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Oscillating water column wave energy converter by means of straight-bladed Darrieus turbine

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Abstract

The present paper deals with a preliminary study on an Oscillating Water Column Wave Energy Converter (OWCWEC). The energy conversion is based on a straight-bladed Darrieus type wind turbine. The design of the turbine for maximum power coefficient is discussed.
A physical laboratory scale OWC wave energy converter model was built to measure velocity field in the column. The air column was built using transparent materials to allow Particle Image Velocimetry measurements.Velocity field around air turbine rotor was measured by means of PIV.
The measured velocities with and without the air turbine are used as inputs in the design procedure and to calibrate and test mathematical models.
Moreover, design criteria were obtained using experimental and mathematical results.

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*Keywords:*Oscillating Water Column; Wave Energy; Straight-bladed Darrieus Trubine;

1. Introduction

Wave energy stands out among the different renewable energy sources not only for its high potential - which, according to the International Energy Agency, can reach up to 80,000 TWh / year – but also for its high energy density, the highest of all renewables [1].

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Wave energy is derived from the winds as they blow across the oceans, and this energy transfer provides a convenient and natural concentration of wind energy in the water near the free surface. Once created, waves can travel thousands of kilometres with little energy loss.

The power in a wave is proportional to the square of the amplitude and to the period of the motion. Therefore, long period (7÷10 s), large amplitude (about 2 m) waves have energy fluxes commonly averaging between 40 and 70 kW per m width of oncoming wave. Nearer the coastline, the average energy intensity of a wave decreases due to interaction with the seabed [2].

In the Mediterranean basin, the annual power level off the European countries coasts varies between 4 and 11 kW/m, the highest values occurring in the area of the south-western Aegean Sea. This area is characterized by a relatively long fetch and high energy potential. The entire annual deep-water resource along the European coasts in the Mediterranean is of the order of 30 GW, the total wave energy resource for Europe resulting thus to 320 GW [3].

Oscillating Water Column (OWC) systems are one of the most popular technologies for wave energy conversion [4, 5]. They consist of a partially submerged chamber with an underwater opening on its front and an air turbine. Waves impinging on the device cause the water column inside the chamber to oscillate, which gives its name to the system. As a result of these oscillations, the water column acts like a piston, forcing the air in the upper part of the chamber to flow alternatively out of the chamber and into it, driving the turbine in the process.

OWC converters present two main advantages over other Wave Energy Converters (WECs). Firstly, their simplicity, they consist exclusively of the two aforementioned elements, the chamber and the air turbine. Secondly, their low maintenance cost relative to other WECs, which is a result of both their simplicity and the absence of mechanical elements in direct contact with seawater.

The chamber and turbine are, therefore, the two essential elements of an OWC converter. Two main types of self-rectifying turbines are used: Wells turbines or impulse turbines [6, 7]. As regards the chamber, a number of works were carried out with the aim of studying and optimising the design of the chamber [8, 9, 10, 11 and 12]. It is worth noting that, in most of the studies carried out so far, these two elements of an OWC converter, the air turbine and the chamber, are investigated separately - in spite of the fact that the coupling between both plays a fundamental role in the performance of the system [13]. In effect, the turbine should ideally provide the pneumatic damping (pressure drop through the turbine) for the chamber to work at, or near, resonant conditions, and the chamber should provide the amount of pneumatic power that maximises the turbine output.

The design of the air turbine and turbine type are strictly related to the wave frequency and amplitude. Several authors proposed different design procedure [14, 15], experiments[16] and mathematical modelling [17] in different seas. As known by the authors, in literature there are no studies of using mini or micro OWCs on board of vessels.

For this purpose, in this paper, a preliminary study of a micro OWC converter using straight-bladed Darrieus type air turbine is presented. In particular, a laboratory scale system was realized and analysed by means of Particle Image Velocimetry methodology [18].

Nomenclature

c_p	Power coefficient
P	Instantaneous power
ϑ	Rotor angular position
T	Tangential Force
λ	Tip Speed Ratio
σ	Rotor solidity

ω	Rotor angular velocity
N_b	Blade number
N_T	Stream Tube number
R	Rotor radius
h	Blade length
V_0	Undisturbed wind velocity
Abbreviations	
OWC	Oscillating Water Column
OWCWEC	Oscillating Water Column Wave Energy Converter
TSR	Tip Seed Ratio
RS	Rotor Solidity
NACA	National Advisory Committee for Aeronautics

2. Turbine design criteria

In order to test the implemented OWC a vertical axis Darrieus-type air turbine was built. The turbine represents the first step in a wider research and it is a non-optimised air turbine. The built micro air turbine main characteristics are reported in Table 1.

