An overview of analytical, numerical and experimental methods for modelling oscillating water columns

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AN OVERVIEW OF ANALYTICAL, NUMERICAL AND EXPERIMENTAL METHODS FOR MODELLING OSCILLATING WATER COLUMNS

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Abstract— **Many researches on Oscillating Water Columns (OWC) have been performed since the early 70's in order to assess the energy yield at a given location on the one hand and to perform parametric studies in order to optimise their efficiency on the other hand. This paper synthetises a literature survey aimed at comparing the Oscillating Water Columns modelling methods, from analytical methods to more recent CFD approaches. The comparison of those different methods also yielded to an analysis of different design parameters of OWC. Therefore, in this paper, we also present some results about OWC performance sensitivity to geometrical or turbine parameters.**

***Keywords*— Fixed Oscillating Water Column, Boundary Element Methods, CFD modelling**

I. INTRODUCTION

The EMACOP [1] (Marine Energies in coastal regions and harbours) project aims at studying the feasibility and pertinence of setting up wave energy converters in coastal regions. The main idea is to take advantage of the rehabilitation or building of breakwaters to set up wave energy converters in order to produce local electrical energy in coastal regions.

For the time being, there are more than one hundred wave energy converter concepts which can be classified under mainly four categories: (1) Overtopping devices, (2) Oscillating devices (floating bodies or (partially) immersed flaps), (3) Oscillating Water Columns, (4) Other concepts.

For the EMACOP project, we of course focus our studies on devices behaving to those families which are suitable for near shore applications and able to be coupled to a breakwater. Numerical tools able to assess the mean power production of different categories of wave energy converters (overtopping devices, oscillating floating bodies, submerged flaps and oscillating water columns) will have to be developed. Prior to those developments, a state of the art of the different methods suitable for modelling each selected category of wave energy converters has been performed. In this paper, we present a synthesis of the state of the art of methods used for modelling Oscillating Water Columns including analytical, numerical and experimental approaches.

This study being performed for the needs of EMACOP project ; the results presented in this paper are limited to fixed OWC structures.

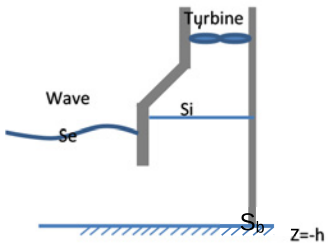


Fig. 1: Simplified OWC sketch

The OWC devices are simple structures consisting of (see Fig. 1) an internal water chamber separated from the open sea by a partly submerged wall. The air trapped between the water free surface and the top of the OWC structure communicates with exterior via an orifice containing a turbine - usually bidirectionnal - such as Wells turbines, impulse turbine or biradial turbine.

The incident waves at chamber entrance will excite the internal mass of water, through pressure oscillations and momentum flux. The oscillating motion of the internal free surface makes the trapped air to be alternatively under excessive pressure or depression compared with external air. This alternating air flux makes the turbine – linked to a generator – rotate.

Since the middle of the 80's, several OWC power plants have been installed worldwide. The main existing OWC plants are listed in TABLE 1.

TABLE **1**

OWC type	Name	country	Power(kW)
Onshore	Pico power plant	Açores Island (Portugal)	400
Onshore	LIMPET	Scotland	500

[1] www.emacop.fr

Onshore (breakwater)	Mutriku	Spain	250
Onshore (breakwater)	Vizhinjam OWC	Trivandrum India	150
Nearshore	Toftestallen	Norway	500 destroyed
Nearshore	Port Kembla	Australia	300
Nearshore	Osprey	Scotland	destroyed

In a first part, we will analyse the different modelling approaches such as analytical methods developed mainly during the 80's, numerical methods - from the different boundary element methods (linear as well as nonlinear models) to more recently developed CFD approaches such as VOF methods - and finally experimental methods.
From that literature review, we also collected interesting data on the sensitivity of OWC performances to geometry or turbine parameters . In a second part we therefore present a synthesis of that literature study showing first the effect of different geometrical parameters on OWC behaviour and then the effect of turbine parameters and control.

II. Onshore OWC modelling methods

A. Hydrodynamic formulation in potential flow theory

1) Rigid piston / pressure distribution approaches

Since the 70's [1], a simple model which considers the internal free surface as a rigid weightless piston has been used in order to establish the hydrodynamic pressure in the OWC. Such models neglect the spatial variations of the internal free surface, and will therefore be valid only when diffraction pressure is small across the horizontal plane. The OWC behaviour may be described using the following equation of motion as used by Sykes [2], assuming a zero pressure at the free surface and constant pressure P across S at z=-L :

$$\rho S(L+\eta_{OWC})\ddot{\eta}_{OWC} + \rho S g \eta_{OWC} = S P_{OWC}\ ; \quad \text{Eq. 1}$$

where ρ is the water density, $\eta_{OWC}(t)$ and $P_{OWC}(t)$ are the free surface elevation of the water column and dynamic pressure in the OWC. The natural frequency can therefore be obtained as :

$$\omega_0 = \sqrt{\frac{g}{L+\eta_0}}$$

The other widespread approach used to asses OWC hydrodynamic behaviour is the pressure distribution theory, which has been initialized by Falcao and Sarmento [3] and generalized by Evans [4]. This theory allows to describe accurately the internal free surface, taking into account at least the sloshing mode besides the piston mode. As sloshing mode is inefficient in terms of energy production, it is therefore very useful to dispose of model capable of predicting that mode in order to be able to keep it away from the working range of a given OWC. In this paper, and for the need of EMACOP project, we have chosen to focus our study on pressure distribution models.

