Experimental Validation of the Capture Chamber Model in Mutriku MOWC Wave Power Plant

AITOR J. GARRIDO, SALVADOR CAYUELA, AMPARO VILLASANTE, IZASKUN GARRIDO
Automatic Control Group - ACG,
Inst. of Research and Development of Processes - IIDP,
Faculty of Engineering of Bilbao,
University of the Basque Country (UPV/EHU),
Pº Rafael Moreno 3, Bilbao, 48013,
SPAIN

Abstract: - Wave energy holds the potential to fulfill 15% of the EU's energy demand by 2050, thereby reducing CO2 emissions by 136 million metric tons per megawatt-hour, as outlined in the EU Energy Road Map. Similarly, the Spanish Renewable Energies Plan underscores the significant marine energy potential in Spain, particularly emphasizing wave energy. Within this framework, Oscillating Water Column (OWC) converters currently stand as among the most promising wave energy conversion technologies, offering the capability to harness ocean energy from various on-shore and floating structures. This paper introduces an analytical model of the wave capture chamber parameterized for a specific on-shore OWC wave power plant. The model is specifically adapted and parameterized for the Mutriku Marine Offshore Wave Power Plant located on the coast of the Spanish Basque Country. Subsequently, validation is conducted using both real wave entry data measured on-site and experimental output power data generated in the plant.

Key-Words: - Wave Energy, Energy Converter, Modeling, Data Collection, Empirical Verification, Validation, Marine Energy, Renewable Energy.

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1 Introduction

Ocean Energy Europe has reported that wave energy has the potential to capture over 3000 terawatt-hours (TWh) annually, a quantity commensurate with the predominant portion of European energy demand. Additionally, the United States Department of Energy has appraised the wave energy resource potential to range between 1,594 and 2,640 TWh per year, [1].

Accordingly, estimates for wave energy production exhibit alignment, indicating an aggregate potential of approximately 29,500 TWh annually.

Concurrently, notable initiatives are underway in the Spanish Basque Country through the Nereida Marine Ocean Wave Current (MOWC) experimental/commercial Project. Spearheaded by the Basque Energy Agency (EVE), this undertaking seeks to validate the feasibility of Oscillating Water Column (OWC) technology with Wells turbine power take-off. Situated within a recently constructed breakwater in Mutriku on the north coast of Spain, the project encompasses 16 18.5 kW turbines, yielding a combined power output of 296 kW (Figure 1). This effort achieved a milestone of 2.4 gigawatt-hours (GWh) in 2021, [2].

Fig. 1: Turbo-generator modules employed within the Mutriku wave plant

2 System Description

OWC-based converters serve as mechanisms designed to convert the mechanical energy inherent in oceanic waves into electrical power. This process is facilitated through the utilization of a capture chamber in conjunction with a turbo-generator module.

The capture chamber, a stationary structure, features a lower section exposed to the sea, consistently submerged beneath the Still Water Level (SWL), as depicted in the schematic representation provided in Figure 2. In this configuration, the undulating motion of ocean waves induces an oscillatory airflow within the chamber, alternately pushing and pulling internal air, resulting in compression and decompression cycles. Consequently, a pressure disparity arises across the turbine, instigating its rotation. The magnitude of this pressure differential (dp) can be characterized by the following equation, [3], [4]:

$$\mathrm{dp} = \mathrm{C_a}\frac{\rho b l_1 n}{2}\frac{1}{a_1}\left(v_t^2 + (r\cdot\omega_t)^2\right) \quad (1)$$

where:
ρ: Air density (kg/m^3).
b: Blade's height (m).
l_1: Blade's chord's length (m).
n: Blades number.
a_1: Blade's section area (m^2).
r: Turbine's mean diameter (m).
ω_t: Turbine's angular speed (rad/s).

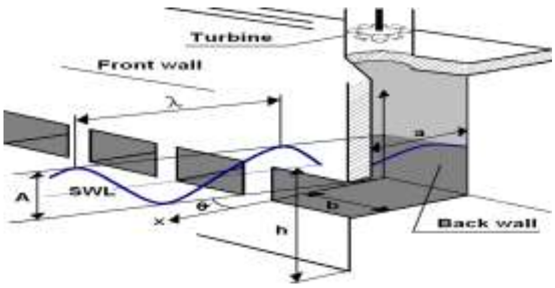

Fig. 2: System's scheme

Regardless of the direction of airflow, the rotational motion of the turbine remains unaffected, primarily attributable to the specific design characteristics inherent in the conventional turbine configuration, notably the Wells turbine, [5], [6] (Figure 3).


Fig. 3: Unused Wells turbine

The symmetric blade configuration characteristic of self-rectifying turbines facilitates unidirectional rotation. Nonetheless, this feature also engenders an undesirable phenomenon known as the Stalling effect, wherein the turbine ceases rotation upon reaching a threshold airflow velocity.

Comprising the power take-off system (PTO), the turbo-generator module incorporates both the turbine and an induction generator, typically of the Doubly Fed Induction Generator (DFIG) type [7], [8], [9]. Its principal function revolves around converting the oscillatory pressure differentials into electrical power. Various control strategies may be implemented to facilitate this process, [10], [11], [12].

The mechanical dynamics governing the turbo-generator block can be described by the following equation:

$$\mathrm{H}\dot{\omega}_t + \mathrm{F}\omega_t + \mathrm{T_e} = \mathrm{T_t} \quad (2)$$

3 Theoretical Model Framework

Various system modeling approaches may be employed to derive an appropriate model, [13], [14], [15]. In this endeavor, the initial step entails determining the pressure drop value based on the characteristics of the input waves. As indicated by equation (1), the properties of the input waves directly influence the airflow speed. Consequently, it is essential to establish a relationship between the waves and airflow speed, [16], [17], [18].

