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On the turbine-induced damping in Oscillating Water Column wave energy converter

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Abstract

The present paper deals with a study of the damping induced by a turbine in the power take off of ~~an~~ small scale Oscillating Water Column Wave Energy Converter. In order to study the turbine-induced damping, an experimental setup was built.

The experimental setup consists of a wave flume 2000 mm long, 190 mm high and 96 mm wide with an impermeable beach as a dissipative system at the end to avoid wave reflections. The system is all built in Plexiglas to allow optical real-time observation.

An Oscillating Water Column chamber model was placed in the measurement area between the wave-maker and the dissipative beach. The chamber was 37 mm long, 200 mm high and 96 mm wide also built in Plexiglas.

In order to study the effect of turbine-induced damping on the system, a calibrated and variable hole was used to simulate the turbine presence, while outflow and inflow air velocity were measured by means of Particle Image Velocimetry (PIV) method.

Pressures and velocities of air and water as well as the free water surfaces evolution were measured at different wave frequencies and heights.

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Keywords: Oscillating Water Column; Wave Energy; turbine-induced damping; Wave flume.

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1. Introduction

Global electricity needs were mainly addressed by using fossil fuels to feed power plants with significant environmental impact. Therefore, there is an urgent need for power from alternative, renewable and sustainable energy sources. Renewable energy is defined as energy sources which are naturally and continuously replenished at a rate exceeding the use thereof [1, 2].

In oceans and seas, surface waves due to wind represent a considerable amount of energy [3]. Wave power is directly proportional to the square of the amplitude and to the period of the motion. Therefore, waves period between 7 s and 10 s, with amplitude of about 2 m lead to energy fluxes between 40 and 70 kW per meter width of approaching wave [3].

Approaching the coastline, the waves energy intensity decreases because of wave seabed interaction. Energy dissipation in near shore areas can be compensated for by natural phenomena such as refraction or reflection, leading to energy concentration indicated as ’hot spots’.

The global wave power resource is estimated at 2 TW [1]. To take advantage of this available energy, several types of wave energy converters (WEC) can be considered [6, 7].

With this potential, wave energy is probably the most promising renewable energy resources. Thus, nowadays research in this sector is being carried out worldwide [8].

Oscillating Water Column is a technology to extract wave energy based on wave-to-air energy transfer driven by an oscillating column of water trapped in a chamber connected to the sea. The energy in the air is extracted normally by means of a self-rectifying air turbines placed in a hole on top of the chamber (the power take-off). While water level oscillates in the chamber, the trapped air inside is compressed and expanded generating a bi-directional flow towards the atmosphere and to the chamber through a self-rectifying air turbine that rotates in the same direction regardless of the direction of the air flow. The air turbine is generally connected to an electric generator producing electricity. Compared to other *WECs*, the main advantage of OWC devices is that they do not have any moving parts in the water, leading to easier maintenance works [9].

In order to investigate the factors affecting the behavior of Wave Energy Converter systems under controlled conditions, Water Flume (WF) tests are usually performed. Water flume tests are commonly carried out to study the link between configurations, dimensions, other design parameters and system performance [2]. The aim of these tests is to better understand the influence of critical parameters on performance and improve, calibrate and test theoretical models.

Due to the scaling effects, system inefficiencies and manufacturing complications the Power Take-Off (PTO) is normally simplified as an equivalent physical PTO *device* [1, 2]. Different turbine types specifically designed are used as PTO in OWC systems [3, 4, 5].

The present paper deals with a study of the damping induced by a turbine in the power take off of an Oscillating Water Column Wave Energy Converter. Velocity and waves heights as a function of time were optically measured in a small-scale wave flume. The pressure differential between the OWC chamber and atmosphere was registered as well. In particular, the effects of the turbine damping induced on the OWC were investigated experimentally.

Nomenclature

d	Damping hole diameter
D	Power Take-Off diameter
WH_in	Wave Height inside the OWC chamber
WH_ou_150	Wave Height outside OWC chamber at 150 mm before chamber centreline
WEC	Wave Energy Converter

PTO	Power Take-Off
OWC	Oscillating Water Column
OWCWEC	Oscillating Water Column Wave Energy Converter
PIV	Particle Image Velocimetry
WF	Water Flume

2. Experimental set-up

A small-scale experimental setup was built in order to test Oscillating Water Column systems. In particular, the experimental setup is composed by a small-scale wave flume able to simulate regular and irregular waves and their interaction with oscillating water column systems. Fig. 1 shows a schematic of the wave flume used in the present paper.