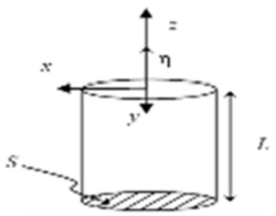


Fig. 1 : from Sykes [2] Schematic of simplified piston

2) Definitions:

As the majority of researches concerning OWC behaviour are based on potential flow theory (analytical as well as boundary element models), it is useful here to introduce the hydrodynamic formulation commonly adopted in potential flow theory to describe OWC:
The flow is here considered irrotational and the fluid incompressible; the fluid motion is given by a velocity potential which must satisfy the Laplace equation:

$$\vec{\nabla}^2\phi = 0 \quad \text{Eq. 2}$$

In analytical models and linear boundary elements approach, the linearized free surface boundary condition is used ([5],[9])

$$\frac{\partial\phi}{\partial z} - \frac{\omega^2}{g}\phi = \begin{cases} \frac{i\omega p}{\rho g} & \text{on internal free surface} \\ 0 & \text{on external free surface} \end{cases} \quad \text{Eq. 3}$$

p being the complex amplitude of the oscillatory pressure acting on the internal free surface, g the gravitational acceleration and ρ the water density, ω the frequency of the incident wave.
Concerning the solid boundaries,

$$\phi_n = 0 \quad \textit{on solid boundaries} \quad \text{Eq. 4}$$

Under these assumptions of linear potential theory, some specific definitions are commonly used to describe the behaviour of the OWC. Following the method of Evans [1], the potential is usually split into two parts :

$$\phi = \phi^D - \frac{i\omega}{\rho g}\phi^R \quad \text{Eq. 5}$$

ϕ^D : solution of the scattering problem of an incident wave, without any imposed pressure on the internal free surface (ie open chamber).
ϕ^R is the solution of the radiation problem due to pressure fluctuations in the chamber, without any incoming wave.
ϕ^D satisfying the following equations :
Induced volume flux accross the internal free surface:

$$Q(t) = Re\{qe^{-i\omega t}\} \quad \text{Eq. 6}$$

$$q = \int_{S_i} \frac{\partial\phi}{\partial z} dS = q^D - \frac{i\omega p}{\rho g} q^R \quad \text{Eq. 7}$$

Again, Evans & Al [2] uses a decomposition of the volume flux due to the radiation potential which is commonly used by authors:

$$-\frac{i\omega p}{\rho g} q^R = (\tilde{B} - i\tilde{A})p \quad \text{Eq. 8}$$

$\tilde{A}$ and $\tilde{B}$ being directly analogous respectively to added mass and radiation damping.
By analogy with electrical theory circuit, Falnes and Mc Iver [6] also define $\tilde{A}$ and $\tilde{B}$ to be respectively radiation conductance and susceptance, $Z = (\tilde{B} - i\tilde{A})$ being the admittance of the system.

$$\tilde{A} = \frac{\omega}{\rho g} Re\{q^R\}\ ,\ \tilde{B} = \frac{\omega}{\rho g} Im\{q^R\} \quad \text{Eq. 9}$$

Another useful relation is often used to model – under linear assumptions - the turbine behaviour : the linear relation between the volume flux through the turbine and the pressure drop across it is defined as : $q = -\Lambda p$ Eq. 10

3) OWC simplified mathematical model :

Using the main definitions and assumptions described hereabove, we simply mention here the equations governing OWC behaviour, still in the frame of potential flow theory:

(1) : Air mass conservation equation :

Establishing the air mass conservation equation allows to link air volume flux through the turbine to the hydrodynamic volume flux. Following Sarmento and Falcao method (1985)[7], which makes the assumption of isentropic evolution, Brito Melo [9], Chatry [8] uses the following expression of the air volume evolution in the chamber :

$$q^t(t) = -\frac{dV(t)}{dt} - \frac{V_0}{\gamma p_a}\frac{dp(t)}{dt}, \quad \text{Eq. 11}$$

Where : V_0 represents the air volume in the chamber when the free surface is at rest, $\frac{dV(t)}{dt}$ is the hydrodynamic volume flux due to free surface motion, $\frac{V_0}{\gamma p_a}$ expresses the effect of air compressibility (p_a : atmospheric pressure, γ : specific heat at constant pressure and volume).

(2) Governing equation for OWC devices :

Therefore, using the hereabove decomposition of the hydrodynamic volume flux into a diffraction-radiation problem, the global equation that allows to model the OWC behaviour is the following :

$$q^t(t) = q^D(t) + q^R(t) - \frac{V_0}{\gamma p_a}\frac{dp(t)}{dt} \quad \text{Eq. 12}$$

The equivalent of this equation in the frequency domain can easily be obtained by Fourier transform.

$$Q^t(i) = H^d(i\omega, x_0)\eta(i\omega, x_0) + H^r(i\omega)P(i\omega) - i\omega\frac{V_0}{\gamma p_a}P(i\omega)$$

Eq. 13

Where $\eta(i\omega, x_0)$ is the free surface elevation ate a given distance x_0 of the OWC and diffraction and radiation transfer functions are respectively defined as :

$$H^d(i\omega, x_0) = \frac{Q^d(i\omega)}{\eta(i\omega, x_0)} \quad \text{Eq. 14}$$

$$H^r(i\omega) = \frac{Q^r(i\omega)}{P(i\omega)} \quad \text{Eq. 15}$$

$P(i\omega)$ being the pressure in the chamber.

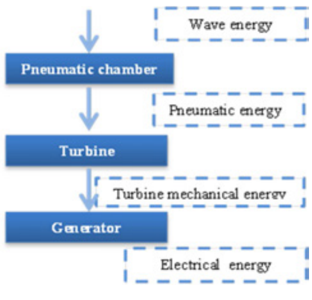


Fig. 2: : OWC energy conversion

Once known the pneumatic pressure and volume flux, the average pneumatic power can easily be established as :

$$\langle P_{OWC}\rangle = \frac{1}{2}\Re e\,(P^* Q^t) \quad \text{Eq. 16}$$

4) Condition for resonance :

As many concepts of wave energy converters such as oscillating bodies, OWC are resonant devices : the OWC concept is efficient when it works in its piston mode, that is, when the fluid between the barrier and the back wall is excited by the incident wave into a resonant piston like motion inside the OWC. Evans [4] has shown that the maximum power absorption occurs theoretically when pressure and wave induced volume flux are in phase, when $\Lambda = \bar{Z}$. He also gives an expression of the theoretical maximum absorbed power in the case of imperfect matching (§II.B.1).

