two component that form the hydraulic head (elevation η and pressure *p*): the subdivision on the two components is obtained evaluating η by continuity arguments, see Fig. 5).

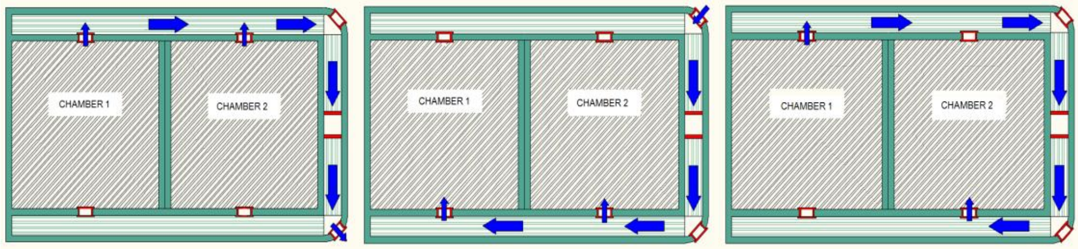

Figure 67 – Possible working conditions: case 1 (left), case 2 (middle), case 3 (right)

Typical model output is presented in Fig. 8, showing the pressures in the chambers and in the node just out of chamber 1, and in Fig. 9 showing the discharge through the turbine.

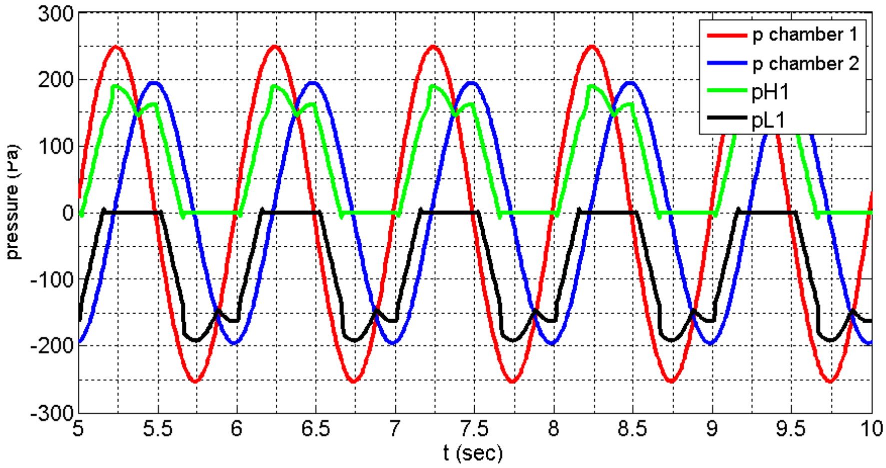

Figure 7 – Example of simulated pressure output under regular waves

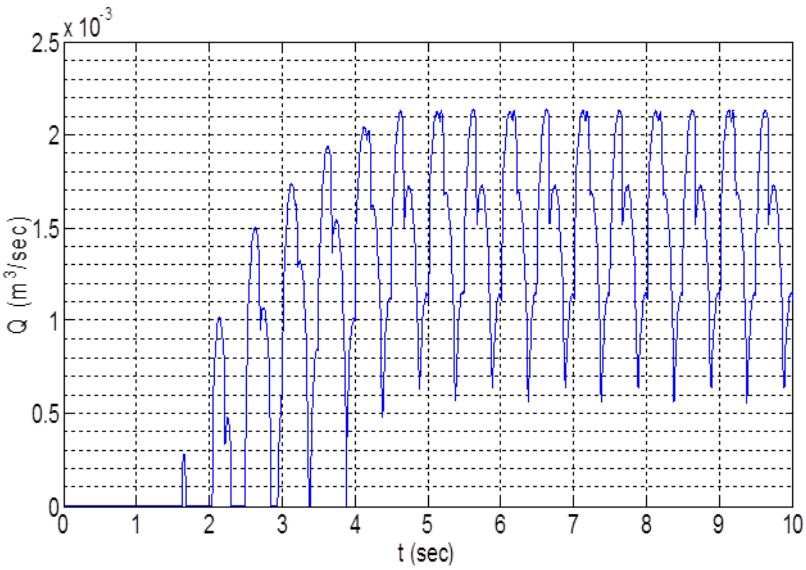

Figure 8 – Example of simulated discharge through the turbine, under regular waves, with transitory phase.