Table 1 Main air turbine geometric characteristics

Parameter	Value
Airfoil	NACA 0012
Number of Blade	5
Blade cord	32 mm
Rotor diameter	70 mm
Rotor height	70 mm

The air turbine should properly designed and optimised by means of Double Multiple Stream Tube Model. Therefore, the turbine will be optimised in order to maximise turbine power coefficient for the specific air velocity. Eq. 1 represents the turbine mean power coefficient as described by Strickland in [19].

$$\overline{c_p} = \frac{\frac{\sum T(\vartheta)}{N_T} R\ \omega\ N_b}{\frac{1}{2}\ \varrho\ (2\ R\ h) V_0^3} \quad (1)$$

Using this equation it is possible to represent c_p-λ curves varying the turbine rotor solidity. In Fig. 1, as an example, a c_p-λ graph for NACA0012 and Re = 2 10^6 is shown. Turbine rotor solidity and tip speed ratio to get maximum power coefficient can be chosen in Fig. 1.

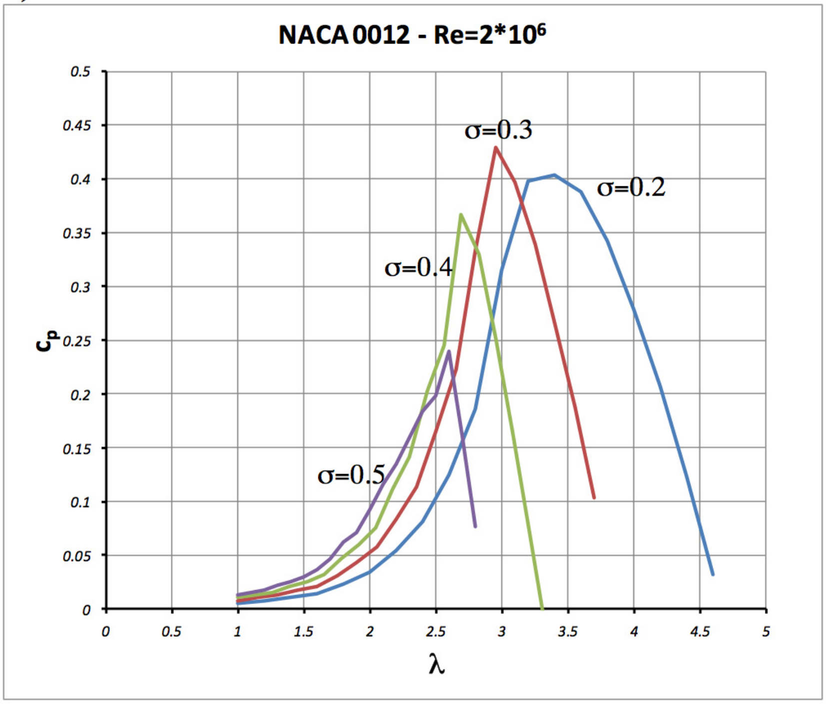


Fig. 1. Rotor solidity effect on power coefficient

3. Experimental set-up

In order to test turbine performance a water column wave energy converter simulator was built. In particular, an airtight prismatic piston moved by an electric motor actuated crankshaft generates a periodic air stream into the column. The air column was built using transparent materials to allow Particle Image Velocimetry measurements. Fig. 2 shows a schematic of the implemented water column wave energy converter simulator.

A straight-bladed Darrieus type air turbine was installed into the air column. The turbine is connected to an electric generator (maximum power of about 0.5 W) to produce power and to an optical encoder (400 pulses per revolution) to measure rotational speed. The rotational speed of the crankshaft can be regulated to change wave frequency and amplitude. Acquisition system and PIV anemometer were used to register turbine performance data and flow field characteristics, respectively. Fig. 3 shows a schematic of the acquisition and control system (Fig. 3a) and PIV setup (Fig. 3b).