The main part of the experimental setup is the wave flume that is 2000 mm long, 190 mm high and 96 mm wide with an impermeable beach at an end and a dissipative system just behind the waves maker at the other side to avoid wave reflections. The whole system was built using transparent materials to have a complete optical access.

The wave~~s~~ maker is a vertical plate moved by an electrically controlled piston with a maximum speed of 46 mm/s in both directions. Sinusoidal, triangular, square waves can be imposed to the piston controller with variable frequency and duty cycle. The plate displacement is related to frequency and piston velocity.

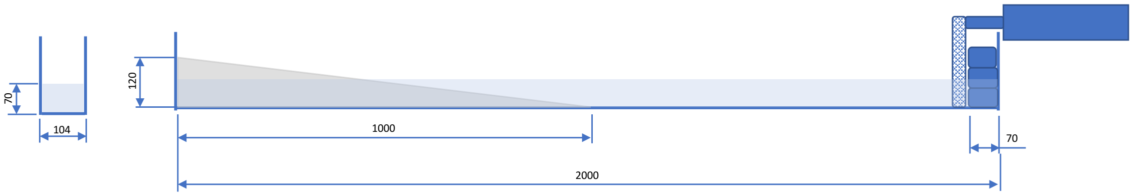


Fig. 1. Small scale wave flume

The oscillating water column studied in the present paper is a semi-submerged chamber with a simulated power take-off on the top of the main chamber.

The OWC tested was installed in the middle of the water flume testing section and the damping hole was varied according to Table 1.

On the side of the OWC chamber a pressure transducer was installed to register in-chamber pressure traces while running. Two Trafag MIT-12-8473_100mbar ceramic relative pressure transducers, with a measurement range from 0 to 0.1 bar with an accuracy of ±0.2% of full-scale, were used.

In order to measure inflow and outflow velocity at the damping hole Particle Image Velocimetry (PIV) technique was used [10]. Velocity field around the damping hole was acquired. PIV trigger system was used to synchronise measurements.

Particle Image Velocimetry is an optical method to visualize and measure flow field with particular attention to velocity field in different applications [10, 11]. This method is used widely to obtain instantaneous velocity measurements and related fluid properties. The fluid has to be seeded with small tracing particles, which are assumed to realistically follow the flow dynamics (the Stokes number is the degree to which the particles faithfully follow the flow). As far as the seeding is concerned, an air-assisted atomizer was used to create small oil droplets in the flow field. The Stokes number of the seeding was maintained lower than 0.1, so that the oil droplets follow fluid streamlines closely. Moreover, the velocity field measurements were performed waiting the complete quiescence of the oil droplets so as the flow conditions were not perturbed by air-assisted atomiser stream.

An Ion laser illuminates the fluid and the entrained particles, so that particles are visible. Dual frames cameras register images sequence and the motion of the seeding particles is used to calculate velocity and direction (the velocity field) of the flow under study. In Fig. 2 the measurement scheme is reported. The measurement plane considered in this work is the wave flume longitudinal symmetry plane. This plane is overlapped with the OWC chamber symmetry plane.

Table 1. Used damping hole dimensions and ratio.

d [mm]	**Ω_{dh} [mm^2]**	**Ratio $\Omega_{dh}/\Omega_{base}$ [-]**
4	12.57	0.05
6	28.27	0.12
8	50.26	0.22
10	78.54	0.35
Reference D = 17	Ω_{base} =226.98	1

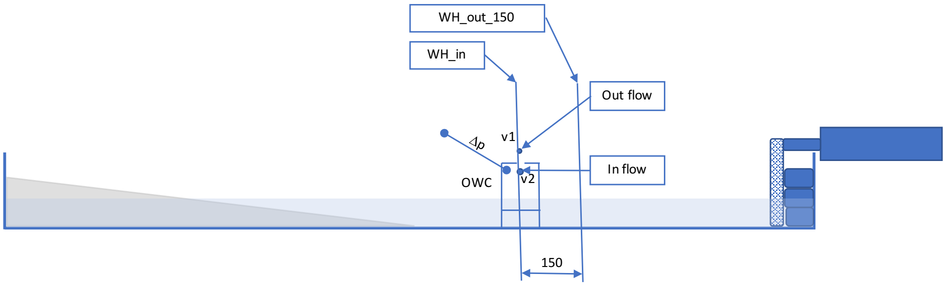


Fig. 2. Oscillating Water Column measurements schema

3. Experimental methods

Nowadays, image analysis and correlation methods are widely used in lots of industrial and scientific applications. Digital images contain several data that can be transformed into information [12]. The accuracy of this technique depends on three factors: image quality, algorithm performance and technique calibration [13].

