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Vertical Axis Air Turbine in Oscillating Water Column Systems

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Abstract. The present paper deals with a study of an air turbine as power take-off in Oscillating Water Column systems. In Particular, the focus of the study is on the analysis of the air turbine performance in ducted configuration. Savonius type turbines were tested as a function of air flux oscillation frequency. In more details, a turbine with an overlap ratio of 1/6 was used, while three air flux oscillating frequencies are imposed: 0.1, 0.5, 1 and 1.5 Hz. In order to measure turbine performance, a specific experimental setup was built, based on an OWC simulator. The testing tube (operating as power take-off simulator) was built using transparent materials to allow Particle Image Velocimetry measurement. A simple band brake system was used to apply load to turbine shaft and to measure turbine torque. Therefore, turbine torque, rotational speed, pressure drop and input air velocity were registered and turbine power and power coefficient as a function of tip speed ratio were calculated.

INTRODUCTION

In a world with a global economy, the overall energy production to meet social and economic developments has become one of the most challenging problem [1, 2]. Moreover, environmental constrains require a stronger utilization of renewable energy sources in energy generation coupled with efficiency improvements in the energy production and a more efficient energy utilization by end-users [1, 3].

Nowadays, carbon dioxide emissions reduction and the increase of the renewable energy share are in the Government agenda in many countries around the world. All are parts of the reaction to global climate changes [4, 5, 6 and 7]. European Union has established ambitious targets for the coming years, and in some countries, scientists, NGOs and even governments formulated the goal of converting the entire energy supply into being based 100% on renewable energy.

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Two major challenges of renewable energy strategies for sustainable development can be identified. One challenge is to integrate a high share of intermittent resources into the energy system, especially the electricity supply [8, 9]. The other is to include the transportation sector in the strategies [10, 11].

Moreover, apart from the finiteness of fossil and nuclear energy sources and environmental necessities, the substantial integration of renewable energy creates significant business opportunities for an energy industry that has been growing for more than a century.

Therefore, a strong penetration of renewables in energy mix has driven research efforts all over the world, in the last decades [1].

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 [12, 13].

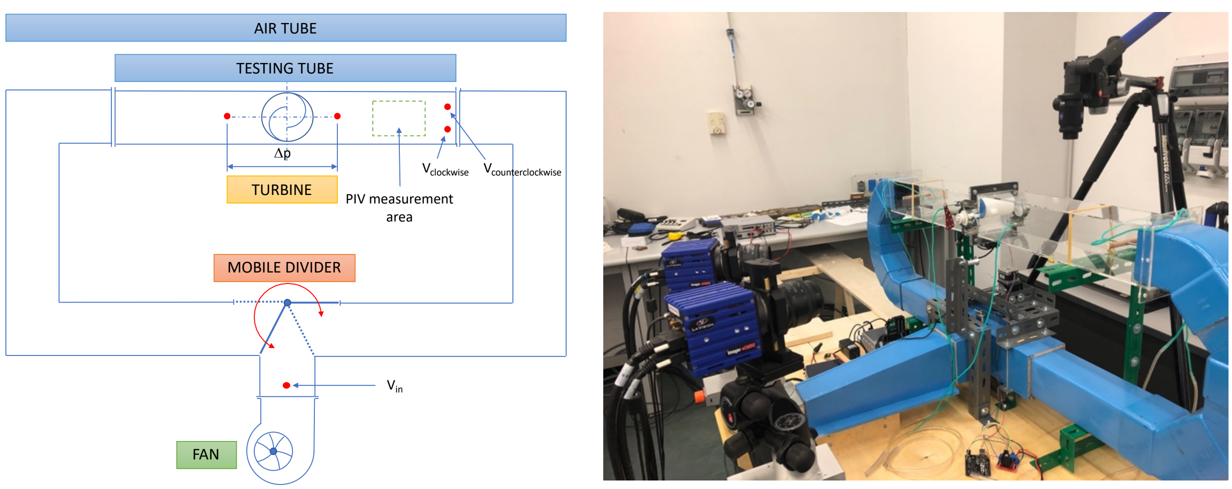
Several technologies were exploited to convert that energy potential in electricity. Among all technologies, Oscillating Water Column Wave Energy Converters are one of the most popular technologies for wave energy conversion [14, 15]. The system is essentially composed by a partially submerged chamber partially opened on its front in the underwater part and an air turbine in a tube (the power take-off). Waves impacting on the front part of the system cause the water column inside the chamber to move up and down inside the chamber. 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.

