Open Sea Operating Experience to Reduce Wave Energy Costs

Technical Note

Test results of control strategies in numerical simulations and in operation at Mutriku Wave power plant

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EXECUTIVE SUMMARY

This document describes the dataset ***DS_Ctrl_Mutriku***, made available on the web via ZENODO platform and presented on a paper published in Renewable Energy [1]. The datasets show both numerical and experimental results of the test of several control algorithms to control the biradial turbine installed in the Mutriku Wave power plant:

- Statistical results of the numerical simulations upon 14 realistic sea states of 3 variable speed control laws, one being a non-linear model predictive controller.
- Statistical results based on operational data of the sea trials at the Mutriku OWC plant of the predictive controller and the best adaptive one.

CONTENTS

1. INTRODUCTION

An innovative Power Take-Off (PTO) system, consisting in a biradial turbine and an induction generator of 30 kW, rated power was manufactured and tested within Work Package WP3. The turbine was designed to fit the Marmok-A5 buoy and the optimal diameter was found to be 0.5 m. It is equipped with a high-speed shut-off valve (HSSV) installed in the front of the turbine rotor. Its function during the presented tests is to avoid the turbine from overspeeding, but thanks to a fast actuation time it can be used to perform latching control.

During the 1st phase of sea testing within the OPERA project, it was installed in the Mutriku OWC plant during 13 months to de-risk the PTO. The 2nd phase will see the deployment at BiMEP in the Marmok. Within WP4, several algorithms were developed to control the PTO power production and tested experimentally in dry test laboratories.

The dataset presented here supports the results presented in the associated paper [1] obtained from:

- the numerical simulations related to the development of 3 control algorithms:
    - CL1: Theoretical turbine torque estimation
    - CL2: Optimum turbine operating region
    - CL3: Non-linear model predictive control
- an experimental analysis based on operational data collected during real sea testing of the controllers in the Mutriku OWC plant of 2 of the algorithms.

Although the PTO was installed in chamber #9 of the plant from June 2017 to June 2018, the dataset presented here only gathers the period centered on the predictive controller and its base controller reference that took place during 2 weeks in June 2018. This is the period where the online wave measurement instrument matched with the availability of the PTO. Still operational results of nearly 500 ½-hour tests were collected.

2. NUMERICAL RESULTS

To obtain the simulation results, the numerical model is run for each of the 3 Control Laws and each of the 14 sea states. Each simulation time is set to 30 min with a timestep of 0.1 s. The analysis is focused on performance and reliability assessment and allows a comparison between the controllers during several wave resource. The tables sum up statistical values of time series and are presented in an excel file, sheet 'Simulation Results':

- Resource: characterised with the significant wave height H_s, energy period T_e, and probability of occurrence Occ. for each sea state SS.
- Avg Power Production: showing the average of pneumatic power, the mechanical one at the turbine shaft and the electrical one. Used to assess the PTO performance.
- Pk power: the peak of the 3 powers. Used for reliability and quality of power assessment.
- Std Dev Power Production: the standard deviation of the 3 powers. Also used for reliability and quality of power assessment.
- Rotational Speed: the average, peak and standard deviation of the turbine speed. Use for reliability.
- Avg Efficiencies: the turbine efficiency as the ratio of the mechanical upon the pneumatic power, the generator efficiency is the ratio of the electrical upon the mechanical power and the PTO efficiency is the product of both partial efficiencies. Used to assess the PTO performance.
- HHSV close: is the time the valve is closed for safety reason. Used for reliability assessment.
- AEP: is the energy production for each sea states as the product of average electrical power by the hourly hours of the sea state.

Mainly results show the conversion steps from the powers inside the chamber with the pneumatic one, at the turbine output and at the generator output. That way the partial efficiencies at the turbine and the generator are known as well as the total PTO efficiency. The table columns are presented as follow:

				CL1: Theoretical turbine to									rque estimation							
Resource				Avg Power Production (kW)			Pk Power Production (kW)			Std Dev Power Production			Rotational Speed (rad/s)			Avg Efficiencies			HSSV close	AEP Mwh
SS	Hs [m]	Te [s]	Occ [%]	Pneu	Mech	Elec	Pneu	Mech	Elec	Pneu	Mech	Elec	Avg	Pk	Std Dev	Turb	Gen	PTO	sec	

3. SEA TRIAL RESULTS

The test results of the biradial from the Mutriku plant show both environmental and operational conditions. They cover a 2-week period during the month of June 2018 when the H_s was 98% of the time below 1 m. The table gathers the following parameters:

		Sea states				Control	Pressure			Pneu Pow [W]	
Test#	Timestamp	Hs [m]	Te [s]	Dir. [deg]	Tide [m]	CL	RMS	min [Pa]	max [Pa]	avg	max