In order to get the real solution in the strong non-linear context, for every time step, specific solutions are searched for, in this order:

- Case 1: chamber 1 and/or chamber 2 have a pressure larger than atmosphere. The flow condition is depicted in Fig. 7, left: the air flows from chamber 1 and/or 2 through the turbine and exit to atmosphere.
- Case 2: chamber 1 and/or chamber 2 have a pressure lower than atmosphere. The flow condition is depicted in Fig. 7, middle: the enters the system from atmosphere, flows through the turbine and enters in chamber 1 and/or 2.

- Case 3: chamber 1 has a pressure larger than chamber 2, and the pressures in the chambers are respectively larger and smaller than atmosphere. The flow condition is depicted in Fig. 7, right: the air flows from chamber 1 through the turbine to chamber 2. The opposite case, i.e. a larger pressure in chamber 2, is handled in a very similar manner.

Hydraulic numerical model: coupling with wave pattern

Experiments carried out within Theseus FP7 project (www.theseusproject.com) aimed at investigating hydrodynamics around the Seabreath device in case of closed air circuit (passive response) and in case of actual work done by the air flow (active response). Fig. 4 shows the results in terms of wave reflection, wave transmission and wave dissipation (obtained on the basis of energy balance) and it is clear that wave transmission is 5% lower in active PTO configuration, i.e. when the WEC produces energy. It may also be observed that dissipation is larger in the active PTO configuration, whereas wave reflection has a behavior dependent on the peak period of the incident wave attack.

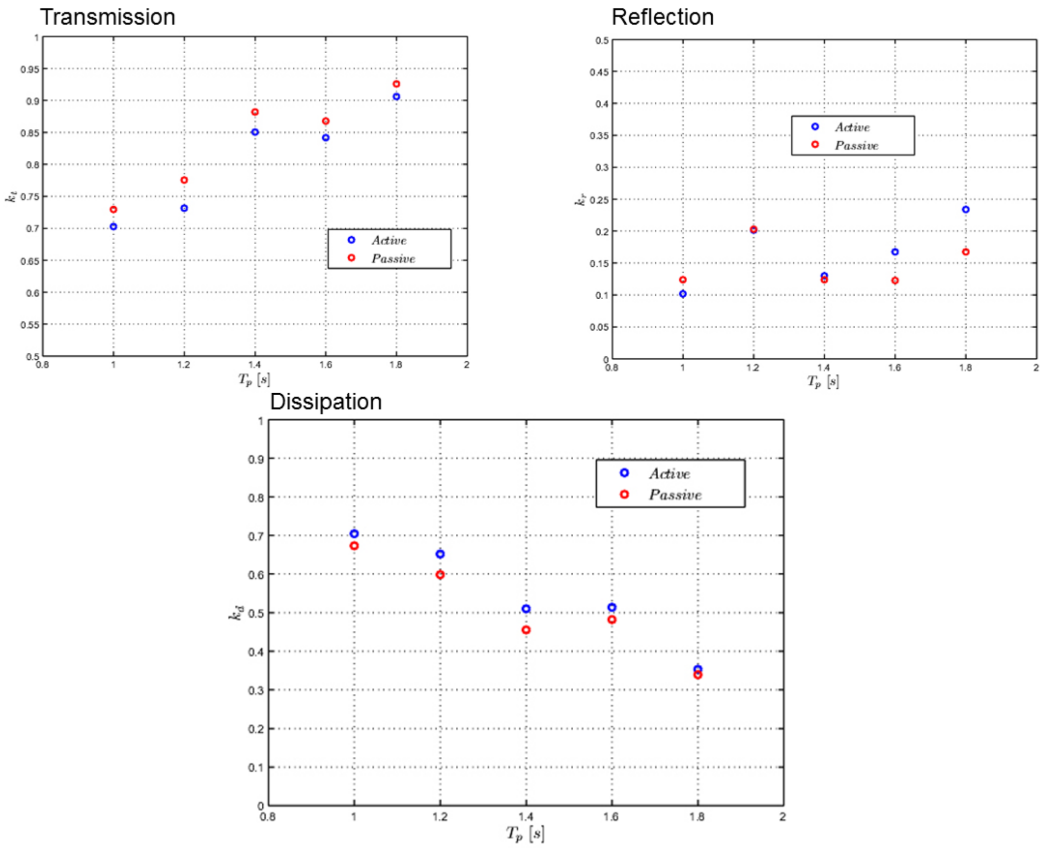

Figure 9 – The effect of the PTO on the overall hydrodynamics – www.theseusproject.com