Different type of auto-rectifying turbines were studied and applied in these type of energy converters. Wells turbine is the most studied and tested [16]. Wells turbine is complicated and its construction costs are relatively high. Therefore, simpler turbine could be used in these systems.

The present paper deals with a study on the performance of ducted air turbine acting as power take-off in Oscillating Water Column Systems (OWC). Savonius type turbines were tested as a function of turbine overlap ratio and air flux oscillation frequency.

EXPERIMENTAL SETUP

In order to test ducted air turbine performance in oscillating air flux, a specific experimental setup was built. This consists of a prismatic air tube (testing tube) in which turbine runs. The testing tube is 100 mm high, 100 mm wide, 1000 mm length and it is made of transparent materials to allow Particle Image Velocimetry (PIV) measurements. It is joined to an air generator at both ends. The air generator is able to blow air at both testing tube ends alternatively with variable velocity and frequency. Thus, is able to simulate the power take-off of an OWC. Figure 1 shows a schema and a photograph of the implemented experimental setup.



(a) (b)

FIGURE 1. Experimental setup: (a) functional schema; (b) photograph of the implemented setup

With reference to Fig. 1(a), a fan blows air into the air tube and a mobile divider deflects air flow alternatively to both testing tube ends. An Arduino [17] based control system moves the divider by means of a step motor. Divider velocity, eventual waiting time, and frequency can be controlled. Thus, the air wave can be imposed. At the same time the air velocity can be controlled varying fan rotational speed.

The experimental setup is completed by measurement system. It consists of:

- Velocity at the air tube entrance (V_{in})
- Velocity at the testing tube end counter clockwise ($V_{counterclockwise}$)
- Velocity at the testing tube end clockwise ($V_{clockwise}$)
- Pressure drop across turbine (Δp)
- Velocity flow field in the testing tube
- Turbine torque
- Turbine speed

As far as the velocities it is concerned, these were measured using pitot tubes and pressure sensors. In the same manner, static pressure drop across turbine was measured using pressure sensors at one dimeter distance from the turbine.

Particle Image Velocimetry system was used to measure velocity flow field in the testing tube. Particle Image Velocimetry (PIV) is an optical method to measure flow field with particular attention to velocity field [18]. 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, an 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. An ion laser illuminates the fluid and the entrained particles, so that particles are visible. Two 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 order to measure torque and determine turbine power a band brake was used to apply load to turbine shaft (see Fig. 2). A nylon-coated metal wire is joined to a load cell fixed to the ground, it passes over the pulley and it suspends a mass at the other end. Varying the suspended mass, it is possible to regulate turbine load and control its rotational speed at operating condition.

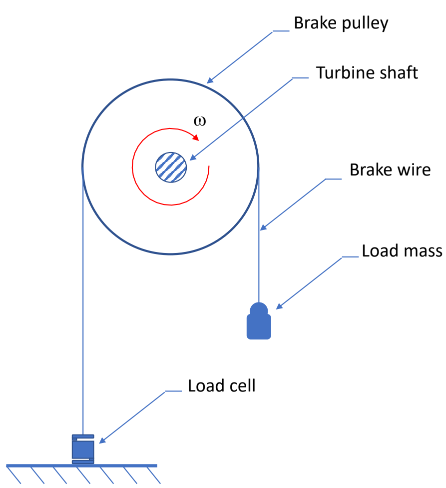
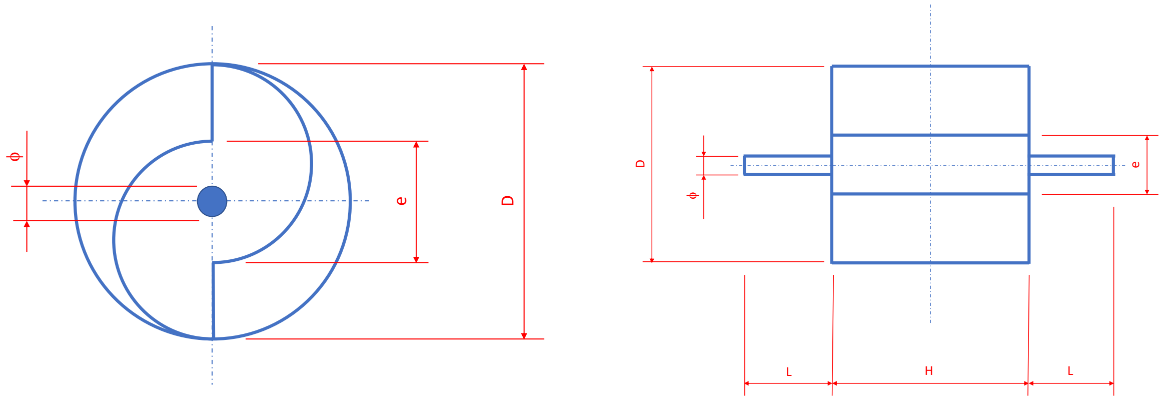