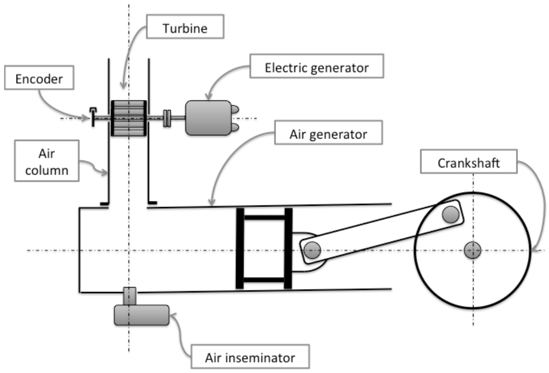
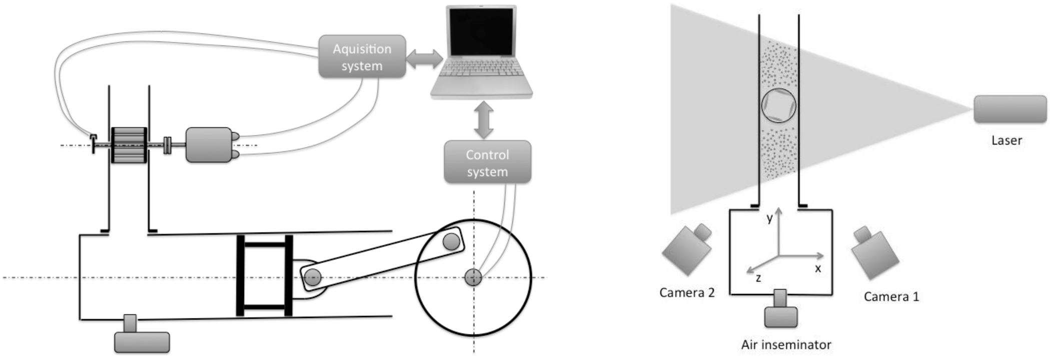


Fig. 2. Oscillating water column wave energy converter simulator



(a) (b)

Fig. 3. Experimental set-up: (a) acquisition and control system; (b) PIV system set-up

Particle Image Velocimetry (PIV) is an optical method to visualize and to measure flow field with particular attention to velocity field [16].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 it is concerned, air atomizer was used to create small oil droplets in the flow filed. The Stoke number of the seeding was maintained lower than 0.1, so that the oil droplets follow fluid streamlines closely.

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.

4. Results and discussion

In this paragraph section PIV results were presented. Fig. 4 shows the average air velocity in the region just before the turbine rotor as a function of time. In the same graph average value V_x, V_y and V_z versus time are reported (see Fig. 3b for coordinate system).