To achieve this, wave dynamics must be taken into account, which are governed by different theories contingent upon the specific attributes of the wave under consideration. According to Airy linear theory, a wind wave can be represented as an ideal sinusoidal wave, [19]. The mathematical expression delineating the surface profile of such waves is formulated as follows:

$$y(x,t) = a\cdot\sin\left[\frac{2\pi}{\lambda}(ct - x)\right] \quad (3)$$

Furthermore, the calculation of the volume of water in the chamber can be performed by considering the volume of air present within the Oscillating Water Column (OWC):

$$V(t) = V_c - V_w(t) \quad (4)$$

where V_c and V_w denote the volumes of the capture chamber and water, respectively.

The water volume can also be determined by integrating the variation of the water level across the Oscillating Water Column (OWC) area, yielding the expression:

$$V(t) = V_c + \frac{wH}{k}\sin\frac{kl}{2}\sin\omega t, \quad (5)$$

being l the length of the chamber.

Hence, the instantaneous airflow can be represented as:

$$Q_a(t) = wHc \cdot \sin\frac{kl}{2}\cos\omega t. \quad (6)$$

Now, by considering the geometry of the chamber, it becomes feasible to derive the airflow velocity required in equation (1):

$$v_t(t) = \frac{8awc}{\pi D^2} \cdot \sin\frac{\pi l}{cT}\cos\frac{2\pi}{T}t, \quad (7)$$

being D the duct's diameter.

However, as it may be observed from equation (1), the rotational speed is also a required parameter. This rotational speed is contingent upon the torque exerted by the turbo-generator module, which can be derived from Equation (2).

$$T_t = C_t K r[v_t^2 + (r\omega_t)^2] \quad (8)$$

The Torque Coefficient (Ct) is, in turn, interconnected with the Flow Coefficient (ϕ) through the characteristic curves of the turbine, as show in Figure 4, [20].

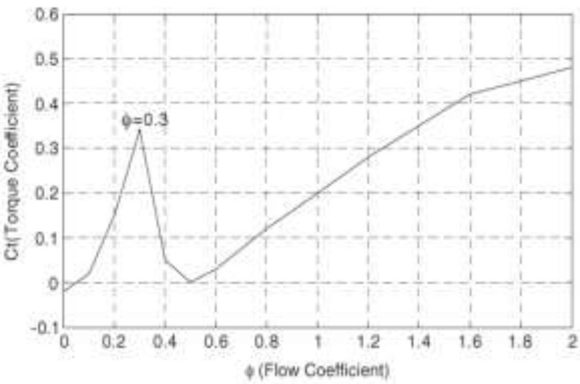

Fig. 4: Torque Coefficient vs. Flow Coefficient

Where the parameter ϕ represents a dimensionless quantity associated with the tangent of the angle of attack at the blade tip that can be straightforwardly calculated as:

$$\phi = \frac{v_t}{r \cdot \omega_t} \quad (9)$$

Hence, the rotational speed of the turbo-generator is derived from the established DFIG equations.

By taken into account all the aforementioned relationships outlined from Equation (1), an expression for the pressure drop across the turbine, in terms of the wave entry, can be formulated as follows:

$$dp = f\left(\frac{v_t}{r \cdot \omega_t}\right) \cdot \frac{\rho b l_1 n}{2}\frac{1}{a_1}\left(\left(\frac{8awc}{\pi D^2} \cdot \sin\frac{\pi l}{cT}\right)^2 \cos^2\frac{2\pi}{T}t + (r \cdot \omega_t)^2\right)$$

Here, the function f(·) denotes the characteristic curve specific to the turbine at hand.

4 Model Evaluation

In this section, the OWC plant model is computed and subsequently validated through the use of experimental data. To achieve this, the model output is calculated using actual wave surface data series gathered at the Mutriku plant breakwater using an acoustic Doppler current profiler RDI 600, with the aim of computing the theoretically predicted pressure drop. The obtained results are subsequently juxtaposed with in situ measured experimental *dP* data furnished by the Mutriku OWC plant (Basque Energy Board/EVE - BIMEP) for the corresponding time frame. All procedures were conducted in adherence to the requisite safety protocols and occupational health guidelines within the production facilities:

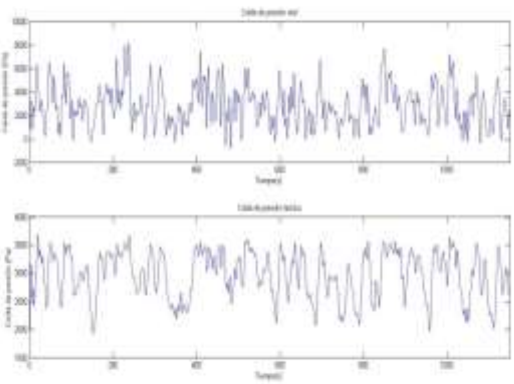

Fig. 5. *dP* comparison

As illustrated in Figure 5, the results present a substantial level of agreement between the values predicted by the model and the experimental data acquired.

5 Conclusion

This paper outlines a thorough methodology for modeling and simulating on-shore Oscillating Water Column (OWC) systems. Building upon prior relevant knowledge, the proposed approach marks a notable progression in engineering proficiency, with a particular emphasis on addressing control aspects. The investigation focuses on the Mutriku MOWC power plant and proceeds to validate its findings utilizing experimental data.

The model incorporates the wave, chamber, and turbo-generator modules, laying the groundwork for validation via experimental data. The outcomes reveal a significant congruence between model projections and experimental observations, thereby enabling deeper exploration into digital twin implementation and advanced control strategies.

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Conflict of Interest

The authors have no conflicts of interest to declare.