As far as image quality is concerned, this is caused mainly by noise or unwanted or disturbed signals in the images. Many techniques can be used to handle the problem of low image quality such as to mount the video camera at the right distance to appreciate image boundary, to create the necessary contrast between water and the background using a dark colour for the back side of the water flume, to install a solid homogeneous plate behind the camera to reduce reflected shadows, to control room light to reduce noise. All these methods were used in the present work to increase image quality as described in [14]. Moreover, Particle Image Velocimetry image analysis technique was used in this work for images acquisition and velocity field calculation on the longitudinal symmetry plane of the wave flume. Image calibration was carried out using a single image of a plane target with round in plane and out of plane marks. A least square method between the target plane coordinates and the image plane coordinates was used to locate target marks. The calibration target global dimensions also define the measurement area.

In order to measure the continuously changing water surface elevation over time on the wave flume longitudinal symmetry plane an edge detection algorithm was used for detecting the water surface as an edge in each frame and converting the pixels between the edge and reference point into water surface elevation [14, 15]. In Fig. 3 an example the of edge detection algorithm results is shown. In particular, a crop of the original image acquired with the PIV camera elaborated by means of Matlab edge detector algorithm is reported. In the image in Fig. 3, OWC chamber walls were highlighted.

The black and white images were analysed with the Matlab Canny edge detector at the appropriate threshold [16, 17, 18]. In the obtained binary image, the foreground (the edge) is the colour white (pixel value = 1), while the background is represented by the colour black (pixel value = 0). After that, the binary image was processed in the algorithm by detecting the edge or water surface elevation and showed the result by referring to the exact scale at the image. The water surface elevation time series were linked to the frame time series. Therefore, the sequence of image frames was equal to the continuously changing water surface elevation over time.

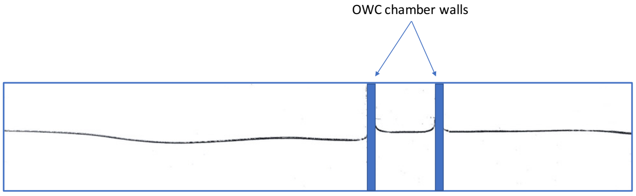


Fig. 3. Edge detection algorithms process results

The final result from the edge detection algorithm was the relationship of water surface elevation at the monitoring positions (wave flume longitudinal symmetry plane). Then the main wave characteristics, represented by wave height, wave period and wave length, were acquired and analyzed to obtain time series data [19].

A parametric experimental analysis was carried out to study the turbine-damping induced effects on the OWC behaviour. In more details, a sinusoidal signal was used as wave generator input with a variable frequency of 1 Hz and 2 Hz, while the damping hole diameter was varied between 4 mm and 17 mm according to Table 1.

4. Results and discussion

Using the described measurement and analysis methods, with reference of Fig. 2, wave height and air velocity outside and inside the OWC chamber, as well as pressure differential between chamber and atmosphere were measured as a function of time for each damping hole diameter reported in Table 1.

For the sake of simplicity, only the comparisons between the damping hole of 4 mm and the reference damping hole of 17 mm for input frequency of 1 Hz (Fig. 4) and 2 Hz (Fig. 5) are reported.

In Fig. 4 (a) and (b), measured wave heights in the OWC chamber centreline and at a distance of 150 mm from that centreline are shown for an input wave frequency of 1 Hz. As it is possible to observe a time shift between the two curves is evident. The smaller *is* the damping hole diameter, the higher is the time shift. This behaviour was observed for all studied damping hole diameters. Considering the results obtained for input wave frequency of 2 Hz (see Fig. 5 (a) and (b)), a constant time shift was observed for whole damping diameters set.

As far as the "v1" position velocity is concerned (see Fig. 2), an average positive velocity is registered for almost all analysed cases (see Fig. 4 (c) and (d), Fig. 5 (c) and (d)). This is probably due to the different fluid dynamic behaviour in suction and pumping phases. The pressure differential for input wave of 1 Hz (see Fig. 4 (e)) is mainly over the atmospheric pressure for the smaller damping hole and mainly under atmospheric pressure for the reference damping diameter (see Fig. 4 (f)), while at 2 Hz the pressure differential shows mainly negative values for the smallest hole and higher values for the largest (see Fig. 5 (e) and (f)). This is probably due to the waves interactions inside and outside the OWC chamber.