Large motions may also occur in the chamber if the fluid is excited under the 'sloshing' mode, this mode being inefficient in terms of energy production. Therefore under a conception phase, the OWC will have to be tuned to work as much as possible in its piston mode.

Theoretically, those hydrodynamic parameters can be determined either analytically, numerically or experimentally. In this first part of the study, we will expose the great principles of those different approaches.

Once the OWC hydrodynamic model has been developed, it is necessary, in order to be able to assess the mean annual power production to model as accurately as possible the different energy conversion stages (see Fig.2) and associated losses. Therefore, we will also mention here several methods used for energy conversion modelling.

B. analytical methods

1) Few elements on hydrodynamics models

In the early 80's, mathematical models used to describe OWC hydrodynamics neglects the spatial variations of the internal free surface caused by the surface pressure [1]. That first approach consists in replacing the free surface by a weightless piston, but requires the determination of added mass and damping for the piston motion. In 1982, Evans [4] generalizes the pressure distribution theory initialized by Falcao and Sarmento [3] suitable to describe accurately the free surface either in 2 or 3 dimensions. In this study, Evans shows at least 2 interesting results: - In the theoretical case of perfect impedance matching (ie Λ=Z), the maximum power absorption can be determined by solely solving a wave diffraction problem. In the case of imperfect matching Evans shows that conditions for resonance exist, for single pressure distributions, either in 2 or 3 dimensions: these conditions link the size of the pressure distribution to the incident wavelength. He shows that, in the case of harmonic incoming wave, only three pieces of information are needed to calculate the absorbed power [5] :

(1) the volume flux through the surface of the chamber when the chamber is open,

(2) the admittance Z of the system, that is the measure of the volume flux through the chamber caused by an imposed harmonic chamber pressure

(3) the turbine constant Λ (the volume flux of air through the turbine divided by the driving).

The mean power absorbed by the system is therefore expressed in [11] by:

$$P_{moy} = \frac{1}{2}Re(\Lambda)|\eta_0|^2|\pi_c|^2, \quad \text{Eq. 17}$$

η_0 being the amplitude of the incoming wave and :

$$\pi_c = \frac{p_c}{\eta_0} = i\omega A_c \xi_0 (\Lambda + \mathrm{Z})^{-1} \qquad \text{Eq. 18}$$

the pressure ratio, A_c, the surface of the chamber and ξ_0 the amplitude ratio when the chamber is open.

The approach used by Evans & Al [5], Malmö & Al [11] consists in describing the velocity potential in the various regions of the systems in terms of eigenmodes consistent with the boundary conditions (solid walls, surface and bottom of the sea). From this matched eigenfunction expansions, several techniques are used to determine surface elevation in the different regions and admittance in order to calculate the efficiency of the OWC : For example, Evans [5] establishes integral equations for the volume flux across the free surface and develops an approximation of the solution by Galerkin method to finally obtain the radiation and diffraction transfer function, and efficiency of the OWC. In these mathematical studies, theoretical maximum conversion efficiency and capture width ratio are evaluated (wave to pneumatic energy). The turbine constant is used to assess the pressure in the chamber, and can even be taken into account as a complex value in order to model the air compressibility.

Main use, advantages and drawbacks

Authors have developed those mathematical models in order to be able to study the sensitivity of OWC behaviour to geometrical or set up parameters. Malmö [12] uses this same theory to demonstrate the interest of installing OWC in reflecting walls in order to improve its efficiency (see III.A.3) More generally, Mc Iver and Evans [13] have also shown the benefit of setting up wave energy devices into 'harbours' and to neighbour various wave energy devices.

During the 70's and 80's, many researches have been performed on OWC and have reached to improve both OWC physical behaviour understanding and OWC analytical models. Those models are able to evaluate OWC performances such as capture width ratio[2] under regular waves conditions for simple OWC geometries, assuming linear turbine behaviour. The analytical approaches are also able to evaluate the sensitivity of OWC efficiency to geometrical parameters modification such as chamber length, harbour length (see § III.). These mathematical models are therefore suitable to evaluate theoretical maximum conversion (wave to pneumatic) under regular waves for simplified OWC geometries, within the limits of potential flow – viscous effects not taken into account- and linear water wave theory. These analytical approaches have also shown the difficulty of tuning an OWC.

C. Numerical models

1) Boundary Element Methods

- Linear BEM models

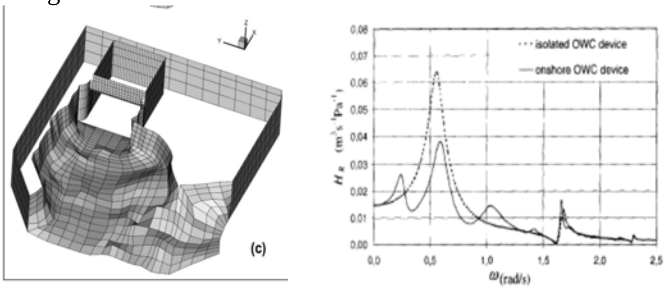
In the continuity of analytical model, numerical codes based on boundary element approaches have been developed since the middle of the 90's. In the linear BEM models mentioned in this section, the diffraction / radiation problem is solved in the frequency domain. For example, Brito e Melo [6] and Delauré [14] have developed BEM numerical models suitable for OWC studies by analogy with BEM codes developed for floating bodies. The principle of the method consists in introducing a decomposition into elementary velocity potentials, expressing the problem in terms of diffraction and radiation problem as defined by Evans and Porter in analytical approaches. By analogy with the classical radiation problem used for floating bodies, a radiation potential due to the oscillating air pressure inside the chamber (without any incoming wave) is introduced. (see Eq. 3). Defined as $\phi_R = \frac{i\omega}{\rho g}\phi_7$ by Brito Melo [9], it can be interpreted as the complex amplitude of the radiated velocity potential generated by a unit amplitude pressure distribution.

