TORNADO concept and realisation of a rotor for small VAWTs

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Abstract: *The concept of a three-tier configuration for a vertical axis rotor was successfully developed into a experimental model. The rotor assembly is divided into three tiers with three straight blades in each tier. The three-tiers are shifted by an angle of* 40^0 *generating a full helical flow field inside the rotor. Thereby the new configuration has some different mechanism of torque generation as other Darrieus rotors. The three-tier configuration facilitates the operation by enabling the turbine to self-start at wind velocity as low as 2 m/s with good performance and a smoother driving torque. At the same time the design couples an esthetic appearance with low noise level.*

Key Words: *VAWT, Aerodynamics, Small wind turbines, Wind-tunnel experiment.*

1. INTRODUCTION

Wind energy became significant in the energy crises experienced in the early 1970s to generate electrical energy instead of mechanical energy and currently there are two categories of modern wind turbines, namely Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT). VAWT is classified into two categories [1]: Savonius-type VAWT and Darrieus-type VAWT. The speed up Savonius wind turbine cannot rotate faster than the speed of the wind and so they have a Tip Speed Ratio (TSR) of 1 or below. The working principle of Savonius wind turbine is shown in Fig.1, where the main driving force of blades is the drag force.

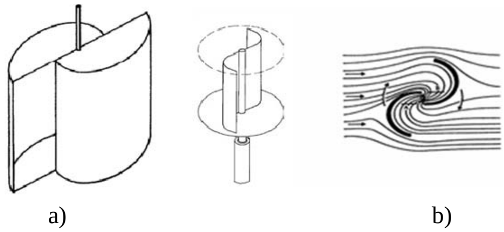
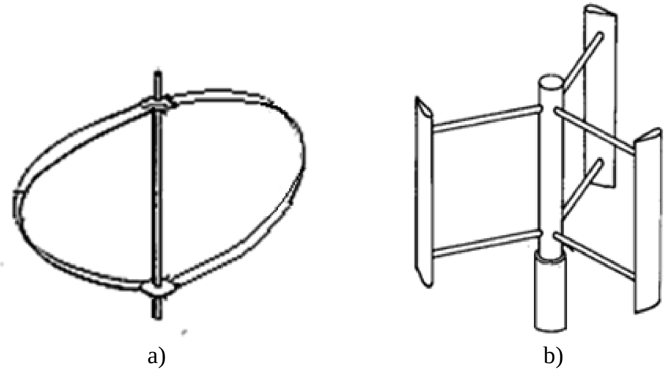

a) b)

Fig. 1 – Savonius rotor: a) concept; b) airflow



a) b)

Fig. 2 – Darrieus rotors: a) concept of curved blade (eggbeater) rotor; b) concept of three bladed H-rotor

Darrieus-type VAWTs are mainly of two types, namely Eggbeater Darrieus rotor and H-Darrieus or simply H-rotor. Figure 2 shows the concept of the types of Darrieus-type VAWT. The Darrieus wind turbine is a lift-driven machine and can spin at many times the speed of the wind, i.e. the TSR is greater than 1. Hence, the Darrieus rotor generates less torque than a Savonius rotor but it rotates much faster. Though the VAWT are slightly less efficient than their HAWT counterpart, they are, by design, insensitive to the direction of the wind, and therefore do not require a yaw control system. Thus, with such an omni-directional turbine there are no power losses during the time it takes for the turbine to yaw and has good performance in complex wind [2].

An omni-directional turbine can be situated at places where the wind is turbulent and where the wind direction changes often. For this reason, VAWTs have an advantage over HAWTs in high mountain areas, in regions with extremely strong or gusty winds and in urban areas. Furthermore, the VAWT is less noisy than the HAWT, which becomes even more important in urban areas [3]. Investigations indicate a clear advantage in using VAWTs at rooftops [4].