Turb Pow [W]		Gen Production				Efficiency			Rot. Speed [rad/s]		Valves	
avg	max	avg pow [	peak pow	std_kW	pk2av	Turb.	Gen.	PTO	avg	max	HSSV [s]	Damp. [deg]

3.1 WAVE RESOURCE

During the sea trials, the resource is measured for each ½-hour test. It is measured by a pressure sensor situated 200m up-front the plant at a mean depth of 9.5m and located at Lat. 43°18'51.59"N, Long. 2°22'33.99"W. It is connected to the plant via a cable and send real time data to the instrumentation system. The method to compute the wave elevation from the pressure and compute the Sea State data are detailed in a technical note published in Zenodo[2]. The wave elevation process consists in using the hydrostatic pressure, without the atmospheric one, to obtain the water column height above the sensor. It is then filtered with the *smooth()* function from Matlab. The ocean tide is computed knowing the 10-min moving average of the variation of the water column. The wave elevation is finally the water column above the sensor with the tide level removed. A spectral analysis allows to extract the wave height and energy period. Also, the wave direction is included and is taken from the SIMAR point 3171032 (the closest to Mutriku), it estimates the direction from the Bilbao buoy operated by *Puertos del Estado* located at Lat. 43.64° N, Long. 3.09° W. Although they are not included in the analysis, the wave crest direction and the tide level are other environmental parameters that can influence the power production.

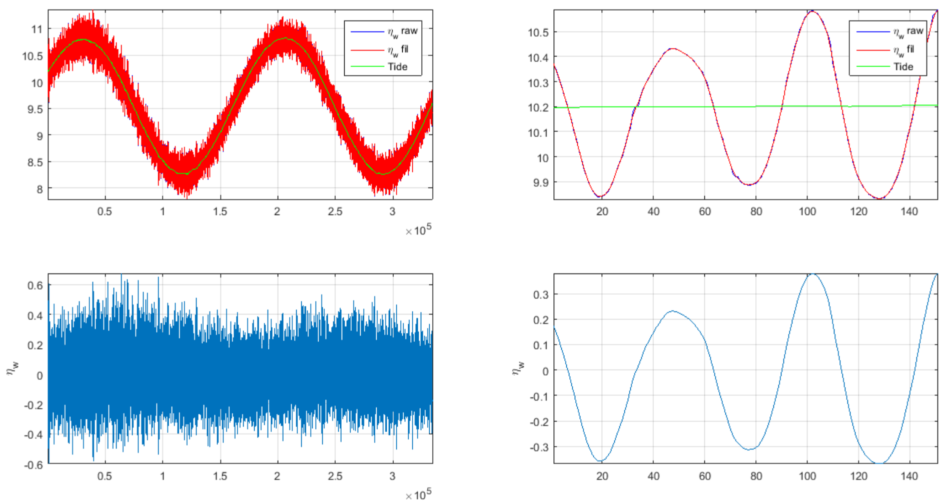

FIGURE 1 - PROCESS TO OBTAIN THE TIME SERIES OF THE WAVE ELEVATION FROM THE PRESSURE SENSOR AT MUTRIKU (LEFT: 24 HOURS AND RIGHT: 2.5 MIN)

The following figure displays a scatter plot of the resource measured during these tests.