The experimental transfer function $t(\omega)$ was related to two cases where no «work» was done, no energy produced, and therefore it is not surprising that the same $\tau(\omega)$ was found for both extreme cases.

Unfortunately, due to an under design of the non-return valves, it was impossible to test the device under a sufficiently wide working conditions. In fact, in case there is a large air flow through the chambers, it is expected that the transfer function $\tau(\omega)$ also changes. But the reduced range of conditions did not allow a general investigation of the transfer function.

In the perspective of an analysis of the interactions between PTO and system dynamics with the model that describes the Seabreath performance, it was essential to have a mechanism that can qualitatively simulate the effects of the PTO, and therefore of different flows through the chambers, on $\tau(\omega)$.

The assumed mechanism is that the «work» done by pressure is modeled as an additional symmetric and antisymmetric oscillation in the chambers, fitting experimental reflection, transmission, dissipation (cfr. Fig. 10). Basically, the chambers act as wave generators, and produces waves in phase or phase opposition depending on the pneumatic power at the turbine, of amplitude calibrated on the basis of Fig. 9, where the produced power was approximately 1/5th compared to the device modeled here.

This mechanism is particularly convenient, as it fits with the proved effects of the PTO on wave transmission, reflection and dissipation. If the device does not produce energy, the effect of closing the valves is merely a modification of reflection and transmission compared to the case of fully open chambers, whereas if the PTO produces some energy, some of the incident energy will be absorbed.

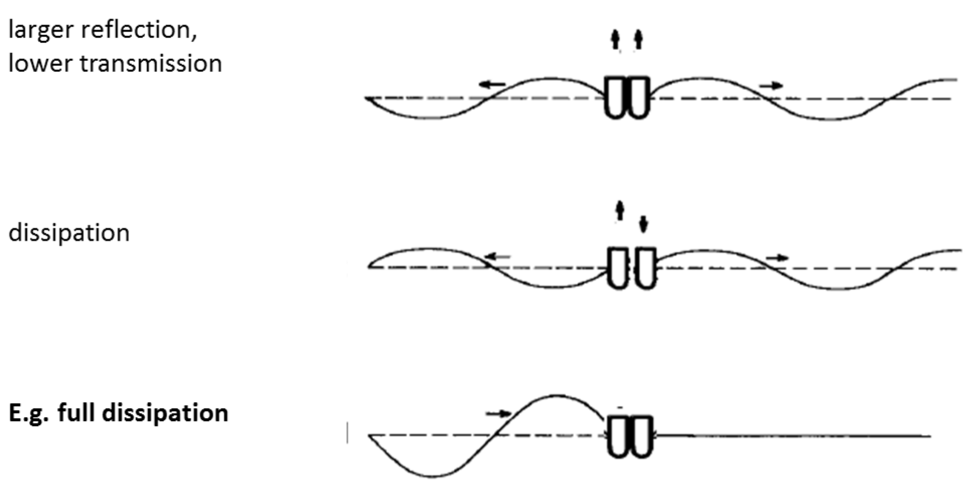

Figure 10 – The concept: the chambers are able to radiate waves in phase and phase opposition

Hydraulic numerical model: coupling with turbine

The head loss through the turbine does not depends only on the discharge but also on the rotational speed of the shaft. Unfortunately, the available hydraulic model does not consider the actual rotational speed, assuming an unrealistic reference curve derived on the "optimistic" hypothesis that the rotational speed is always the optimal one, i.e. the "red" curve in Fig. 10. It goes without saying that in order to define a control strategy, a different approach is needed.

