New Urban Vertical Axis Wind Turbine Design

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Abstract: *This paper develops a different approach for enhancing the performance of Vertical Axis Wind Turbines for the use in the urban or rural environment and remote isolated residential areas. Recently the vertical axis wind turbines (VAWT) have become more attractive due to the major advantages of this type of turbines in comparison to the horizontal axis wind turbines. We aim to enhance the overall performance of the VAWT by adding a second set of blades (3 x 2=6 blades) following the rules of biplane airplanes. The model has been made to operate at a maximum power in the range of the TSR between 2 to 2.5. The performances of the VAWT were investigated numerically and experimentally and justify the new proposed design.*

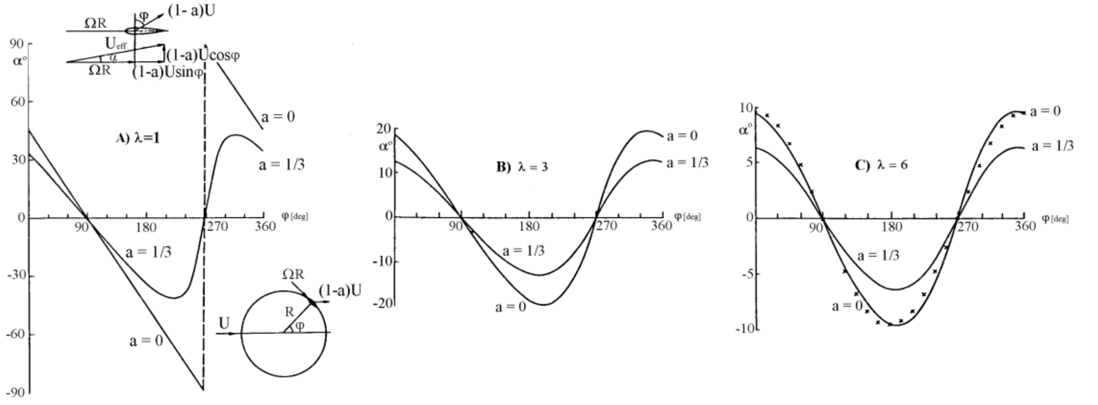
Key Words*: biplane solution, VAWT, numerical and experimental analysis.*

1. INTRODUCTION

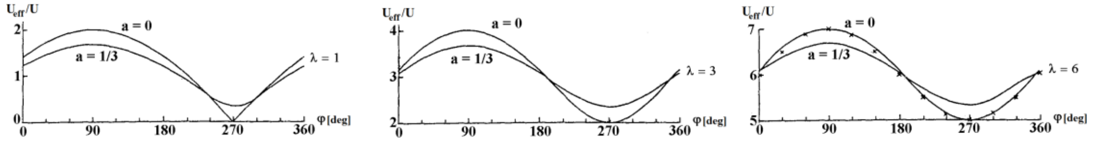
Recently, for urban users, the wind turbine with vertical axis (VAWT) has become more attractive due to its benefits in exploitation, the power range usually covering the domain ranging between 2 kW and 20 kW. As compared to the widely used Horizontal Axis Wind Turbines (HAWTs), VAWTs have many advantages. VAWTs operate with wind blowing from any direction (thus simplifying the wind turbine system); they are designed for low wind speed, and operate at low/medium RPM, have lower vibration and small noise levels and have lower manufacturing and maintenance costs [1]. Unfortunately, VAWTs have many complicated aerodynamic issues, of which the dynamic stall is an inherent phenomenon which appears at low values of the tip speed ratio (TSR < 4**)** and has a significant impact on vibration, noise, and power output of the VAWTs. Figure 1 illustrates one of the typical features of VAWTs (Durries H-type): the magnitude, U_{eff}, and the direction of the effective velocity, α, perceived by the blade, change in a cyclic manner as the blade rotates through different azimuthally angles φ (eq. (1)). As a result, the aerodynamic loads that act on the blade change cyclically with φ.

$$\lambda = TSR,\ \alpha = \arctan\{(1-a)\cos\varphi / [\lambda + (1-a)\sin\varphi]\},\ U_{eff}/U = \left\{\left[\lambda + (1-a)\sin\varphi\right]^2 + \left[(1-a)\cos\varphi\right]^2\right\}^{1/2} \quad (1)$$

The dynamic stall of VAWTs mainly occurs under the circumstances of low values of relative tip speed ratio (TSR < 3...4) and has a significant impact on vibration, noise, and power output of the VAWTs.



a.



b.