FIGURE 2. Schema of the implemented band brake for torque measurement

MATERIALS AND METHODS

In order to study the effects of flux oscillation frequency on ducted turbine performance in OWC power take-off, Savonius type air turbines were tested in OWC simulator. In particular, a turbine with aspect ratio and overlap ratio of 1 and 1/6 respectively was tested. In Fig. 3 and Tab. 1 main geometric characteristics are reported.



(a) (b)

FIGURE 3. Turbine schema

TABLE 1. Turbine main geometric parameters.

Parameter	Value
Turbine diameter (D)	90 mm
Turbine height (H)	90 mm
Turbine gap (e)	15 mm
Overlap ratio (OR)	1/6
Aspect ratio (AR)	1
Turbine axis diameter (ϕ)	10 mm
Turbine axis length (L)	60 mm

In the present paper, turbine power coefficient as a function of tip speed ratio, as well as turbine torque and power as a function of turbine rotational speed were measured.

In more details, quantities varying sinusoidally were mediated using Setoguchi method [16].

$$\overline{v_a} = \frac{1}{T} \int_0^T |v_a| \, dt \tag{1}$$

$$\overline{\Delta p} = \frac{1}{T} \int_0^T |\Delta p| \, dt \tag{2}$$

where v_a and Δp are the instantaneous turbine upstream air velocity and pressure drop across the turbine, while the overlined variables represent the averaged values. Moreover, T is the velocity wave period.

Considering used torque measurement method, it is possible to determining average power generated by the turbine by means of average torque and rotational speed.

$$\bar{P} = \bar{T} \, \bar{\omega} \tag{3}$$

where overlined P, T and ω are average turbine power, torque and rotational speed.

Knowing average power, upstream velocity and pressure drop, turbine power coefficient comes out.

$$Cp = \frac{\bar{P}}{\frac{1}{2} \varrho \, \Omega_T \, \overline{v_a^3} + \Omega_T \, \overline{\Delta p} \, \overline{v_a^3}} \tag{4}$$

where Ω_T is the turbine swept area, ρ is the air density, while C_p is the average power coefficient. Power coefficient was determined as a function of Tip Speed Ratio (see Eq. 5).

For each flux oscillation frequency (0.1, 0.5, 1.0, and 1.5 Hz) at fixed turbine overlap ratio (OR = 1/6) and peak velocity (5 m/s), 5 repetitions were carried out.

$$\lambda = \frac{\omega R_T}{\overline{v_a}} \tag{5}$$

RESULTS AND DISCUSSIONS

In order to study ducted Savonius turbine performance in oscillating air flux, several tests were carried out using OWC simulator. Turbine torque and power were determined experimentally as a function of turbine rotational speed for different oscillation flux frequencies. Moreover, turbine power coefficient as a function of turbine tip speed ratio was calculated using Eq. 4 [13].

For the sake of simplicity only flux frequency equal to 0.1 Hz for pressure drop and 1 Hz for input air velocity are reported in Fig. 4 and Fig. 5, respectively. In particular, in Fig. 4 an example of pressure drop across the turbine as a function of time is shown, while in Fig. 5 air velocity upstream the turbine is shown as a function of time. In both cases one complete wave was reported.