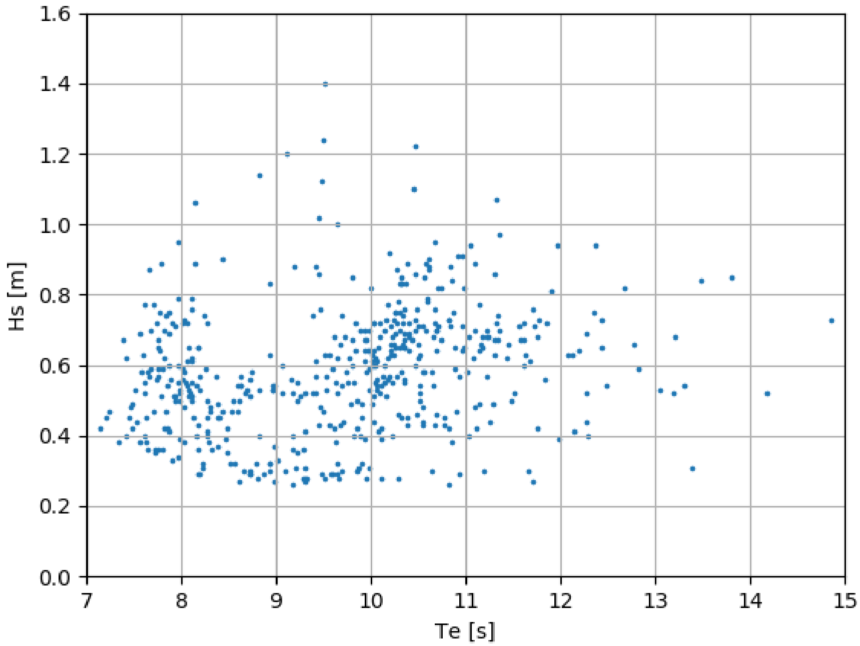

FIGURE 2 - SCATTER PLOT OF THE WAVE RESOURCE IN MUTRIKU DURING THE 2-WEEK TEST IN JUNE 2018

3.2 DATA PROCESSING

Most of the operational data are either measured from sensors installed in the plant, either they are derived from these measurements. As detailed in OPERA Deliverable D3.3 [3], the pneumatic and turbine powers, respectively P_{pneu} and P_{turb}, cannot be directly measured but instead they rely on operational values and the turbine performance curves obtained during variable flow dry lab testing as discussed in OPERA Deliverable D3.2 [4].

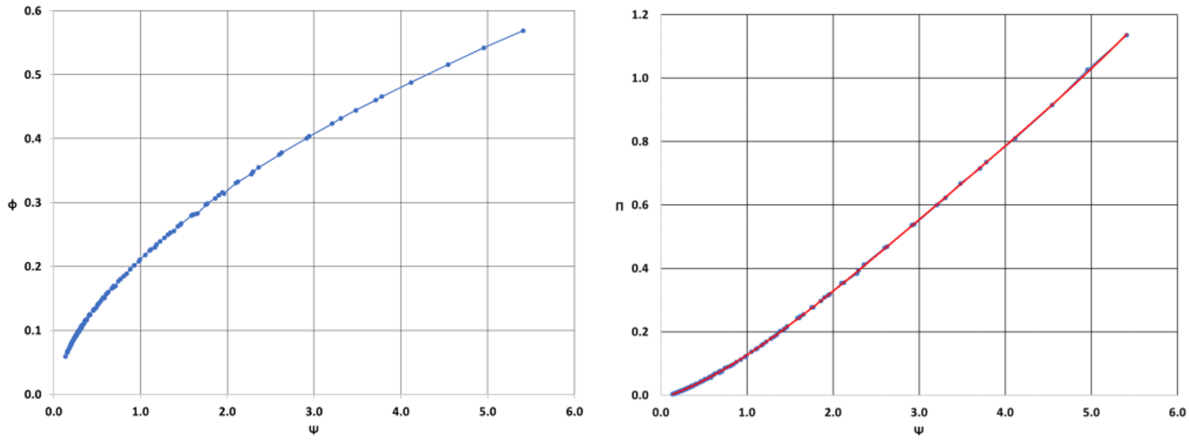

FIGURE 3 - BIRADIAL TURBINE CHARACTERISTIC CURVES. LEFT DIMENSIONLESS FLOW RATE IN FUNCITON OF THE DIMENSIONLESS PRESSURE HEAD; AND RIGHT DIMENSIONLESS POWER IN FUNCTION OF THE DIMENSIONLESS PRESSURE HEAD.

The dimensionless coefficient of pressure head $\boldsymbol{\Psi}$, flow rate $\boldsymbol{\Phi}$ and turbine mechanical power $\boldsymbol{\Pi}$ are calculated as follow:

$$\boldsymbol{\Psi} = \frac{p_{ch}}{\rho \Omega^2 d^2} \tag{1}$$

$$\boldsymbol{\Phi} = \frac{Q_t}{\Omega\, d^3} \tag{2}$$

$$\boldsymbol{\Pi} = \frac{P_{turb}}{\rho \Omega^3 d^5} \tag{3}$$

$$\boldsymbol{\eta} = \frac{\Pi}{\Psi \Phi} = \frac{P_{turb}}{p_{ch} Q_t} = \frac{P_{turb}}{P_{pneu}} \tag{4}$$

Being the turbine inlet p_{ch} [Pa]

the air density $\boldsymbol{\rho}$ [kg.m^{-3}]

the turbine rotational speed Ω [rad.s^{-1}]

the turbine rotor diameter d [m]

the volumetric flow rate Q_t [m^3.s^{-1}]

We can then derive the pneumatic power from Eq. (4) the air pressure measured at the turbine inlet, the rotational speed from the generator encoder and using Eq. (1) and (2) and the relation $\Phi = f(\Psi)$ of Fig. 3. The turbine power is obtained the same way sing Eq. (3) and the turbine characteristic curves.

In what concerns the electrical power, a measurement campaign at the Mutriku OWC plant revealed that the estimated value of the electrical power made at the input of the power converter was clearly not realistic. As stated in OPERA Deliverable D4.2 [5], the drive power corresponding to the output of the generator and the dv/dt filter had to be calibrated.