Figure 1. The variation of the effective velocity (b) and the incidence (c) as a function of the azimuthally angle φ (the parameter a is the induction factor) [2].

Figure 1 illustrates that at TSR=1...2 the (theoretical) incidence has values over the critical (static) value of the profile, forcing the turbine to operate at deep dynamic stall. Hence, to achieve better performance at this operation level (close to the operation level in urban areas) suitable design solutions are necessary; some of these solutions are based on either the passive flow control to ensure increased carrying at high incidences (without a significant increase of the drag) or the biplane configuration.

In this paper we aim at developing the model of a Vertical Axis Wind Turbine (VAWT) with the short-term goal of physically executing this turbine to operate at a maximmum power of 5kW. The turbine is designed for household users in the urban or rural areas and remote or isolated residential areas (hardly accsessible).

The proposed solution is based on a Darrieus turbine with straight blades, with the initial solidity of 0.3, adding a second set of blades parallel to the first set (increasing the solidity to 0.48), but placed at an offset given by aerodynamic rules peculiar to biplane configurations used in aircraft design.

The biplane configuration ensures an increased lift coefficient, especially at high local incidence, and a compact design compared to a single plane configuration. The detailed advantages of such configurations are later presented in a separate section. We have numerically investigated the passive control solutions that improve the blade flow, for a specific flow regime.

Preliminary results indicate the utility of these solutions through the increase of the power coefficient of the turbine. For future work, we intend to add these control elements to the biplane cofiguration to achieve maximal aerodynamic performances (i.e., efficient energy extraction from a given air flow).

2. URBAN AREA PLACEMENT OF A VAWT

It is well-known that typically the wind flows by the minimal drag path through or over obstacles such as buildings, trees, etc. The borders of these obstacles, i.e., the straight edges of buildings, lead to increased wind speeds of up to 2-3 times the wind speed value of an unperturbed flow.

This phenomenon may be capitalized through placing the turbine in this specific area. Using the ANSYS Fluent software to analyze the wind flow we have evaluated the effect of the presence of a building within the flow field.

Due to the computation limitations we have only simulated the 2D case. First we have remarked that the deviation from the direction of the wind starts long before reaching the obstacle and continues long after leaving it behind. Secondly, we have remarked that the flow spectrum depends on the size of the building and the shape of its edges (straight or rounded). Over the building edge the air flows with a certain deviation. Below this particular flow line the wind flow becomes turbulent with high variations of its horizontal speed. The base or the pedestal of the turbine can be built using this flow line as a reference, such that the entire rotor lies in the high speed flow.

The pole and the upper part of the turbine are profiled such that these elements also play the role of wind concentrators. We have performed numerical tests on three types of buildings.

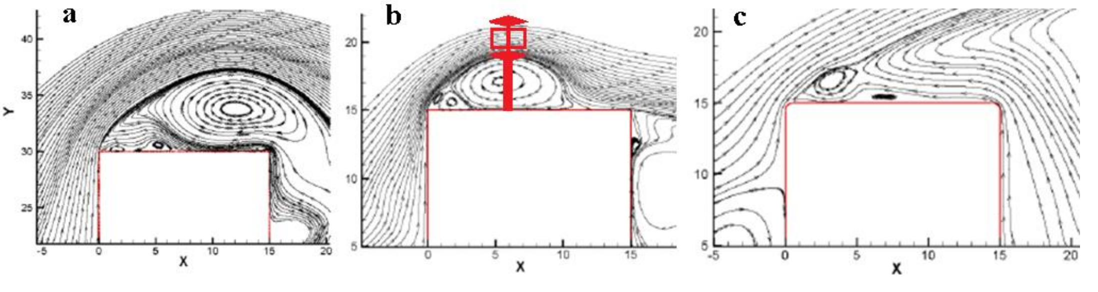


Figure 2. Various shapes of building: (a) – building profile 30m x 15m (H x l), (b) – building profile 15m x 15m, (c) – building profile 15m x 15m with rounded edges (r = 0.5m)