As you can see in the graph the pressure drop across the turbine is almost symmetric and has the same period of the input wave. This behavior is evident in all registered pressure drop across turbine. The same behavior is evident for input air velocity (see Fig. 5). The symmetry of the input is due to operation of the OWC simulator [19, 20].

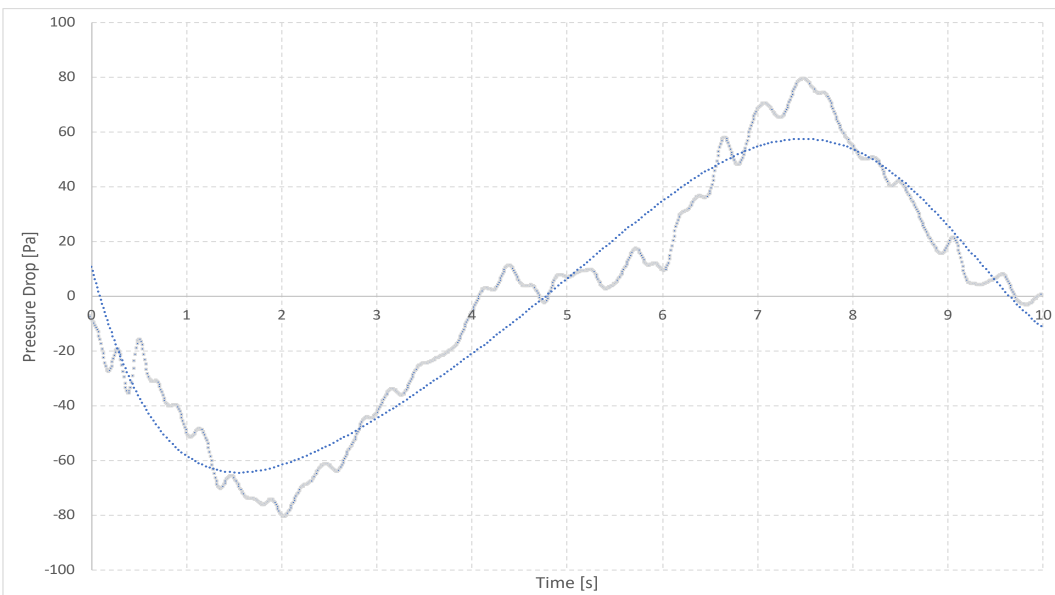


FIGURE 4. Pressure drop across turbine versus time at fixed flux oscillation frequency (FF = 0.1 Hz)