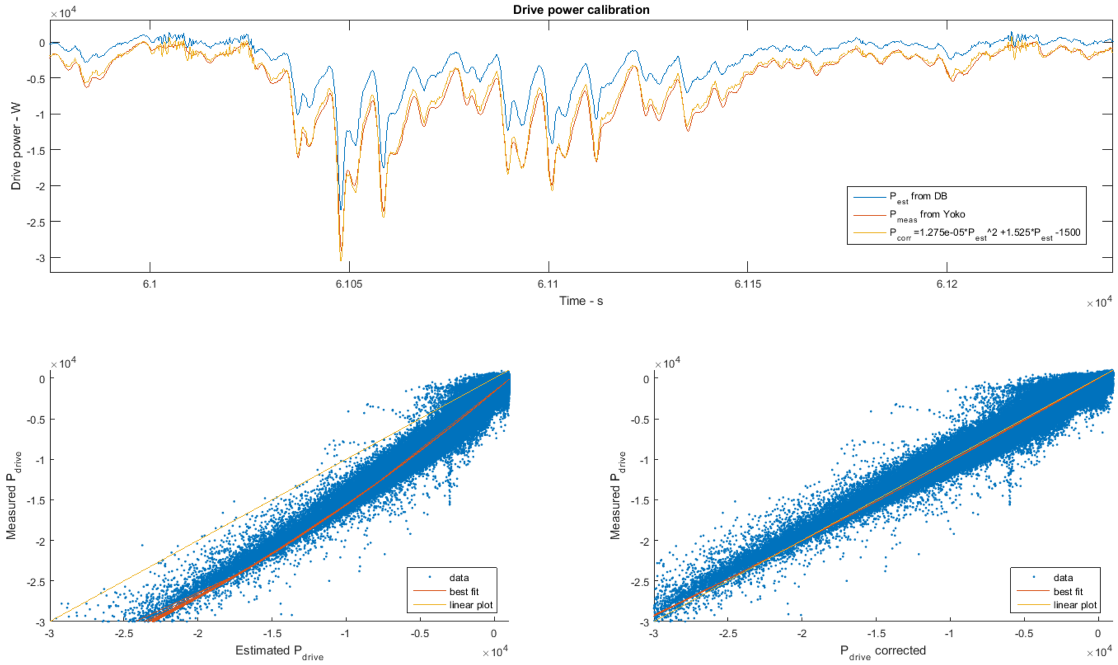

FIGURE 4 - CALIBRATION OF THE ESTIMATED ELECTRICAL POWER [5]

Finally, the last 2 columns of the results table are related to the 2 valve systems operating in the plant. First of all, the HSSV is the one part of the PTO and closes when the turbine speed goes beyond a certain threshold to prevent overspeed events. The table presents the time when the valve was closed. The other one is the butterfly valve of the chamber duct and was either opened (around 90deg) or closed (0deg) during the test. The value in the table is the average of the butterfly valve angle. In sea states more energetic, it can regulate the air flow and used to dissipate the excess of energy.

CONCLUSIONS

This document explained the datasets of the test results used in the publication [1]. Both results from numerical simulations and operational data from sea trials were commented in the journal paper and are present in an excel file attached with this document. The post processing to obtain these results is also detailed in the present technical note.

BIBLIOGRAPHY

[1] F.-X. Faÿ, E. Robles, M. Marcos, E. Aldaiturriaga, and Eduardo. F. Camacho, 'Sea trial results of a predictive algorithm at the Mutriku Wave power plant and controllers assessment based on a detailed plant model', Renewable Energy, 2019.
[2] J. Berque and I. Txarterina, *DS_Wave_Mutriku: Wave resource at Mutriku (Spain)*. 2017.
[3] L. M. C. Gato, A. A. D. Carrelhas, J. C. C. Henriques, B. S. Lopes, J. Varandas, and F.-X. Faÿ, 'OPERA D3.3 - Turbine and electrical equipment performance and reliability in shoreline OWC wave plant', Jul. 2018.
[4] L. M. C. Gato, A. A. D. Carrelhas, F. X. C. da Fonseca, and J. C. C. Henriques, 'OPERA D3.2 - Turbine-generator set laboratory tests in variable unidirectional flow', Jun-2017. [Online]. Available: http://opera-h2020.eu/wp-content/uploads/2016/03/OPERA_D3-2_Dry_Testing_IST.pdf. [Accessed: 19-Mar-2018].
[5] F.-X. Faÿ *et al.*, 'OPERA D4.2 - Shoreline OWC wave power plant control algorithms', Jul. 2018.