The heights of the turbine tower estimated for the three buildings, for three different locations on the roof with respect to the edge of the building such that the aforementioned criteria are met, are presented in Table 1. The study is made for a 3kW turbine model.

Table 1. Tower height for the analyzed shapes

Roof location	Profile – c	Profile – b	Profile – c
2.5m	4.0m	3.5m	2.5m
5.0m	3.6m	4.1m	4.5m
7.5m	7.5m	4.5m	5.5m

3. THE BIPLANE SOLUTION

The aerodynamic solution for the biplane aircraft ensures aerodynamic characteristics at least equivalent to those of a single plane configuration of identical lift area (under the assumption of ideal fluid). In real life, due to the viscous effects, the characteristics yielded by the bipolar configuration are equivalent to those of a single plane configuration with an area of 20-40% larger and identical to the tale of the biplane. Figure 2 shows the parameters that define the biplane configuration.

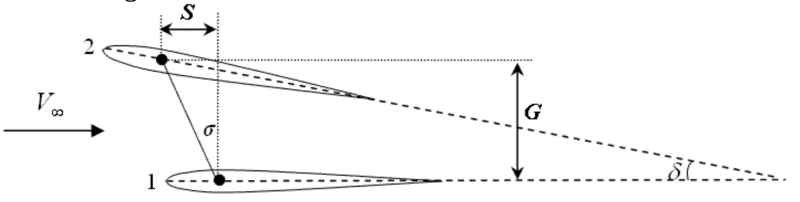


Figure 3. The geometric elements which the aerodynamic characteristics depend on , i.e., stagger- S, gap angle (δ). The positive direction is the one presented in the figure, using the lower wing (lower plane) as reference.

The biplane theory has been developed by Prandtl and Munk. The results of both theories are different from a quantitative perspective, based on the assumptions made, repectively. In the general theory of the biplane, based on experiment Munk [3] mathematically developes, a formula that describes the lift increase,

$$\Delta C_L = \pm 2\, C_L \frac{S}{b^2}\left(\frac{1}{k^2}-\frac{1}{2}\right)\frac{b}{R}\frac{Sg}{b} \tag{2}$$

where S is the total area; Sg is the stagger; b is the span; k is the span factor for a single plane equivalent and R is the distance used to compute the air flow deflection behind the configuration. The term $\Delta C_L = \left(\frac{1}{k^2}-\frac{1}{2}\right)\frac{b}{R}$ is a function of the ratio between the gap and the span (G/b) called the Munk factor. Figure 4. shows the influence of the gap increase at the same span: the Munk factor decreases and the unitary lift coefficient C_L decreases, too.

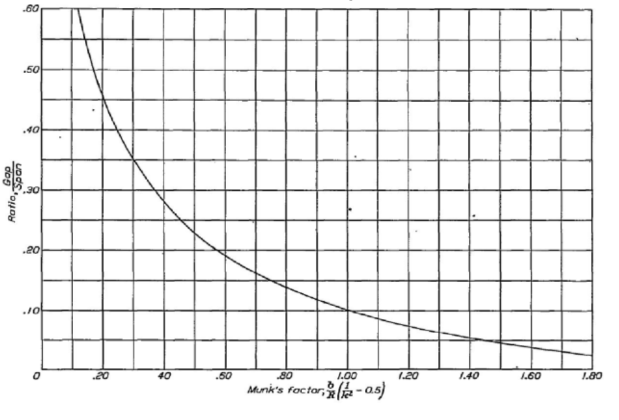


Figure 4. The Munk factor as a function of the ratio between the gap and the span [3]

The induced drag is calculated using Munk's formula

$$C_{D,ind} = \frac{C_L^2}{\pi}\frac{S}{b^2 k^2} \tag{3}$$

where the variables have the same meaning from the drag coefficient formula. Rough computations yield $k = 1$ for all monoplanes and k = aprox. 1.1 for the biplane.