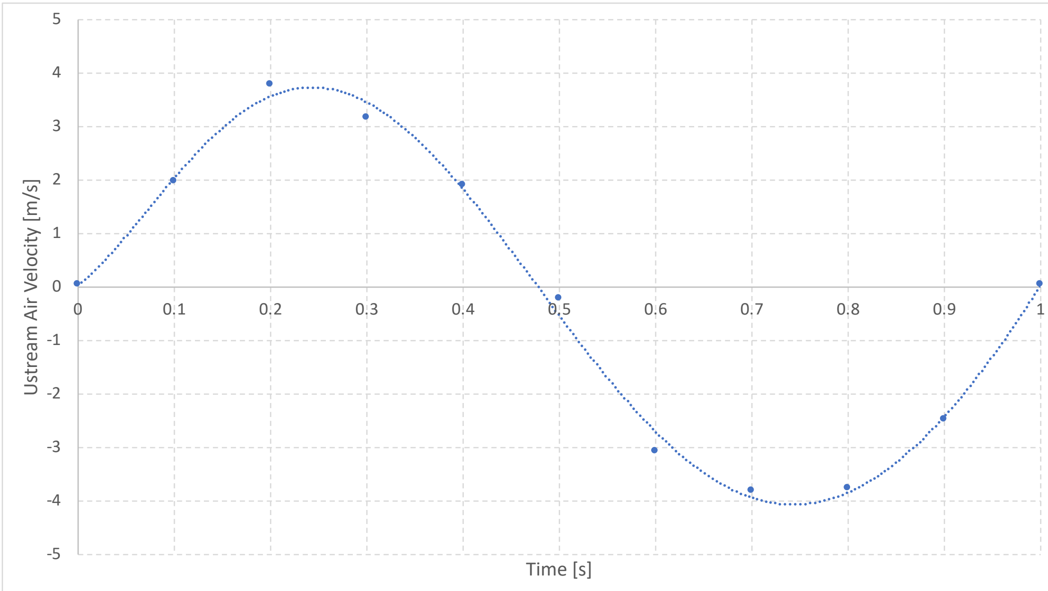


FIGURE 5. Upstream air velocity versus time at fixed flux oscillation frequency (FF = 1 Hz)

Generated power and torque as a function of turbine rotational speed for different air flux frequency were reported in Fig. 6 and Fig. 7, respectively. Observing the graphs, it seems that there isn't an evident relation between torque and power with the air flux frequency.

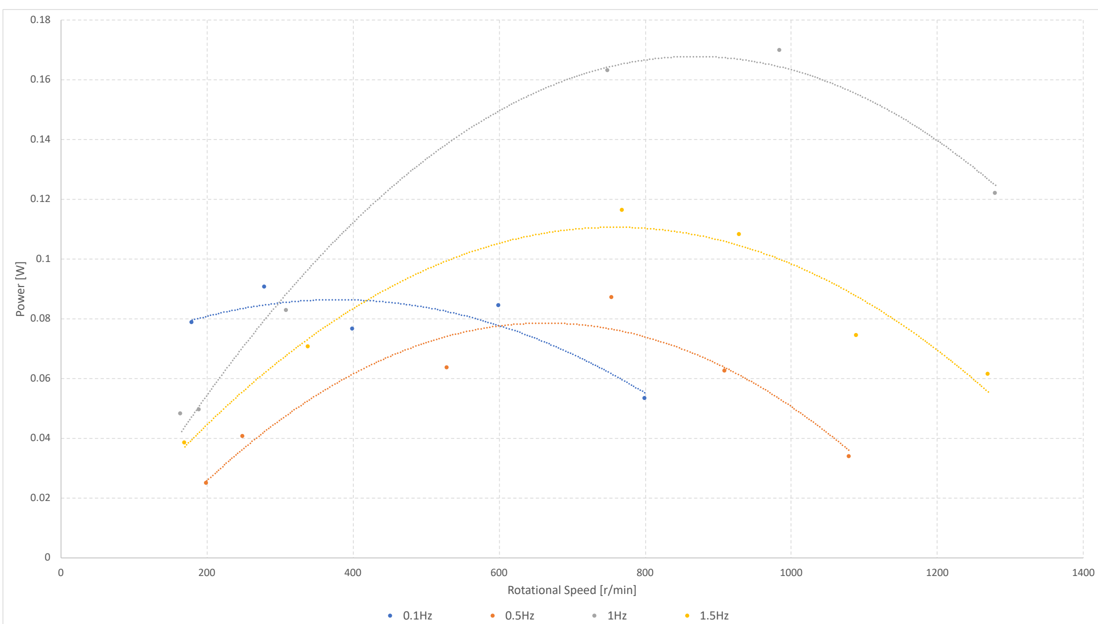


FIGURE 6. Turbine power versus rotational speed at different flux oscillation frequencies