To solve the problem defined by equation 1 to 3, Brito Melo has therefore chosen to extend a BEM code AQUADYN [15] suitable for seakeeping of floating bodies introducing the pressure distribution oscillation as a seventh degree of freedom. This addition leads to a modification of the internal free surface which is modelled by a massless surface described with piston and sloshing mode. The concept of hydrodynamic effort is extended so the global surface $\{S_b + S_i\}$ corresponding to the body surface plus internal water free surface – see Fig.1 :

$$F_7 = i\omega\rho \int_{S_i} \left(\phi_0 + \phi_d + \frac{i\omega p}{\rho g}\right) n_7 \, dS \qquad \text{Eq. 19}$$

The 1st term of Eq.15 corresponds to the excitation force – ie resulting from an incident wave in an open chamber-, the radiation term may be expressed in term of added mass and radiation damping $\tilde{A}$ and $\tilde{B}$ as defined in Eq.8.

Integral equations of the boundary condition problem are then established using 3rd Green formula. A mixed singularity distribution is then used to solve integral equations. AQUADYN-OWC finally computes the radiation and diffraction transfer function (Fig. 3). As opposed to analytical methods, the 3D BEM OWC models are able to model real – ie complex- OWC structures and may take into account surrounding coastline and bathymetry. For example, Brito Melo has modelled the PICO OWC power plant and studied the impact of surrounding coastline and bathymetry on radiation and diffraction transfer function [10]. Wang [41] has also shown reasonably good agreement with experiments by adding surrounding topography in its 3D boundary integral equation method - the hydrodynamic flow is here described using 3D shallow water Green function.



[2] Dimensionless ratio between the absorbed power and incident wave power

Fig. 3 :– Extract from [10] - Impact of the surrounding coastline and bathymetry on the diffraction (on top) and radiation transfer function –

- *Non linear BEM models*

In our literature review, we have also made an inventory of non linear BEM models. These models, in which the diffraction/ radiation problem is solved in time domain enable to describe a non-linear internal free surface and also transient phenomena. Clément[16] has implemented an OWC in the 2D non linear wave tank CANAL developed by Clément and Mas and studied the influence of various geometrical parameters on the OWC response. In CANAL, the initial boundary value problem is solved by the mixed Euler Lagrange method. Chatry [8]has carried on this same approach and implemented an advanced control technique called SAFF (self adaptative Feedback Feedforward). In order to avoid the problem of non causality of an optimal controller arising from the condition for maximum absorption [4], a sub-optimal approximation is made, based on the estimation of the instantaneous incident wave frequency. That kind of control has proven to be theoretically efficient to enlarge the hydrodynamic efficiency of the device over a large frequency band for random sea states. Another approach was used by Josset and Clément [17] and consists in coupling a linear approach outside of the OWC to a nonlinear description of the internal problem in order to be able to describe accurately the internal free surface behaviour. The internal problem is modelled using an approach again based on the 3rd Green formula – as in linear BEM models presented hereabove –associated here with Rankine singularities. The model developed by Josset ([17], [18]) is a 3D model able to model realistic OWC powerplant; compared with a frequency domain approach, this model also allows to include more realistic PTO control laws.

- *Associated energy conversion models*

Most of onshore and nearshore OWC projects are equipped with bi-directionnal WELLS turbines. Therefore, many researches aiming at assessing the OWC performances focuses on WELLS turbines modelling. Otherwise, that kind of turbine appears to have a great interest from a modelling point of vew because its behaviour characteristics pressure/flow rate is approximately linear.

Several types of energy conversion strategies can be associated with BEM hydrodynamic codes in order to be able to model as accurately as possible the energy conversion process, and especially the associated non-linear behaviours. As an example, it is at least necessary, for an OWC equipped with a WELLS turbine to be able to model regulation devices (Fig. 4) such as discharge valve commonly used in order to prevent turbine from stall .

Therefore, among the different approaches, we can mention :

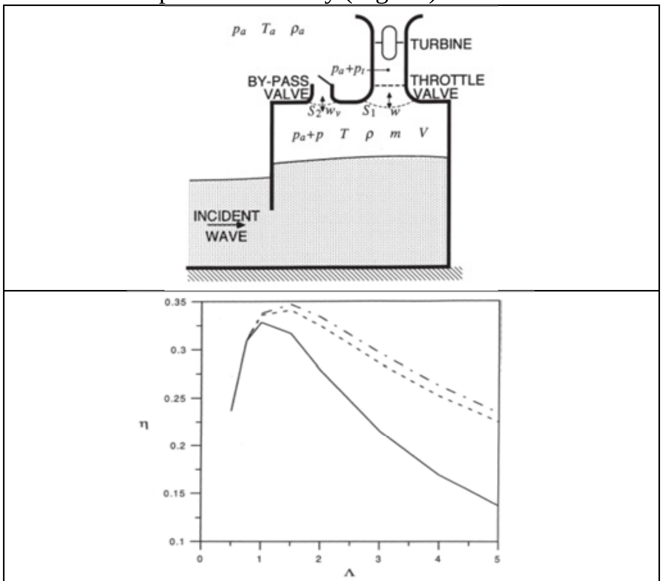
(1) *Time domain models* which is the most often used strategy : For example, Brito Melo [9], .Josset [17], Chatry [8] Falcao [19] and Kurniawan [20] use time domain approaches in order to be able to model non linear phenomena. The time domain approach therefore allows for example to model :

Discharge valves (throttle or by-pass), Variable pitch Wells turbines ([8], [9]), Hysteretic effects in the flow ([8]), Control process ([8]), Mechanical losses in the turbine and losses in the generator ([9]), Non linearities related to the spring-like effect due to air compressibility in the chamber.