Simulation of the rotational speed of the turbine is complicated by the presence of the generator, attached to the same shaft. Clearly, the shaft will generally rotate faster as a consequence of the turbine conversion between pneumatic to mechanical energy, and rotate slower in consequence to the torque applied by the generator, that converts mechanical energy into electricity. In some cases, however, usually in order to increase efficiency or to reduce extreme loads, it may be convenient to use the generator as an engine, and spin the shaft. Similarly, it may be decided to break the rotor without extracting energy, to reduce possible the power peaks that are larger than design and may risk to damage the electrical equipment.

The modification of the hydrodynamic model to include the coupling with the turbine was straightforward, since once the rotational speed is approximately known, an accurate turbine behavior can be obtained with simplicity based on the turbine characteristic curves. The model was run in time domain, with an explicit scheme, using as input the rotational speed of the shaft of the previous time step. Clearly, such input is derived by the electrical (physical or numerical) model.

Two turbines were tested, whose non-dimensional characteristic are given in Delmonte et al. (2014). The simulated turbines proved to be not totally suited to the requirements, and in fact a new set of tests has been planned in a second (already approved) Marinet access.

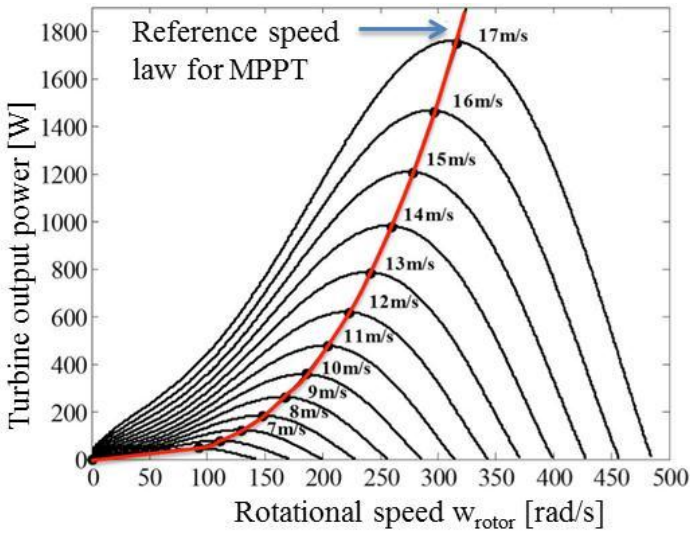

Figure 11 – Relation between rotational speed of the turbine rotor, power output and air flow velocity.

Hydraulic numerical model: application

The structure under exam is studied in fixed configuration, formed by two square chambers with 2 m side, suffit placed 1 m above the msl, drought of the chambers 1 m below msl. The air conduits have diameter 0.4 cm.

Although the model is suited to run both regular and irregular wave conditions, only regular waves were tested (See tab. 1) to simplify the result interpretations in a first phase.

Table 1 Regular wave attacks

Wave	H (m)	T (s)
1	0.6	3.1
2	0.8	3.6
3	1.0	4.0
4	1.2	4.4
5	1.4	4.7
6	1.6	5.1

The results of the applications are available at each time step, once the actual rotation of the turbine is obtained by the electric (physical or numerical) model. An example of the result is visible in Fig. 13. All results are given in the final report of the tests, Delmonte et al. (2014).

THE ELECTRICAL MODEL

Tests

The tests studying the electrical power take off (PTO) were carried out in the electical laboratory of Tecnalia in Bilbao, using a test bench equuipped with a Hardware In the Loop (HIL) consisting of the system presented in Fig. 12.

In the bench, one engine emulates the air turbine of the Seabreath, driven by a frequency converter (AC/AC converter) controlled by a personal computer on the basis of the hydraulic model described above, run through a symulink function.

The generator in mounted on the same shaft of the engine. The interface between the generator and the electric is a AC/AC back-to-back converter, controlled a PLC. Through the PLC, different control strategies can be implemented, changing the speed and the torque, usually with the objective of maximising the maximum energy, for any incident wave condition.

The control system may define a desired or “design” shaft rotational speed, based on the air flow velocity. A typical strategy is implemented by an algorithm that uses a target curve based on the rotational speed that gives maximum power (Maximum Power Point Tracking o MPPT).