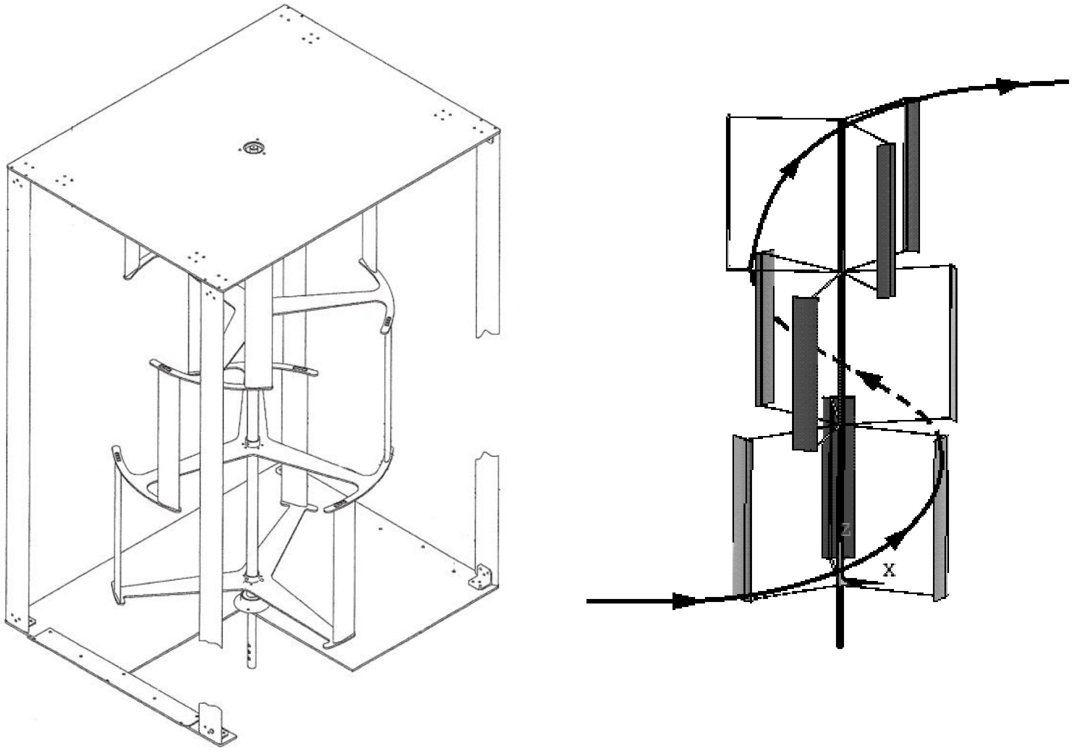
Blades of VAWT may be uniform section and untwisted or slightly twisted [5], making them relatively easy to fabricate or extrude, unlike the blades of HAWT, which should be twisted and tapered for optimum performances. Furthermore, almost all the components requiring maintenance are located at the ground level facilitating the maintenance work appreciably [6]. However, its high torque fluctuations with each revolution, no self-starting capability are the drawbacks [7].

The novel Tornado concept removes the major self-starting obstacle and is designed for small scale applications in suburban areas and also the use in the built environment where a severe restriction on the noise is considered.

Tornado is such a small urban wind turbine developed for use on buildings and also for local generation of electricity.

2. THE CONCEPT

The Tornado is a lift type VAWT using a three-tier rotor. Each tier is shifted by the angle of 40^0 and the nine, straight blades of rotor are positioned forming a helical array (Fig. 3). This set-up induces a helical flows inside the rotor augmenting the rotation of fluid. The bulk circulation generated by rotation and called rotational circulation is added to the local circulation producing by the aerodynamic operating of blades. In this aspect the design differs from other types of VAWTs operating with the lift principle.



a) b)

Fig. 3 – Tornado rotor: a) concept; b) airflow

Apart from this novelty there is another important feature giving by the self-starting capability of the rotor.

The occurrence of the rotational circulation facilitates the operation by enabling the turbine to self-start at wind velocity as low as 2 m/s and thus eliminating the use of variable pitch rotor or other extra power source as the standard Darrieus rotors.

Since Tornado is designed for urban conditions there is a severe restriction with respect the noise production.

Hence the need to reduce the operational tip speed and thus the design tip speed ratio as much as possible without significant penalty in its performance.

Positioning the blades along a helical array is another adaptation to prevent impulsive noise reduce the overall noise level, and obtain smoother driving torque.