These formulae indicate that the drag and the stagger have a significant influence on yielding an aditional lift force. Another approximation proposed by Prandtl (the orthogonal biplane) leads to an induced drag as in [4],

$$C_{D,ind} = \frac{C_L^2}{\pi} \frac{S}{b^2} (1+\delta) \tag{4}$$

where δ is a mutual influence coefficient which depends on the ratio between the drag and the span:

$$\delta \cong \frac{1-0.66 \cdot (G/b)}{1.05+3.7 \cdot (G/b)} \tag{5}$$

The work of [5-9] have analysed in detail the influences of several parameters on the lift coefficient of the biplane. Assuming the a perfect fluid, using a vortex lattice method-based software (Figure 5), extensive research has been done for angles of 5 degrees (Figure 6).

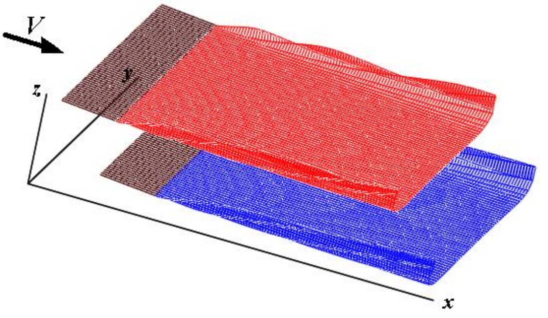


Figure 5. Vortex lattice method applied to biplane configuration

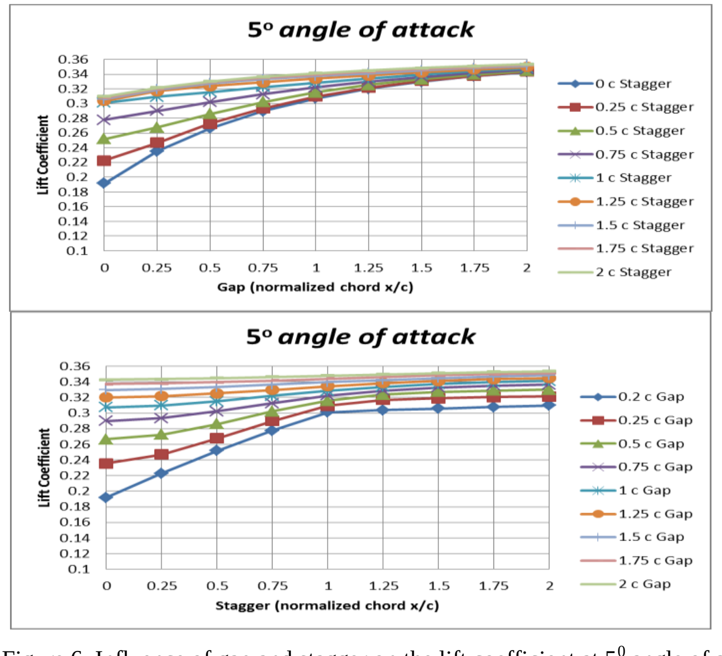


Figure 6. Influence of gap and stagger on the lift coefficient at 5^0 angle of attack

In work [5], several experiments in the aerodynamic tunnel have been performed on a biplane configuration consisting of two thin profiles at a Reynolds number of 60,000.