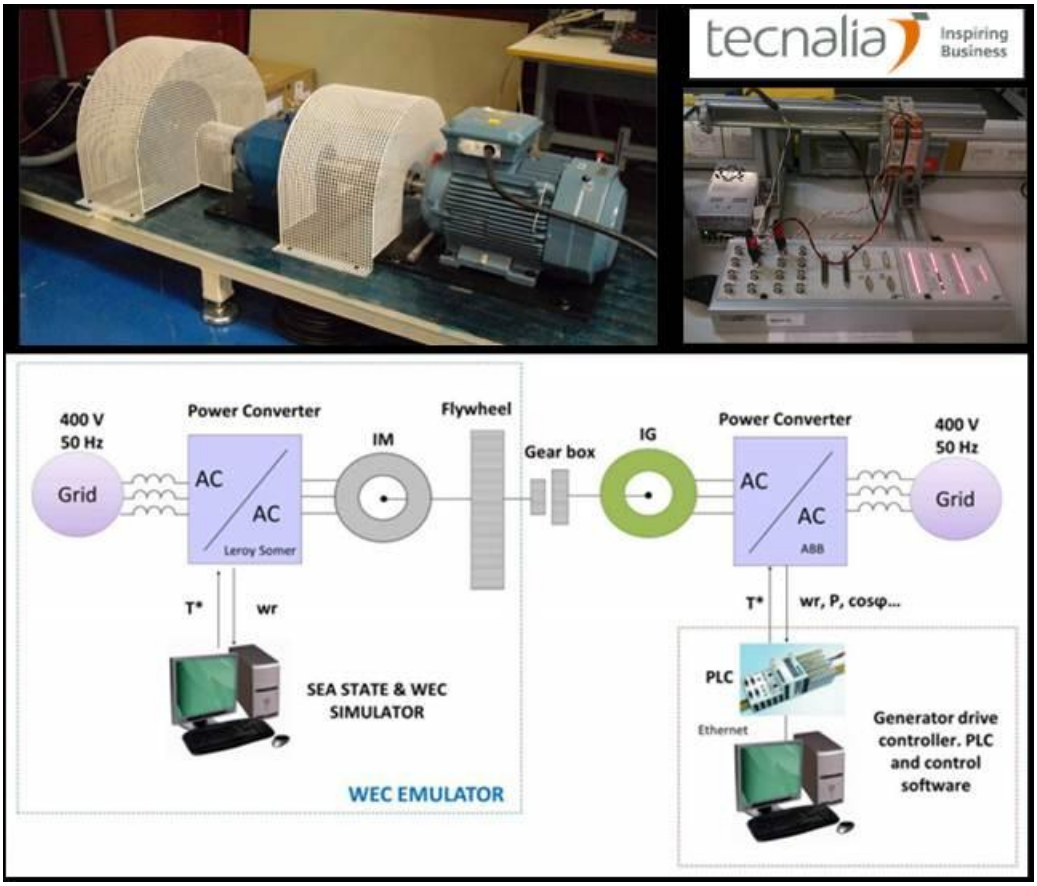

Figure 12 – TECNALIA Electrical PTO Lab.

The MPPT strategy was, however, not suited to the analysed WEC structure, due to the occurrence of rapid air flow variation of in a few seconds. Under some of the shortest (regular) waves, the air flow changed (periodically) from the highest value to very low ones. This in fact induced unacceptable loads on the shaft, possibly cause for large vibrations, malfunctioning and damages. In presence of a flywheel (not used in the device), the system inertia allows to keep a more constant speed, making it even more difficult to actually reach the optimal conditions (but easier to stay in its proximity). It is also possible to loosen the MPPT requirements limiting the speed used to reach the optimal conditions, or the band of minimum and maximum range, having at the limit a fixed optimal speed. However, the ambition of a dynamic control is to reach better results than having a fixed velocity.

A more satisfactory approach was implemented selecting a target curve based on the torque, rahter than on the rotational speed.

Details of the implementations are found in Delmonte et al. (2014), where all results are presented. Fig. 13 shows an example of the result, for the largest wave state. The pneumatic power (top figure) is much more fluctuating than the electrical power (bottom figure), thanks to the implemented control strategy. The control strategy acts like a sort of electrical flywheel.