(2) *A stochastic approach* has also been developed by Falcao [21] and used to optimize the turbine parameters and evaluate the average performances of OWC. This approach is based on the assessment of the variance and probability distribution of the air pressure inside the chamber, assuming a linear WELLS turbine. It is limited to linear water wave theory and uses a statistical theory of random waves, assuming Gaussian probability density of the sea states.

Once computed the air pressure inside the chamber, and knowing the performance curves of the turbine, Falcao then leads to assess the average power output and efficiency. This approach is then applied to the optimization of Pico plant turbine parameters (see Fig. 14), and has proven to be quite powerful. Even if the process of adding discharge valve introduces non- linearity in the relationship between the air flow rate and the pressure inside the chamber, Falcao included the effect of control (discharge) valves in its model by modelling simultaneously two valves, one in series, the other being installed in parallel so that the system {turbine + valves} remains linear.

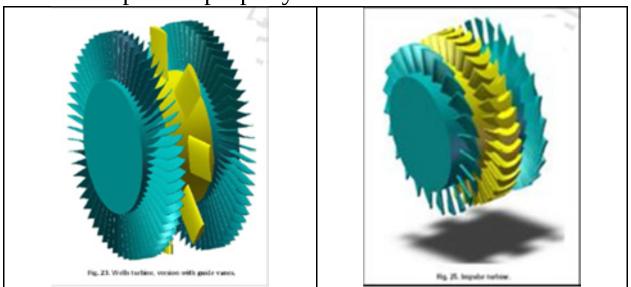
(3) *Global spectral approach* : this simplified approach used by Delauré [22] to perform parametric study of an OWC assumes linear turbine behaviour, and does not consider any discharge valve and as opposed to previous listed approaches neglects the air compressibility in the chamber. Working on the yearly average efficiency, that approach could be considered at an early design stage in order to obtain great tendencies in a parametric study (Fig. 12).



Average efficiency η for irregular waves, with air flow control by a throttle valve (broken line), a by-pass valve (chain line) or no flow control (solid line), where $\eta = \int_{t_1}^{t_1+\theta} P(t)dt \left[b \int_{t_1}^{t_1+\theta} E_i(t)dt\right]^{-1}$, *P being the pressure inside the chamber and Ei the incident wave power*

Fig. 4: From Falcao A.F, Justino P.A.P, OWC wave energy devices with air-flow control, Ocean Engineering 26, 1999 [16]

Fewer OWC projects and studies consider impulse turbines instead of WELLS turbines for the energy conversion process of OWC. Impulse turbines – patented by Babinsten in 1975 are mainly composed of a classical type axial-flow turbine (such as Laval turbine) equipped with 2 rows of guide vanes in order be able to work under alternative flows. The rotational speeds of impulse turbine are lower than WELLS turbines; impulse turbines will therefore be less adapted than WELLS turbines to energy storage (based on flywheel effect). Setogushi & Al. [23] and Jayashankar & Al. [24] have been comparing experimentally impulse turbines to WELLS turbines, and found that impulse turbines are more efficient than WELLS turbines, especially in random and energetic seas. However, Falcao [25] has pointed out that impulse turbines suffer from performance limitation due to aerodynamic stalling downstream of the guide vanes. Moreover, concerning the comparison between impulse and WELLS performances, Falcao also mentions that results of comparison should be considered with reserve, due the difficulty of extrapolating WELLS turbines test results from model scale to full scale because of high sensitivity to Reynolds number.
More recently, Falcao ([26], [27]) has studied both numerically and experimentally a new self-rectifying impulse turbine concept called bi-radial turbine adapted to alternative flows. It appears to give promising results in terms of efficiency[3], up to 0.7 for the time-averaged efficiency if the rotational speed is properly controlled.



Wells Turbine | Impulse turbine

Fig. 5: From Falcao [22] Left : Wells Turbines (with guide vanes), Right : Impulse turbines

Falcao [25] also describes the characteristics of the Denniss Auld turbine developed in Australia to equip the Port Kembla OWC.
Concerning the air compressibility, the approach introduced by Sarmento & Al.[7] based on an isentropic evolution description gives satisfactory results as long as the volume of the chamber varies weakly. Nonlinear description of the compressibility has been introduced by Chatry[8] and Kurniawan[20] in order to describe accurately the air chamber behaviour when significant volume variation occurs in the chamber.
To improve potential theory based hydrodynamic models that suffer from lack of accuracy (inviscid fluid description), some authors ([28], [20]) suggest to introduce resistance load factor in order to take into account losses arising from viscous effects.

2) CFD approaches

The literature review shows that CFD approaches are much less used and developed than potential models to assess the OWC performances. El Marjani & Al.[29] have used CFD code Fluent in order to calculate pneumatic energy in the chamber. Zhang & Al [30] have been developing a method based on a two-phase level set with global mass correction and immersed boundary method to simulate the hydrodynamic efficiency of a 2D OWC in regular waves. The governing equations here are the mass conservation equation and the Navier-Stokes momentum equation, here in 2 dimensions.
The finite volume method is here used to discretize the Navier-stokes equations, and an immersed boundary method is implemented to model wave-structure interactions. The effect of power take of is modelled by a rectangular orifice (Fig. 6)

$\frac{\partial u_j}{\partial x_j} = 0$ and

$$\frac{\partial u_j}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} + f_i,$$

with $\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$, the viscous stress tensor

Concerning its application case, as expected, the computed efficiency using a CFD model is lower than that evaluated theoretically under the assumption of perfect fluid (Fig.7). Also, the numerical model seems to over-estimate the efficiency at resonance – compared with experiments. We can notice that the model developed by Zhang & Al. does not take into account the air compressibility. It would therefore be interesting to study how this parameter affects the results, particularly at resonance.