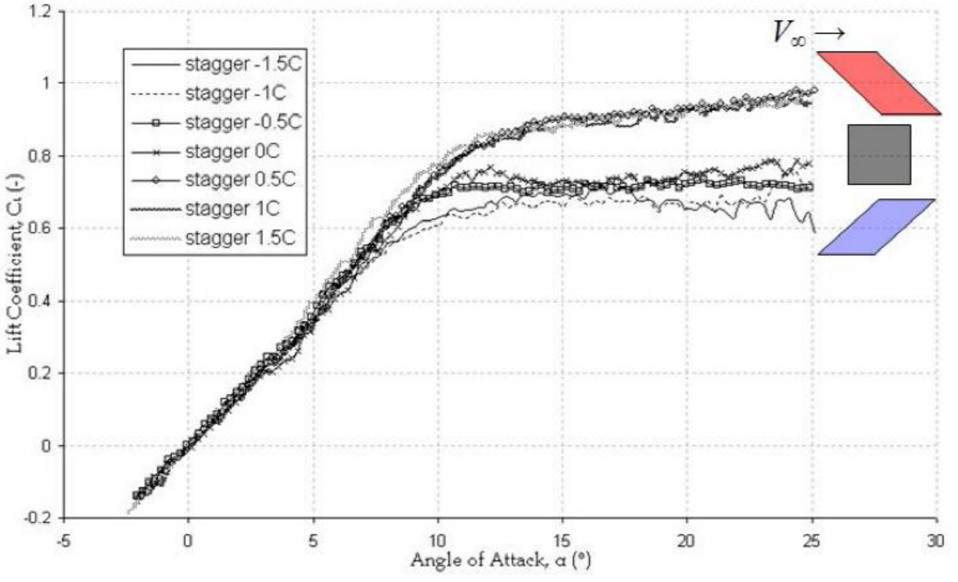


Figure 7. Experimental results for *Re*=60,000

The presented plots emphasize two significant aspects: (1) As expected, the biplane possesses lift characteristics which are better than those of an equivalent isolated wing, especially at high incidences. (2)

At the same gap, the positive stagger configuration (the upper blade in front of the lower blade – red color) exhibits a 20% enhancement in the aerodynamics with respect to the negative stagger configuration (blue color) (Figure 7).

Figure 8. NEW VAWT and NUMERICAL SIMULATION

In Figure 9. we can see the influence of the second set of blades on the solidity. The baseline turbine was a H-type Darrieus vertical axis wind turbine.

The new biplane turbine was made by keeping the radius and adding in the interior a row of three blades with similar airfoil and chord, but staggered with respect to baseline blades with 0.5 c in a tangential direction and staggered across with 0.625 c.

The numerical investigations on 2D model (experiments are currently underway) led to a higher power coeficicient, as expected, compared to classic H-type configuration.

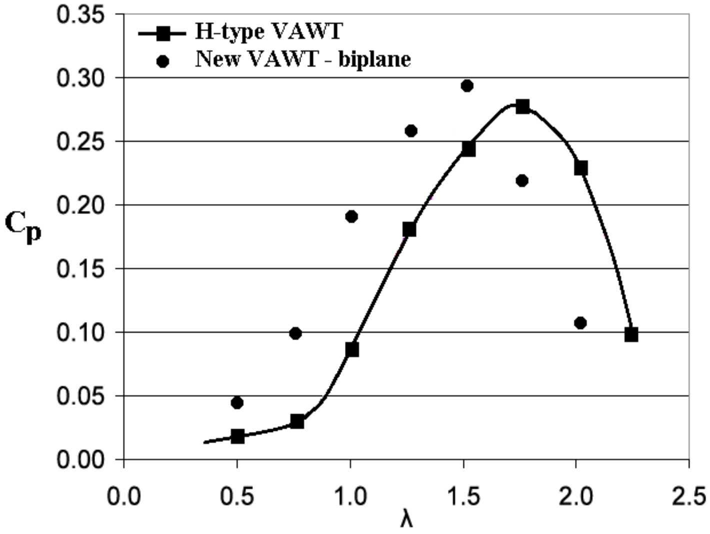


Figure 9. Power coefficient for the baseline configuration (H-type) and the proposed configuration (new VAWT - biplane)

4. PASSIVE CONTROL METHODS FOR VAWTS

To identify which system of passive control is the most efficient on a typical vertical axis wind turbine for the urban environment, we perform a series of numerical simulations using three systems of passive control: turbulence promoter, thin channel and step.