Obviously, the measured delivered power is lower than the pneumatic one, due to reduced efficiency of the real electric devices and of the simulated turbine.

CONCLUSIONS

Electrical experiments were carried out in a Hardware in the Loop (HIL) test bench in Tecnalia laboratories (Bilbao), with the aim of studying the best control strategy to use for a test application of the Seabreath WEC.

Many procedural details have been sorted out, and new experiments will be carried out (within a second approved Marinet call), where more appropriate turbines will also be examined.

Experiments have confirmed that:

- The modified hydraulic model was in the correct form to interface with the HIL tests.
- The use of an HIL is able to tests different sea states, control systems (necessary step to design the power electronics), and turbines (of known characteristics).

- Among the tested strategies, the MPPT torque control was fount better than the MPPT speed control.

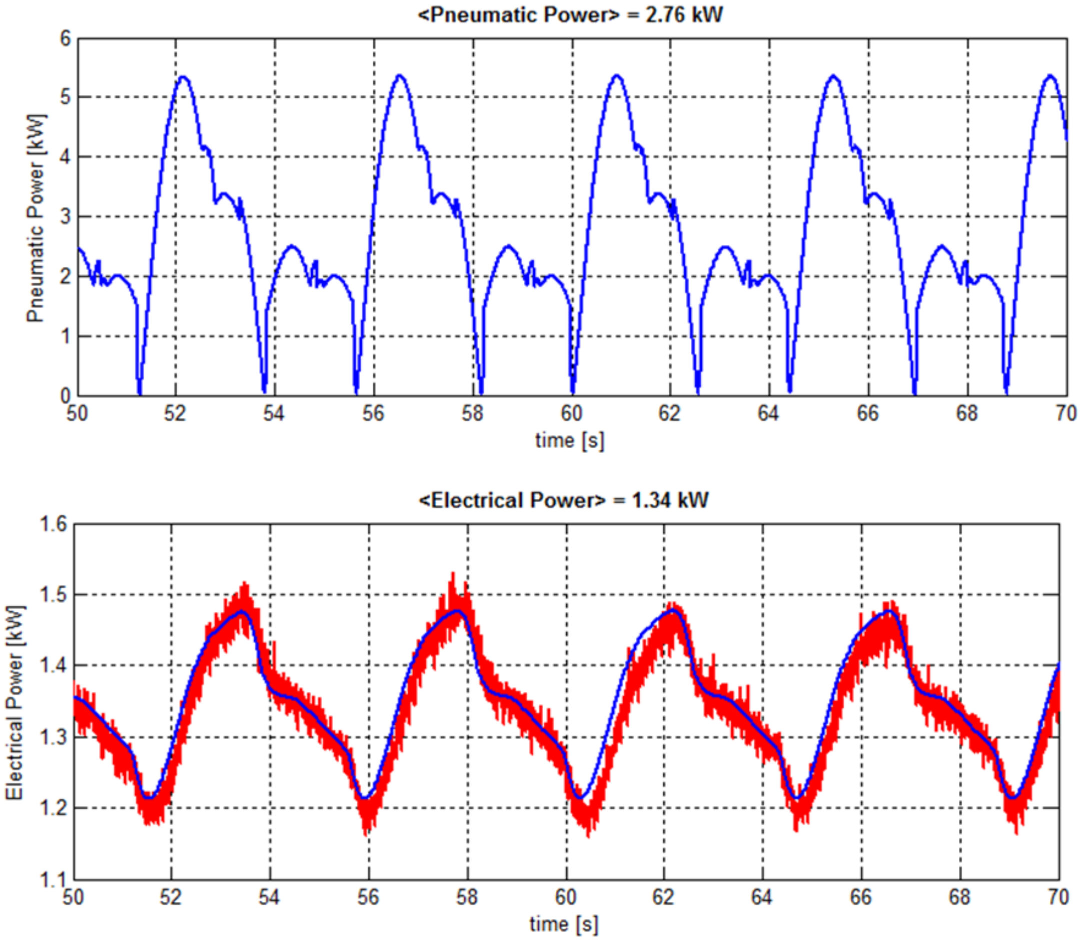

Figure 13 – Pneumatic power and electrical output

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