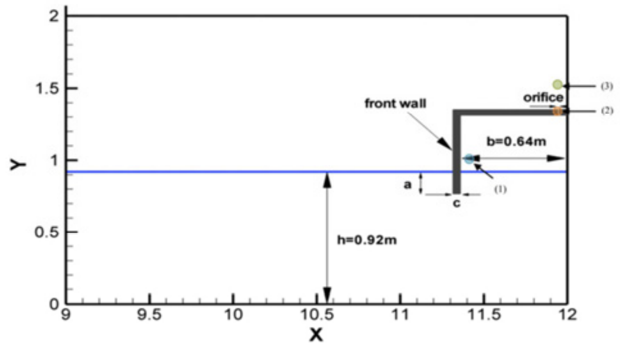


Fig. 6: OWC numerical tank of Zhang & Al [30]

However, on the illustration case described Fig. 6, the results obtained by Zhang using a CFD approach agrees more closely with experiments than the theory of Evans. That result shows the interest of viscous fluid approach to represent adequately the internal free surface and associated complex phenomena such as vortex generation at the front wall mouth. The drawbacks of that kind of advanced methods which could again be improved –as suggested by the author – on several points such as turbulence models, air compressibility, lies on several points such as irregular wave generation and

[3] η= power output / (volume flow rate x pressure head)

propagation, computational times, 3D extensions. Therefore, even if that kind of hydrodynamic models are more accurate than BEM approaches, they are – up to now- not adapted to assess the mean annual power production of a given OWC.

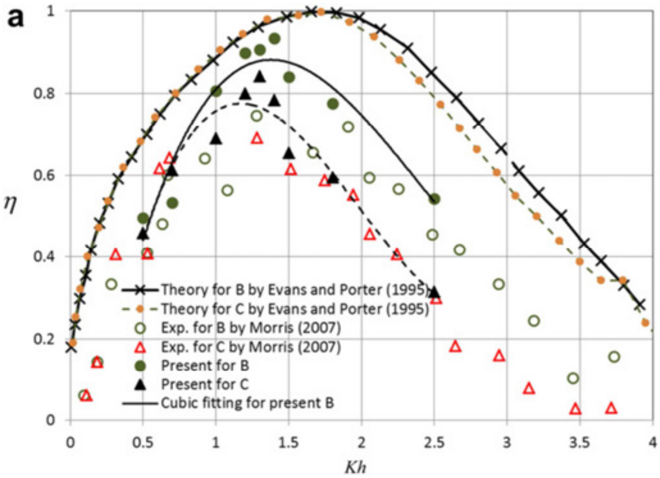


Fig. 7: Computation from Y.Zhang & Al [30]: Hydrodynamic efficiency versus kh, effect of the immersion depth of the front wall on the hydrodynamic efficiencies of cases B (front wall immersion : a=15cm, front wall thickness c=4cm) and C (a=15cm, c=8cm)

D. Experimental approaches

Few experimental approaches described in the literature aim at studying OWC performances in terms of energy yield. For example, some model tests have been performed to evaluate the efficiency of Mutriku breakwater OWC [32]. The pneumatic energy has been measured on 14 wave spectra selected to be the most representative of Mutriku location.

Fig. 8 Source : Y. Torre-Enciso 1, I. Ortubia 2, L.I. López de Aguileta 3 and J. Marqués 4 - Mutriku Wave Power Plant: from the thinking out to the reality – Proceeding of EWTEC conference 2009

Ikoma & al.[33] also conducted model tests to assess the efficiency of a floating OWC, showing the interest of using a 'harbor' surrounded by projecting sidewalls in front of the OWC in order to improve the OWC efficiency : As in the theory developed by Malmö [12] in the 80's, Ikoma exploits the presence of standing waves in the harbor, therefore leading to improve the efficiency of the OWC over a large frequency band (see fig.10). Here, the effect of the power take off is modelled by an orifice on top of the chamber. Experimental studies allows to characterize important complex phenomena which are not successfully taken into account in actual numerical codes : Many experimental studies have been undertaken to study hydraulic losses in OWC ([35], [36]) such as viscous effects on the one hand and to provide viscous damping coefficients for BEM models [36] on the other hand. Another important research topic concerns the effect of non linear shallow water waves on OWC behaviour which has also been experimentally studied [34].

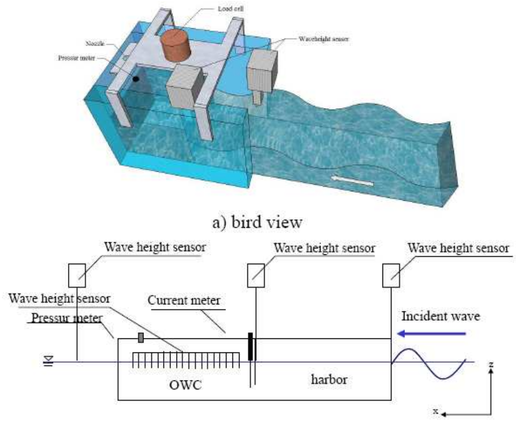


Fig. 9 Model tank testing configuration of Ikoma & Al. [31]

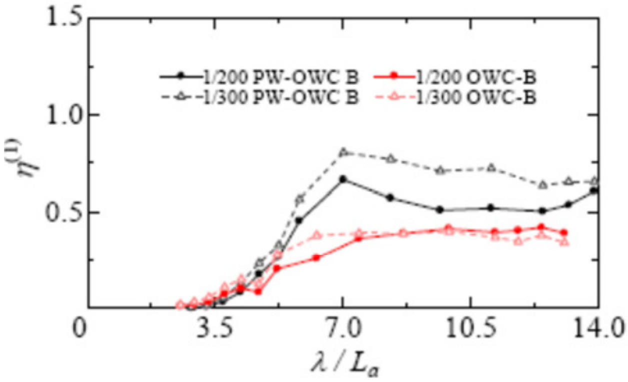


Fig. 10 Ikoma & Al. [33] Efficiency improvement due to harbour in OWC-B; PW-OWC –in red - are the projecting sidewalls types, OWC-B : without projecting walls

As an assessment of that literature survey, we can summarize the advantages and drawbacks of the different analytical and numerical approaches (see table 2). Concerning the analysis of the different hydrodynamic methods, one can see that, even if CFD models such as VOF approaches naturally appear to be the most accurate hydrodynamic models, they does not seem ready nowadays to assess the mean power production of OWC. Indeed, such method would need to be improved to be able to assess the yearly mean power production of an OWC in the field of irregular wave generation and propagation over many periods, extension to 3 dimensions geometries, and of course computation time which is much more important than in BEM approaches. On the other hand, some 3D BEM approaches are currently used to compute OWC yearly absorbed power, but suffer from lack of accuracy due to potential flow theory use.