Also, we perform a numerical investigation for biplane configuration. For the present study, we have used Ansys Fluent 13 with Reynolds averaged Navier-Stokes (RANS) model and completed with the turbulence model k-ω *SST*.

To perform these investigations we have constructed a computational 2D model of the vertical axis wind turbine with 3 blades (airfoil NACA 0018) and 0.48 solidity which is placed in a uniform flow with 15 m/s velocity and medium turbulence (5%), the operating regime corresponding to an TSR (tip speed ratio) = 1. The biplane configuration has the same solidity, i.e. 0.48%.

The computational domain contains two zones: the internal zone that contains the rotor which executes a rigid motion with constant angular velocity 60 rad/sec and the fixed external zone (Figure 10.).

Discretization was made in order to respect all the simulation requirements; the number of nodes is around 6 x 10^5, the network contains both quadrilateral and triangular elements. The time step was chosen according to physical aspects and is of the order $\Delta t \cong 10^{-4}$ sec.

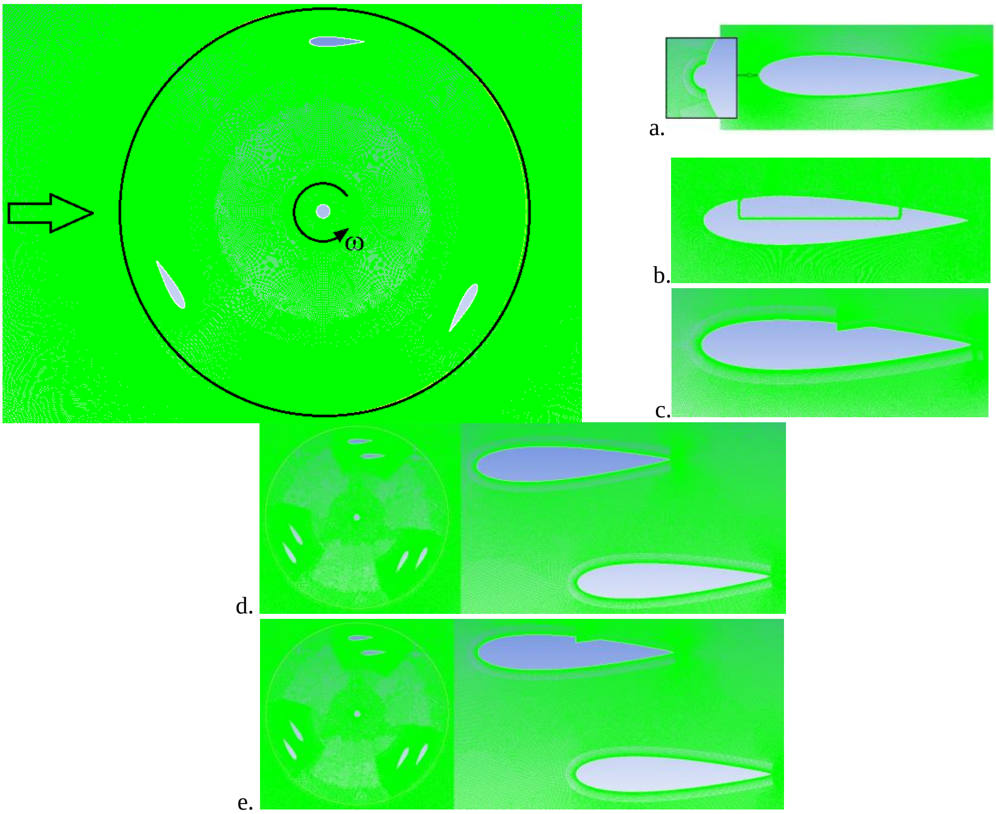


Figure 10. Computational domain for: a. turbulence promoter, b. thin channel, c. step, d. biplane, and e. biplane with step