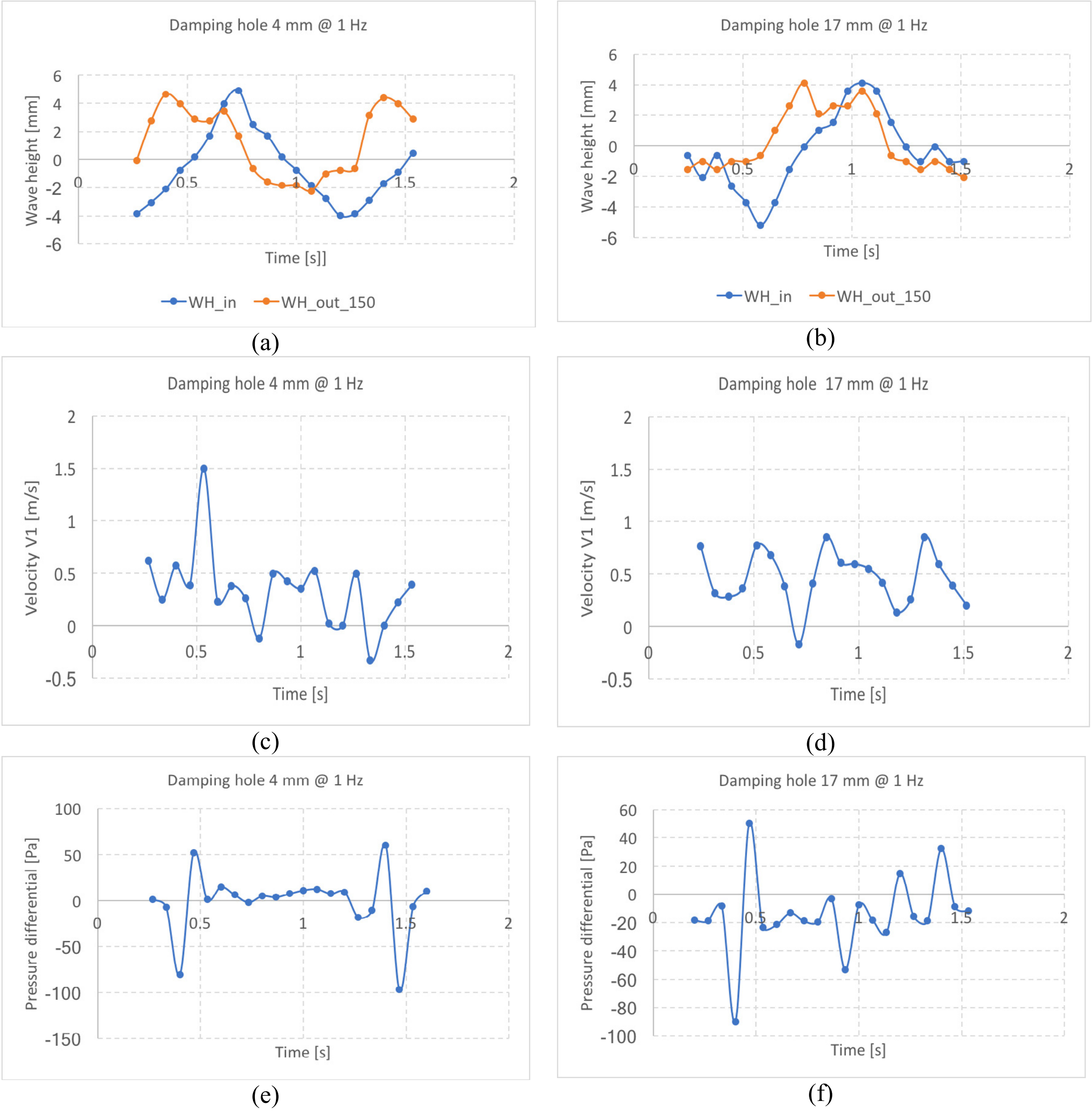
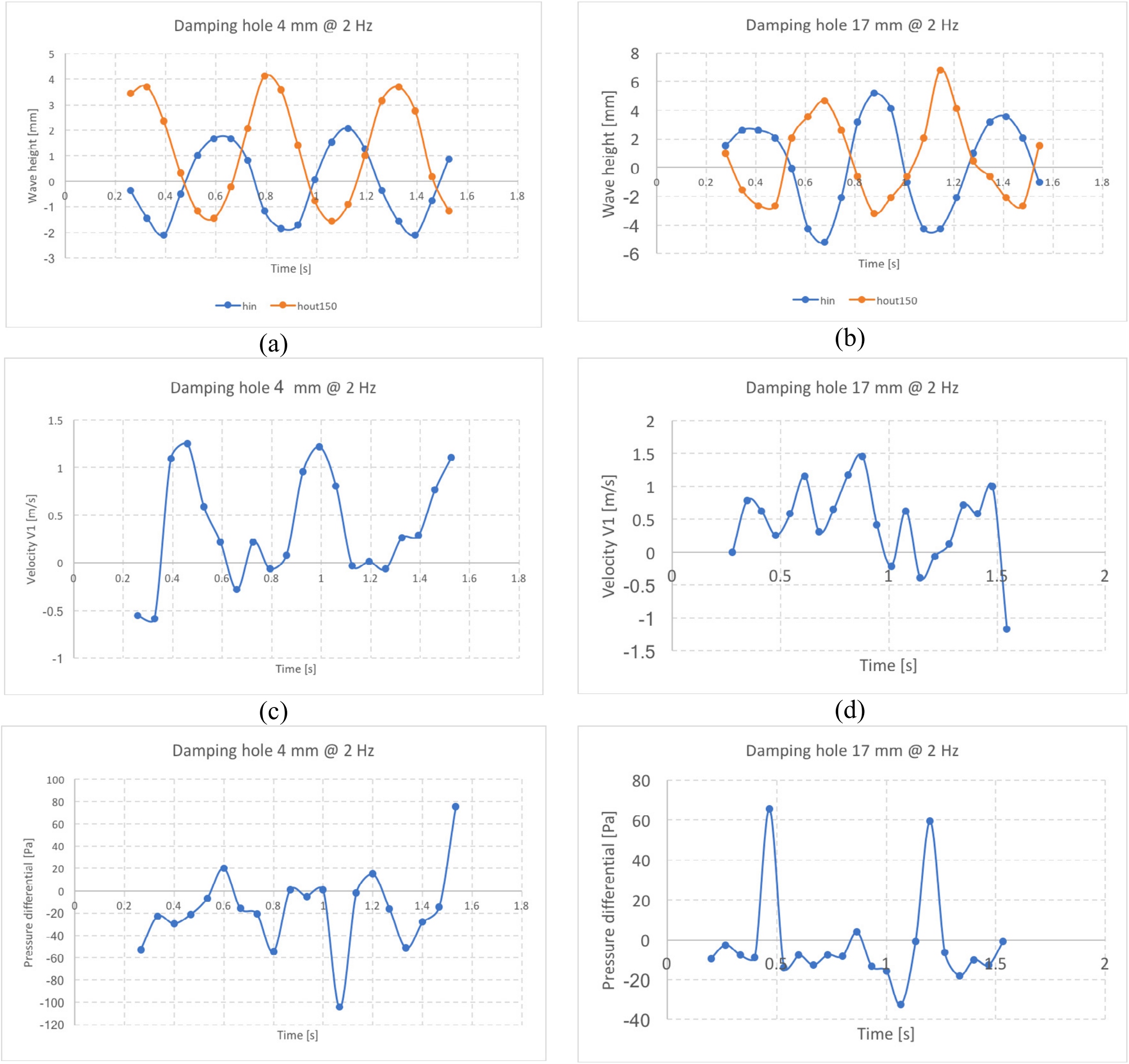