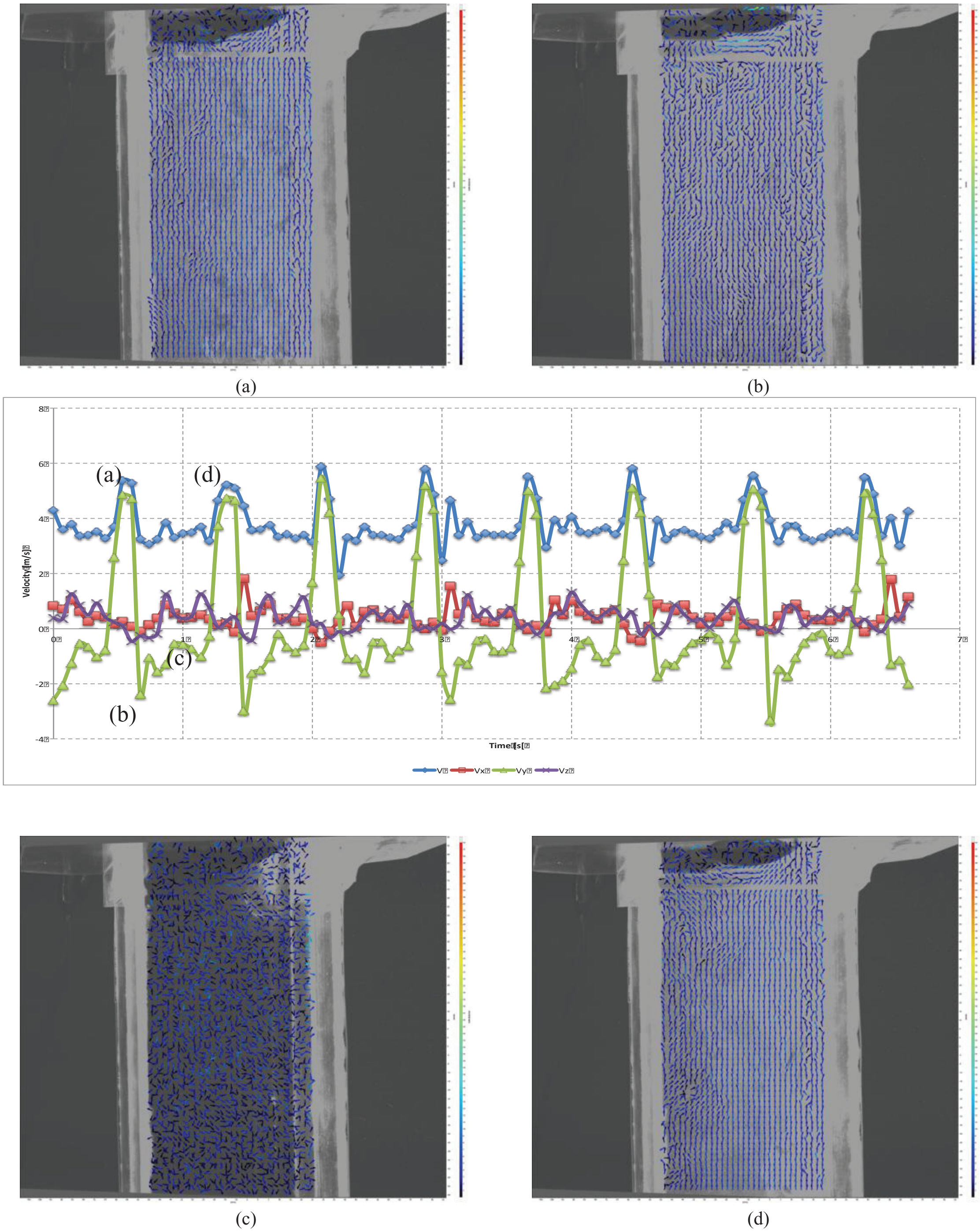


Fig. 4. Average velocity versus time and velocity fields at different time.

In the same figure some PIV measured velocity field are also reported. In particular, registered flow velocity field in a complete piston (wave) cycle are reported as an example. The PIV fields were measured at a frame rate of 15 Hz, while the piston (wave) frequency was about 1.23 Hz.

As it is possible to observe in Fig. 4 (graph), piston cycles are well evident. The magnitude of the average velocity has an increment up to 6 m/s each piston stroke, while maintain a value slightly less than 4 m/s in all others piston phases.

According to the logic, x and z direction average velocity values are very low, while average velocity in y direction, as one might expect, has the main contribution to the velocity in the air column. This velocity component oscillates between -3 m/s and 5 m/s with the same piston frequency.

According to the average velocity four PIV measurements are shown in Fig. 4. In the graph the image reference lettersare reported near each corresponding average velocity value.

The velocity field shown in Fig. 4a corresponds to a top dead centre (piston stroke end) that leads to a velocity peak. It is well evident that the velocity vectors are almost aligned with the air column axis (y-axis in Fig. 3b). A slight interaction with the air column walls is also evident, while a stronger deviation of the velocity field is observed very close to the turbine rotor (top of the image). On the contrary, Fig. 4b is the velocity field at the bottom dead centre. A stronger interaction between turbine rotor and air flow is observed, while in Fig. 4c the new piston stroke almost stops the air column. At the top dead centre a new cycle begins (see Fig. 4d).

5. Conclusions

In the present paper a transparent Oscillating Water Column Wave Energy Converter simulator was built and tested. The system is able to run performance tests with different air turbines at different wave frequency and amplitude. Moreover, flow characteristics and velocity field around turbine rotor can be measured by means of Particle Image Correlation method.

In particular, in this paper a straight-bladed Darrieus type air turbine was tested. Using the PIV system velocity field around the turbine rotor was measured. On the basis of the obtained results the system allows to study velocity field in the air column and around the rotor, while carrying out air turbine performance assessments. This tool can be used to obtain reference experimental data to validate OWCWEC and air turbine design procedure, as well as to calibrate and verify 1D/3D mathematical model predictions.

6. Copyright

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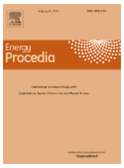

Biography

Actually Sebastian Brusca is a researcher in energy systems and environment at the University of Messina. He is involved in research on the topics of ICE and GT running on conventional and alternative fuels, mathematical models, optimization techniques and renewable energy technologies. The research includes the theoretical and applied aspects.