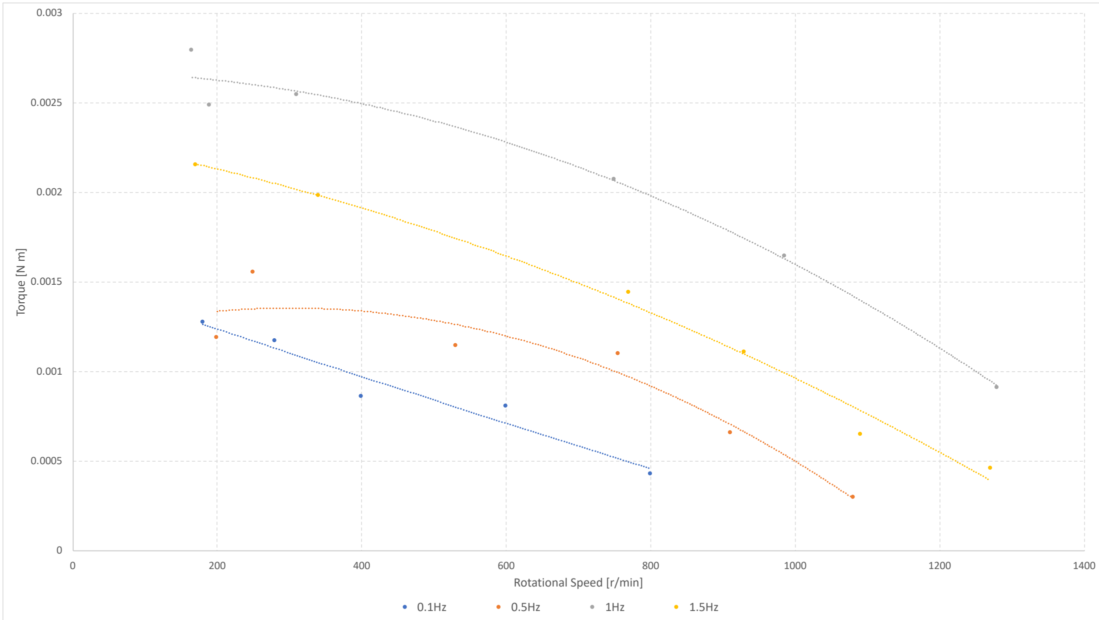


FIGURE 7. Turbine torque versus rotational speed at different flux oscillation frequency

Turbine power coefficient as a function of tip speed ratio for different air oscillation frequencies are reported in Fig. 8. Observing the graph, as for torque and power, power coefficient has a different behavior varying flux frequency. Therefore, observing the maximum of power coefficient as a function of air flux oscillation frequency (see Fig. 9), it is evident that the maximum power coefficient seems to have a sinusoidal behavior. This is probably due to a resonance condition. For an air flux oscillation frequency of about 1.2 Hz a maximum of the turbine power coefficient should be reached.

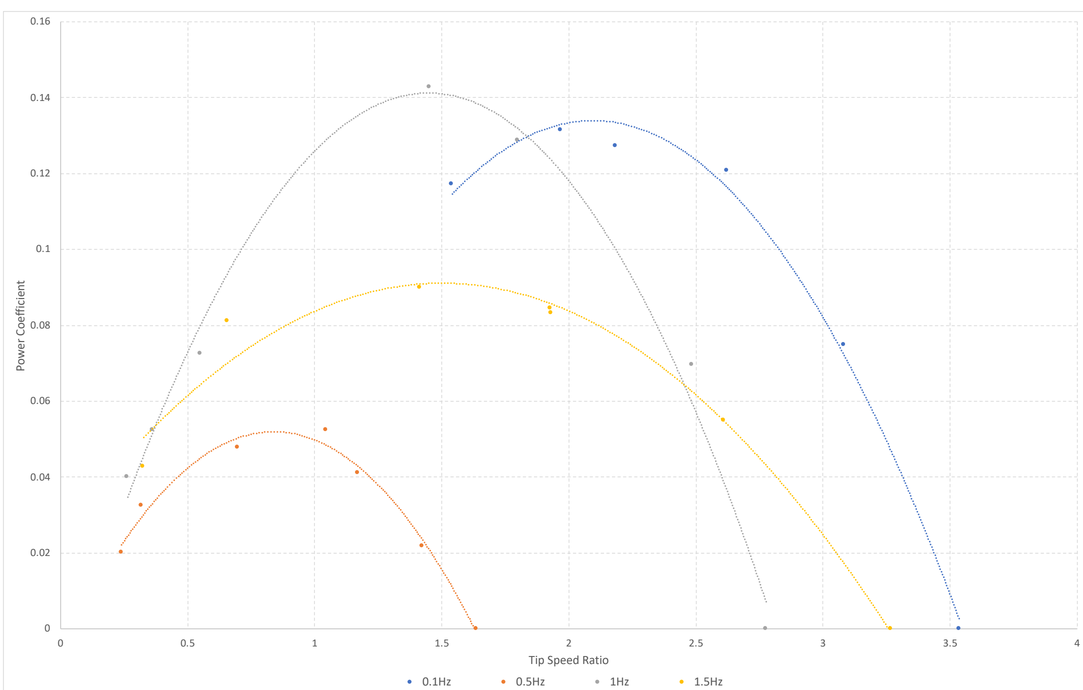


FIGURE 8. Turbine power coefficient versus tip speed ratio at different flux oscillation frequencies