In the shown configuration, for a uniform flow in upstream, without taking into consideration the shaft, the flow spectrum will be the same with a periodicity of 120^0. The presence of the rotating shaft will create an asymmetry in the velocity field and in the pressure distribution around it, and it will lead to an asymmetry in the boundary layer separation on the shaft and asymmetry of wake formed behind the cylinder. The interaction between the rotating blades and the shaft will lead to a slight modification of the flow at every 120^0, which will affect the values of the aerodynamics coefficients for the entire rotor.
Figure 11. shows the variation of the aerodynamic momentum with respect to the rotation axis, at TSR=1 (tip speed ratio=1), for the reference VAWT and the five passive flow control solutions (biplane among them).

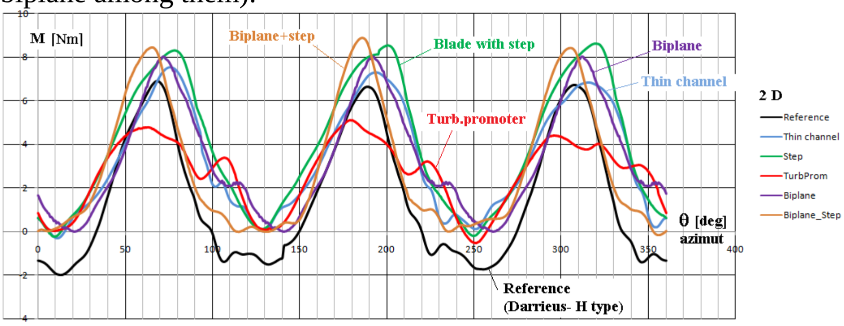


Figure 11. Variation of the aerodynamic momentum of the rotor with respect to the roation axis TSR=1 (for a single roation)

Figure 12 shows the stream lines and the isopressure lines ($\Delta p = p - p_{atm}$) for the biplane configuration (motion is periodic, hence only a few snapshots of the flow field are presented). The vortex structure formed by the biplane configuration are illustrated.