Viscous loss simplified models may be used to improve the results of such models .

III. LITTERATURE REVIEW SYNTHESIS : PERFORMANCE OWC SENSITIVITY TO GEOMETRICAL AND TURBINE PARAMETERS.

The literature survey made for the EMACOP project in order to choose a suitable numerical approach to assess the mean power production of an OWC also enabled to study the performance OWC sensitivity to geometrical and turbine parameters.

A. Geometrical OWC parameters

Many researches evocated hereabove and associated model developments have to do with the tuning of resonance frequency of a given OWC in order to optimize the performances of an OWC at a given location. Indeed, two of the major difficulties when studying an OWC project are (1) to be able to tune the resonant frequency and (2) to assess the power production, and that's why many models able to perform parametric study have historically been developed, from analytical to CFD approaches since the 70's. We will try here to summarize few results issued from the analysis of the capabilities of the different approaches.

1) Chamber dimensions

Logically, Malmö ([11], [12]), Brito-Melo [37], Evans [5], Zhang [30], Delauré [22], have shown or observed that, an augmentation of the front wall immersion or of the length or width of the chamber – ie an increase of the volume of the chamber- leaded to a shift down of the resonance frequency of the OWC. Delauré has studied the optimisation of an OWC chamber for the site of Rossbay (Ireland) and has shown that the yearly average efficiency is improved by increasing the front wall thickness and draft and chamber length (Fig. 12). Malmö has also shown an improvement of the capture width ratio by increasing chamber length. However, as mentioned by Evans & Porter [5], or Delauré [22], if chamber length or front wall immersion becomes too important, the risk of sloshing mode apparition will be enhanced. Evans & Porter and Brito Melo observed that the amplitude of resonance peak is enhanced in the case of shorter chamber.

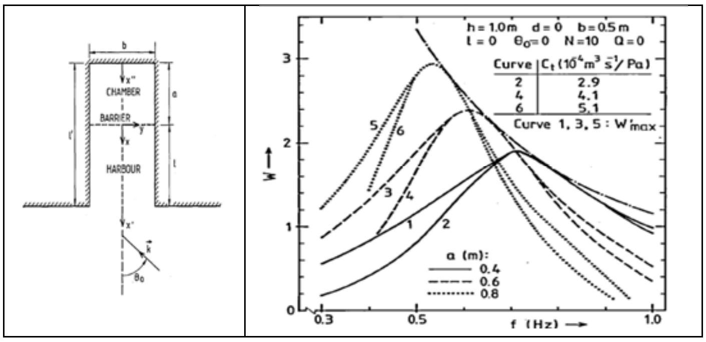


Fig. 11 :From O.Malmö , A.Reitan [11] : Capture width ratio versus frequency for various chamber lengths

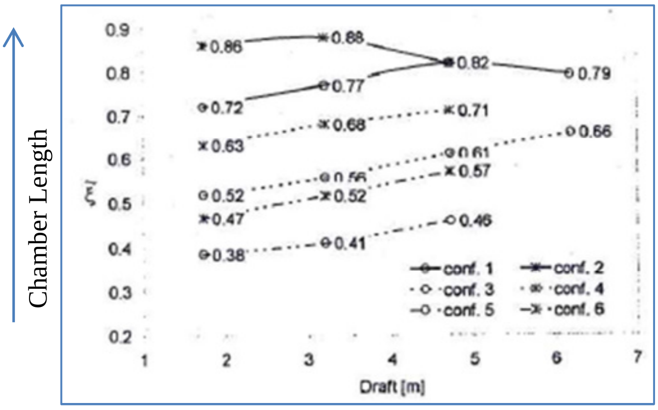


Fig. 12 From.Delauré & Al [22] : Maximum yearly average efficiency at optimal turbine damping against front wall draft for varying OWC length and front wall thickness

2) Site topography / bathymetry

As mentioned in part 2 of this paper, the bathymetry/ topography of the concerned site has great influence on OWC behaviour as shown by Brito Melo (see Fig.3). Indeed, in the case of Pico plant, Brito Melo has shown that the OWC difraction and radiation transfer function are significantly modified by the close bathymetry of the site.

3) Effect of 'harbours' and reflecting walls

From their theoretical model, Malmö & Al ([11], [12]) have been studying the effect of setting up an OWC into reflecting side walls called 'harbour'. The idea is to take advantage of the development of standing waves into the artificial harbour in order to improve the OWC performances over a wide frequency range.

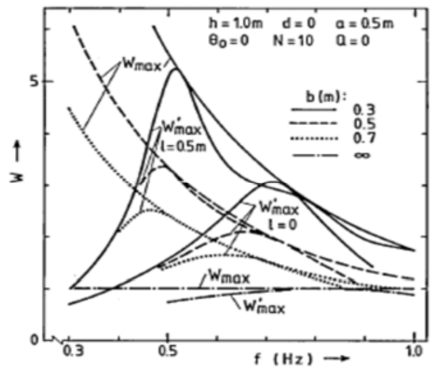


Fig. 13 : From O.Malmö and A.Reitan [11] Capture width ratio versus frequency for various chamber width and two different harbour length

Icoma & Al [33] have experimentally demonstrated the benefit of projecting side walls to improve the performances of an OWC over a large frequency range (see fig.10). Brito Melo [37] also studied the effect of the length of projecting sidewalls on hydrodynamic coefficient of the OWC. She has noticed that, by increasing harbour length, resonance frequency shifts down, therefore enabling the risk of sloshing frequency. Malmö & Al ([11], [12]), as well as McIver [13] have also demonstrated the interest of setting up the harbour into reflecting walls to improve OWC performances. More recently, Martin Rivas [38] has also shown the interest of taking benefit from the reflection of the incident waves for an OWC installed on a straight coast.