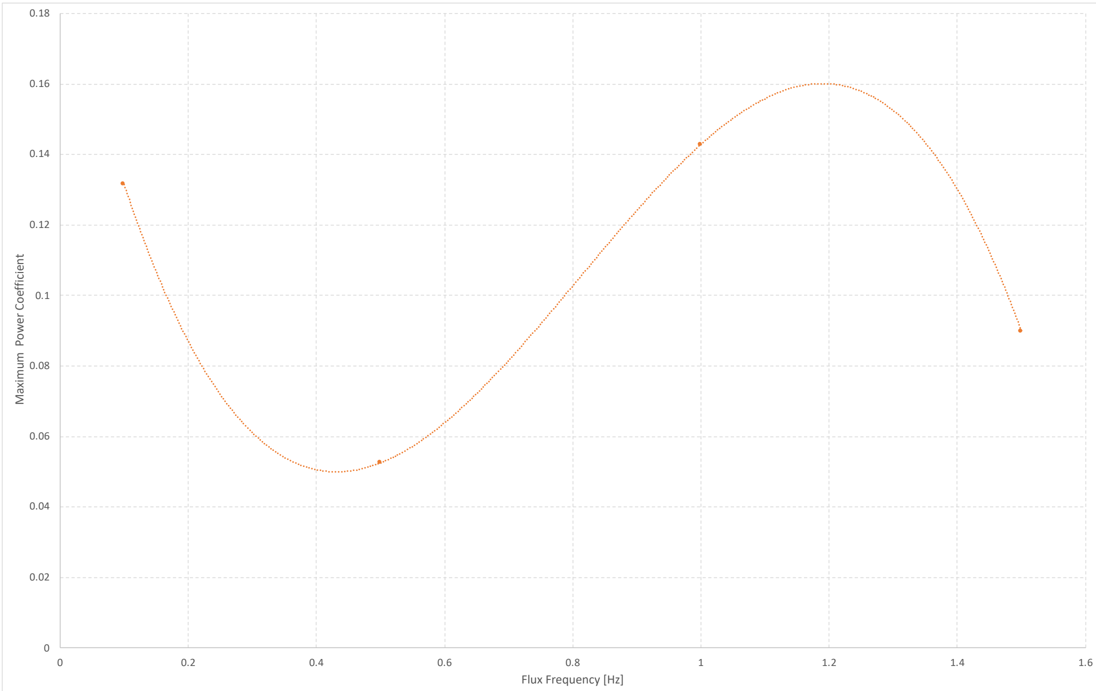


FIGURE 9. Maximum value of turbine power coefficient versus flux oscillation frequency

CONCLUSIONS

The focus of the present paper is the study of ducted Savonius type turbine acting as power take-off in oscillating water column wave energy converter. In more details, a Savonius turbine with an aspect ratio equal to 1 and an overlap ratio equal to 1/6 was tested with an oscillating air flux with different frequencies (0.1, 0.5, 1, and 1.5 Hz) at fixed maximum air velocity (5 m/s).

Turbine torque and power as a function of turbine rotational speed as well as pressure drop across the turbine and input air velocity were determined using an ad hoc implemented OWC simulator.

On the basis of the presented results, it is possible to state that:

1. Turbine power coefficient seems to have a sinusoidal trend with oscillation frequency;
2. The sinusoidal trend of power coefficient is probably due to a resonance with the input wave;
3. A maximum of turbine power coefficient should be reached at 1.2 Hz.

In future works the authors will investigate about the turbine behavior at resonance condition to confirm the actual evidence. Moreover, it is the authors intention to investigate the turbine performance with different overlap and aspect ratios, as well.

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