The three-tier rotor can drive a direct drive permanent magnet generator with integrated bearing at the bottom of the rotor.

3. DESIGN OF TORNADO MODEL

3.1 Aerodynamic design

The solidity of Tornado-rotor is, equivalent to the solidity of straight bladed Darrieus rotor, defined as

$$\sigma = \frac{Bc}{2R} \tag{1}$$

where R is the rotor radius, c is the chord of blades and B is the number of blades.

The theoretical power coefficient of a straight bladed Darrieus wind turbine can be written as:

- after Wilson and Lissaman [8]

$$C_P = \pi\sigma\lambda - \frac{16}{3}\sigma^2\lambda^2 + \sigma^3\lambda^3\left(\frac{3\pi}{4} - \frac{\overline{c}_d}{\sigma^2}\right), \tag{2}$$

where λ is the tip speed ratio and $\overline{c}_d$ is the average sectional drag coefficient,

- or after Shankar [9]

$$C_P = \frac{4\sigma\lambda}{kk_1}\left(\frac{2\pi + c_{d_0}/2 - c_1}{2} - c_{d_0}\lambda^2\right), \tag{3}$$

where $k = \frac{27}{16}$, $k_1 = \frac{2H}{R}$, H is the span of blade, c_{d_0} is the drag at zero incidence and c_1 is the coefficient of quadratic term in the drag polar.

Equations (2) and (3) can only be used for the higher tip speed ratios. At small λ the blade will stall, and the assumed relation between c_l and the angle of attack α: $c_l = 2\pi\sin\alpha$ is no longer valid.

Furthermore it will be difficult to make a proper estimate of $\overline{c}_d$ for low λ. According to [2] the minimal tip speed ratio necessary to prevent blade stall is equal to

$$\lambda_{\min} = \frac{1}{\tan\alpha_s + \sigma}, \tag{4}$$

where α_s is the maximum angle of attack of the airfoil at which attached flow is found.

Evidently the value of α_s is dependent upon the airfoil chosen and the Reynolds number at which it is operating.

For the wind tunnel model using a NACA 0018 airfoil this angle at $\mathrm{Re}_c = 50000$ has the value of $\alpha_s = 8^0$ [10].

The solidity can be calculated easily with the model properties given in Table 1: $\sigma = 0.3$; and hence the minimal tip speed ratio for the wind tunnel model to operate in attached flow conditions is: $\lambda_{\min} = 2.2$.

The design tip speed ratio, which is the value at which the maximum C_p is established equals $\lambda_{opt} = 2.0$, according to equations (2) and (3), Fig. 4.

Another important aerodynamic problem of VAWTs is the self-starting process, namely the rotor must be able to continuously produce of thrust and accelerate from rest up to high tip speed ratios ($\lambda > 1$), when it starts to produce a useful output.

Evidently, the behaviour of the rotor at low tip speed ratios than the typical (design) value of 2.5 is very difficult to predict, and thus a series of wind tunnel experiments were performed in order to demonstrate unaided start-up of the Tornado rotor in a steady wind.

Table 1 – Design properties of the wind tunnel model:

Radius [m]	0.25
Height [m]	0.9
Number of blades	9
Blade skew angle [deg.]	0^0
Blade chord [m]	0.05
Solidity, σ	0.3
Airfoil	NACA 0018
Reynolds number	50000

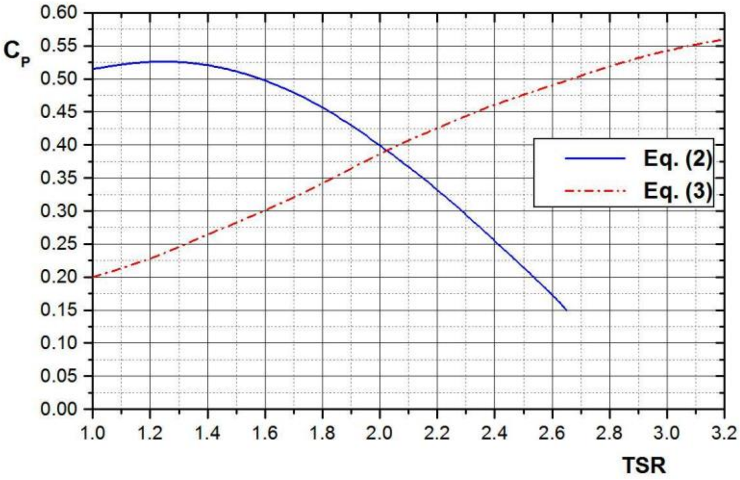


Fig. 4 – Predictions of $C_{P\max}$

3.2 Wind tunnel experiments

a) b)