B. 'Power take off' parameters : WELLS Turbines Parameters and control

Many studies on turbines and especially WELLS turbine parameters have been performed during the last twenty years in order to improve OWC performances. We will give here few examples of studies to illustrate the importance of optimizing turbine geometry and operating parameters.

For example, Falcao [21] has been using his stochastic modelling method (§ II.C.1) in order to make an optimisation study of PICO OWC turbines. He has shown that great improvement of OWC performances may be achieved by optimising rotor diameter and controlling rotational speed of the turbine (see Fig.14) . He has also shown that, in this case study, the optimisation of rotational speed for each sea state allows to obtain improvement in OWC performance much more significant than with the use of control valves. In a previous work, Falcao [19] has pointed out – at fixed rotational speed – the significant role of control valves and shown their interest to achieve OWC performance improvement (see fig.4).

Variable pitch blades WELLS turbines will allow to work on an extended air flow range, avoiding control valve use; however, their cost compared with fixed bladed turbines will restrain their use to specific projects. For example, Chatry [8] has set up a sub optimal control technique in order to improve OWC performances in random seas which require the use of variable pitch blades WELLS turbines. The control concept is based on the estimation of the instantaneous frequency of incident wave; the operating conditions of WELLS turbine will then be optimised for each sea state by imposing the air flow characteristics as a function of the pressure in the chamber. Under a theoretical approach, this kind of control has proven to be efficient. In his approach, Chatry has pointed out the need to take into account the dissymmetry of inlet/outlet flow and taken that phenomenon into account by introducing differentiated inlet / outlet energy yield for the turbine. Latching phase control of small OWC (oscillating weightless piston description) have otherwise been considered by Lopes [40] as an interesting control strategy, getting free from incident wave estimation as opposed to SAFF control introduced by Chatry.

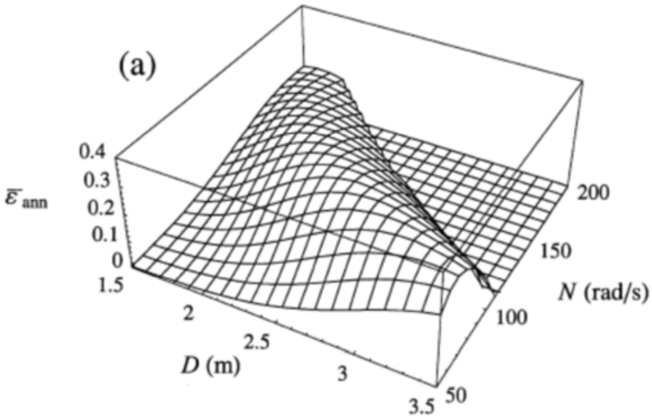


Fig. 14 : Falcao & A(l[18])Annual-averaged plant efficiency 1_ann (no valve) versus turbinerotor diameter D and rotational speed N

Method	**Hydrodynamic model**	**Capacity vs wave generation**	**Viscous effects modelling**
Analytical	Diffraction / radiation theory	Linear, mainly regular waves	Viscous effects not taken into account, limited to small amplitudes waves
Frequency BEM	Diffraction / radiation theory	Linear, regular/irregular waves	Viscous effects not accurately modelled, possibly taken into account via a loss resistance
Time domain BEM	Diffraction / radiation theory	Non linear, regular/irregular waves (non breaking waves)	Viscous effects not accurately modelled, possibly taken into account via a loss resistance
CFD / VOF + immersed boundary	Solves Navier Stokes Equation	Fully non linear, but difficulty to generate / propagate irregular waves over many periods	Good

Table 2 .Comparison of hydrodynamic models ..

IV. Conclusions

Through this study performed for the EMACOP project, we made an inventory of analytical as well as numerical or experimental approaches able to model OWC behavior and assess the energy yield of fixed OWC wave energy converters. Each method has its proper strengths and limitations. The study has shown that 3D frequency domain BEM methods associated with time domain 'power take off' models able to model accurately the power conversion chain (discharge valves, variable pitch turbines, control process,…) are the most commonly used methods to compute OWC yearly power production. At an early design stage frequency domain BEM models associated with stochastic method may be considered to perform quick parametric study. Non linear time domain BEM codes able to compute non linear wave structure interaction and to model advanced control processes may be used for detailed analysis. Experimental studies may provide viscous damping coefficients to improve BEM models. The importance of 3D description to describe OWC behavior has also been pointed out since the development of analytical models. CFD approaches such as appropriate VOF models able to compute complex viscous phenomena (such as vortex generation at the front mouth) may also be used for detailed analysis or wave structure interaction of extreme waves with OWC [41]. Moreover, from that literature study focused on model capabilities, we analyzed data issued OWC parametric studies the difficulty of tuning an OWC for a given site is explained by the great number of significant geometrical parameters. Depending on the site constraints and configurations, it may also be useful to evaluate the effect of setting up a new OWC in reflecting sidewalls. We should remind here that many aspects of OWC have not been even evocated in this study, such as U-OWC or OWC in array, for example. Concerning the 'power take off', this study has shown, through the variety and number of study concerning turbines parameters and control how crucial it is, for a given project to be able to optimize the power conversion chain. Therefore it is necessary to resort to time domain approaches in order to be able to model at least discharge valve operation. Some recent researches performed on novel radial impulse turbine show the capability of improvements concerning turbine efficiency. Also, probably some other kinds of PTO – ie excluding pneumatic PTO- could be studied and compared to air turbine developed approaches.

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