Fig. 4. Wave height (a), (b), air velocity in "v1" (c), (d) and pressure differential (e), (f) as a function of time at 1 Hz for damping hole diameter of 4 mm and reference diameter of 17 mm respectively



(a) (b)

(c) (d)

(e) (f)

Fig. 5. Wave height (a), (b), air velocity in "v1" (c), (d) and pressure differential (e), (f) as a function of time at 2 Hz for damping hole diameter of 4 mm and reference diameter of 17 mm respectively

5. Conclusions

The present paper deals with an experimental study of the behaviour of an Oscillating Water Column systems as a function of incident waves characteristics and power take-off damping. The latter was simulated by means of a variable diameter hole.

The present study was carried out by means of a small-scale water flume with variable wave frequency and height. An optical method, based on Particle Image Velocimetry technique, was used to measure wave heights and air velocity inside and outside the oscillating water column chamber. At the same time pressure was registered.

The presented results highlighted that using an input wave frequency of 1 Hz a correspondent 1 Hz wave was obtained, while a 2 Hz input frequency leads to a correspondent frequency of about 1.6 Hz.

A time shift between inside and outside waves was observed and smaller the damping hole diameter higher the time shift is for the case of 1 Hz input wave. Imposing a 2 Hz input wave the time shift observed is constant with damping hole diameter changing. The implemented small-scale wave flume with optical measurement methods can be used for the study of general principles governing the behaviour of Wave Energy Converter systems under controlled conditions.

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