Fig. 5 – Wind tunnel model a) at rest; b) at spinning

The wind tunnel model had a height of 0.90 m and a diameter of 0.50 m (Fig. 5). This size was chosen such that it would have a high solidity to alleviate the self-starting. The wind tunnel is a closed-loop circuit, which has a circular test section with a diameter of 1.50 m, and operating velocities up to 25 m/s.

Further, it was considered that the solid blockage of 25%, caused by the presence of the rotor, would have a negligible effect on the starting process.

Dimensions and other properties of model are given in Table 1.

With this wind tunnel model a number of starting curve were generated. They are presented in Figure 6, where the measured tip speed ratio is plotted as a function of wind speeds, for various pitch angles of blade.

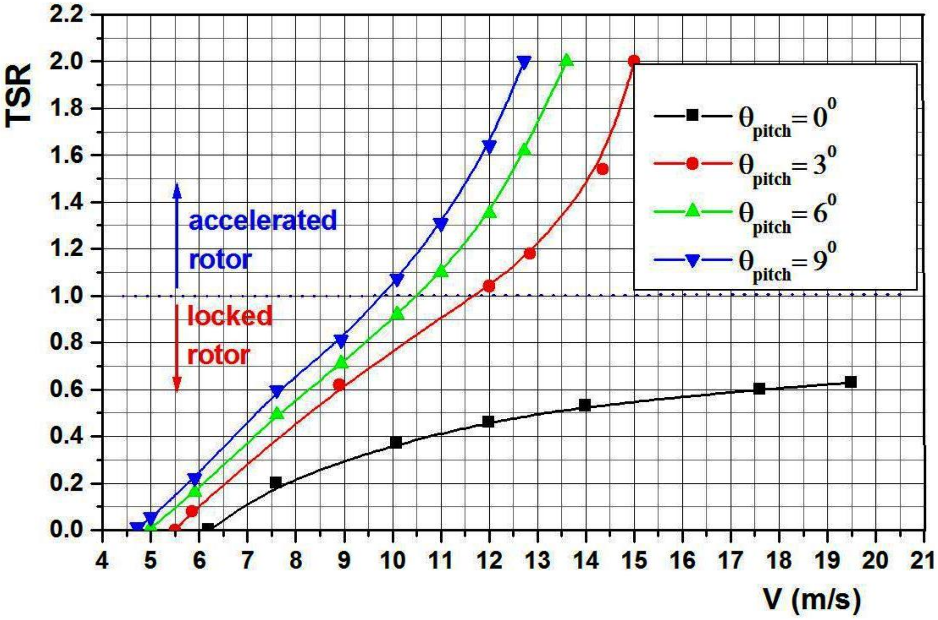


Fig. 6 – Measured rotor speed against wind speed for the pitched blades at 0^0, 3^0, 6^0 and 9^0.

Figure 6 shows that the Tornado rotor has the self-starting capabilities both at low Reynolds numbers and at moderate values of solidity.

Also it can be concluded from these curves that there is a clear influence of the pitch angle on the self-starting behavior of the rotor; small values of pitch angle can reduce significantly the acceleration period.

This meant that two important of the targets: achieving a reasonably aerodynamic efficiency at a low value of λ and self-starting at low Reynolds number were met.

4. CONCLUSIONS

The concept of a small VAWT for use in the built environment was demonstrated through wind tunnel experiments.

The design requirements as good aerodynamic performance self-starting capability, low noise level, simple-rugged design, and esthetic appearance, were met.

Compared with other wind turbines of similar size, the Tornado rotor shows both good aerodynamic and self-starting performance, although this must be checked further in free-air testing on a prototype.

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