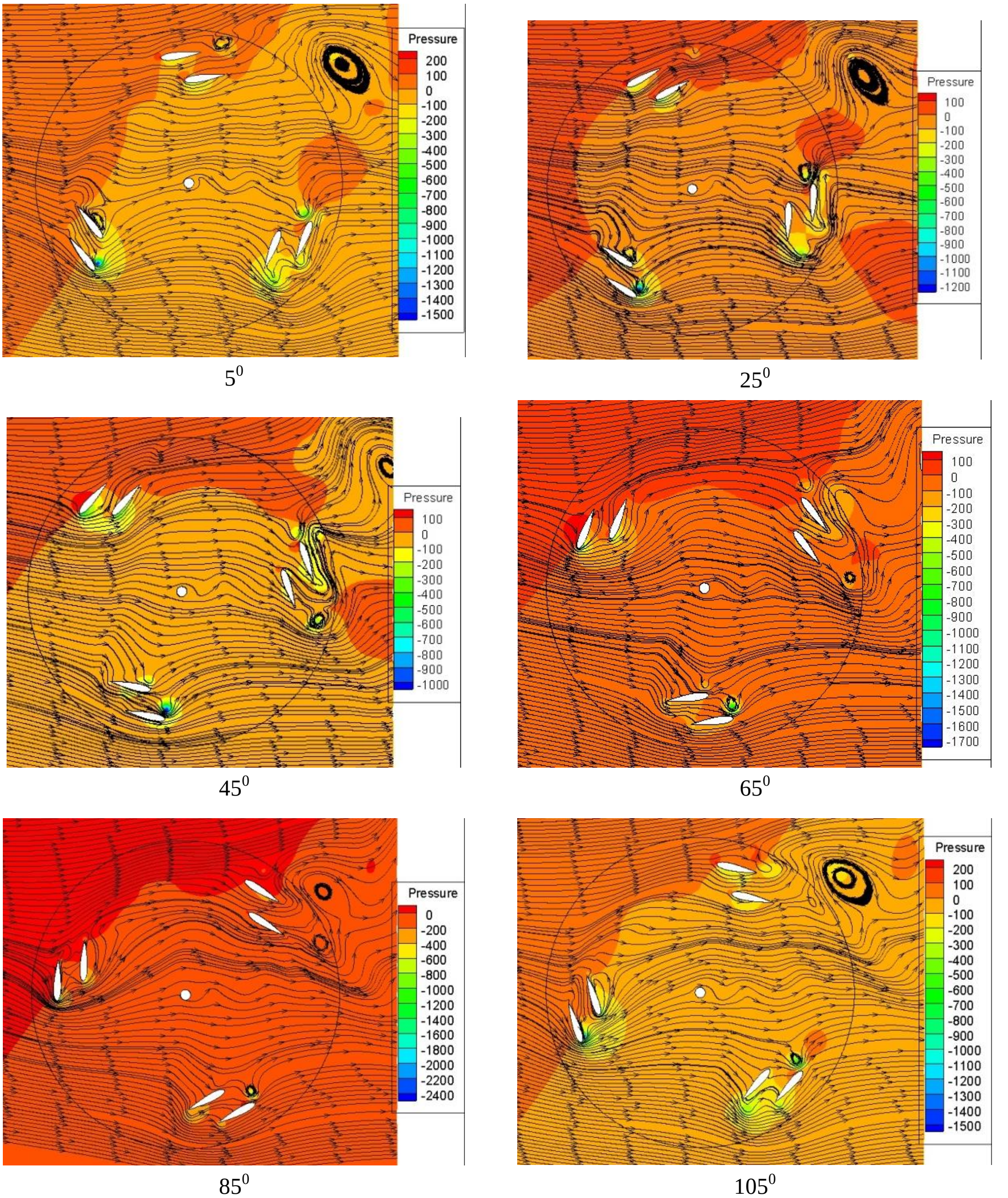


Figure 12. Stream lines for the biplane configuration

Computing the average momentum for a single rotation

$$\bar{M}_z = \frac{1}{T}\int_0^{T=2\pi} M_z(\theta)d\theta \tag{6}$$

and the power coefficient

$$C_p = \frac{\bar{M}\,\omega}{\rho\, U^3\, 2RH/2} \tag{7}$$

for ω=60 rad/s, H=1 m, R=0.25 m, ρ=1.225 kg/m^3, we get the following:

	Basic configuration	**Turbulence generator**	**Thin jet**	**Threshold**	**Biplane**	**Biplane + Step**
M_z [N m]	**1.504**	**2.686**	**3.319**	**3.994**	**3.314**	**2.964**
Cp	**0.087**	**0.156**	**0.193**	**0.232**	**0.195**	**0.175**
$C_{p,i}/C_{p,1}$	**1**	**1.786**	**2.207**	**2.656**	**2.23**	**2**

Analysing the results for TSR = 1 (in 2D) shows that the passive flow control solutions lead to a significant increase of the power coefficient, getting the best result using the profile with a threshold on the back of the blade profile.

5. CONCLUSIONS

In this paper we have presented a new model of vertical axis wind turbine (VAWT) using a blade system with a biplane configuration on each arm. Under certain conditions, the biplane configuration yields an increased lift and, depending on the relative position of the blades that form the biplane, yields a high CL/C_D ratio, compared to the equivalent monoplane configuration. The preliminary results show that in urban areas, the biplane solution is superior to the classic solution, i.e., of H – Darrieus type.

Additional research of the passive control systems, indicates that they have a positive influence on the VAWT, at TSR of 2 to 3 peculiar to urban areas.

Note that VAWTs can be used efficiently if they use the wind potential amplified by the edges of the buildings.

For future work we will continue the numerical and the experimental studies of the proposed configuration, aiming at designing a VAWT with high performances.

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