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Analysis of the influence of the aspect ratio on the vertical axis wind rotor performance

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Abstract. The aspect ratio (AR) of the vertical axis wind rotors defined in this paper as the ratio between the height and the diameter of the rotor is an important factor when considering the performance of the rotors. However, choosing the most appropriate AR when designing a wind rotor, based on literature review, is not fully reliable as different sources point out contradictory data. This paper presents an analysis regarding the influence of the AR on rotors performance based on experimental data.

1. Introduction

As climate change is a problem of global concern nowadays, renewable energy is considered an important link from the chain of solutions that are to be applied for tackling this problem. Wind turbines represent machines that convert wind energy into electricity. Over the last few decades, they became a usual feature of the landscape in many countries. The vast majority of them are horizontal axis wind turbines (HAWTs) (figure 1). HAWTs have been heavily researched and developed until high efficiency has been achieved for the largest ones [8]. The main disadvantage of this type of turbine is that it needs a yaw mechanism that points the turbine's rotor perpendicular to the wind direction. This disadvantage is not a problem for vertical axis wind turbines (VAWTs). By design VAWTs can catch the wind coming from any direction. As a consequence, it is considered that they are better suited for electricity generation at a small scale, like covering the electricity needs for one household where minimal maintenance is desirable [7]. Though big VAWTs can reach fairly high efficiency, they are surpassed in performance by HAWTs. In this regard, more research is needed for achieving a higher efficiency as theoretically this thing is possible. This paper presents an analysis in which the performance of the straight bladed vertical axis wind turbines is related to the dimensional aspects of the turbine.

2. Theoretical background

The general formula for calculating the power output of a wind turbine is expressed as follows:

$$P = \frac{1}{2} C_p \rho A U^3 \tag{1}$$

where P is the output power of the wind turbine; U – the wind speed before the interaction with the turbine; ρ – the air density; A – the swept area of the turbine; C_p – the performance coefficient of the turbine. C_p ranges from 0 to 1 with a theoretical maximum of 0.593 called Betz limit. Big modern

HAWTs can reach a value of about 0.5 whereas VAWTs a maximum of 0.4. Nevertheless, Paraschivoiu [4] writes that for VAWTs a maximum of 0.64 can be theoretically reached.

Figure 1. VAWT (Quiet Revolution) and HAWT (Technical University of Moldova).

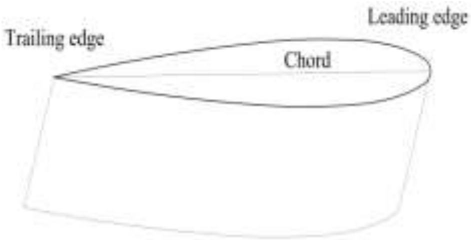

Figure 2. The blade's chord.

As can be noticed from the formula (1) the power output of the turbine is directly proportional to the swept area A. However, for the same area there could be different shapes. The shape of the swept area is characterized by the Aspect Ratio (AR) of the rotor. More precisely the AR is defined as:

$$AR = \frac{h}{D}, \tag{2}$$

where h is the height of the rotor, (for the straight bladed wind turbine the height of the rotor is the same as the blade's length) and D is the diameter of the rotor. When designing a vertical axis wind turbine one can ask which aspect ratio is the best for a higher power output or if the aspect ratio is of any importance at all. As it turns out, choosing a specific aspect ratio will influence the performance of the turbine and the energy output respectively.

The recommendations regarding AR seem to be contradictory. For example, Brusca [1], defining the aspect ratio in the same way as in the equation (2), recommends a smaller AR for the turbines, as this facilitates a higher Reynolds number. The authors have done their analysis using the Multiple Streamtube Model proposed by Strickland [2]. On the other hand, Ionescu [3] recommends a smaller AR but defining it as the ratio between the diameter and the height of the rotor (D/h). Ionescu's analysis was done using the software QBlade which is based on Double Multiple Streamtube Model developed by Paraschivoiu [4]. Both models are based on the same principles.

When analyzing the AR, there can be two options or rather directions. One can analyze the influence of the aspect ratio on the turbine performance by keeping the solidity of the rotor constant or by keeping the length of the chord constant. The chord (c) is defined as the line connecting the leading edge of the blade's cross section with the trailing edge (figure 2). For the straight bladed VAWT, the solidity (σ) is defined as the ratio between the sum of the chord lengths of the three blades and the diameter of the rotor:

$$\sigma = \frac{3c}{D}. \tag{3}$$

This paper presents the analysis of the aspect ratio influence on the straight bladed vertical axis wind turbine's performance by keeping the length of the chord constant. Three turbines are analyzed, each one having a different set of lengths for the diameter and height of the rotor but the same swept area. The schematic configurations are presented in the figure 3.

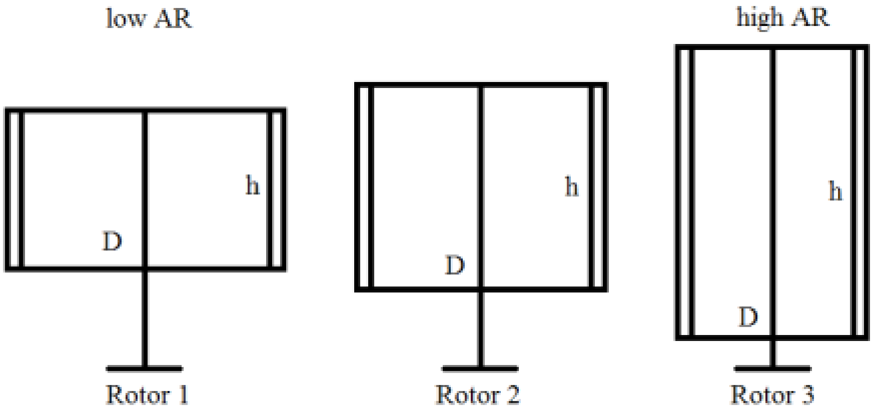

Figure 3. The three rotor configurations have the same swept area and chord lengths.

For all three cases, the chord length of the blades remains constant. By changing the diameter of the rotor, the solidity must vary consequently (formula (2)). Hence, there is a low σ for a larger diameter and a high one for the smaller diameter.

The type of airfoil used for the blades is NACA 0018. This particular airfoil is chosen as NACA airfoil family is historically one of the most used for VAWTs [6].

The whole analysis is done experimentally by observing the wind turbine behavior when exposed to different wind speeds generated with a wind tunnel.

3. Experimental setup

The three rotors that are analysed have a swept area of 0.16 m^2. This particular area is chosen in order to fit into the air flux generated by the wind tunnel. For all three configurations, the length of the blade chords is constant with a value of 0.05 m. The constructive dimensions for each rotor are presented in the table 1.

Table 1. The constructive parameters of the analysed rotors.

Rotor's number	Aspect ratio, AR, (/)	Height, *h*, (m)	Diameter, *D*, (m)	Swept area, *A*, (m^2)	Chord, *c*, (m)	Solidity, σ, (/)
1	0.64	0.320	0.5	0.16	0.05	0.300
2	1.00	0.400	0.4	0.16	0.05	0.375
3	1.78	0.533	0.3	0.16	0.05	0.500

The experimental setup consists of two main components: the wind tunnel and the vertical axis wind turbine. The experimental VAWT (figure 4) was designed in a way that allows for easy change of the blades and their supporting struts. This solution allows the analysis of different characteristics of the VAWTs in the same external conditions. External conditions refer to the wind speeds and the turbine's tower, which is positioned at a specific distance from the wind tunnel. The turbine's tower comprises also the electric generator that powers a 200 Ω resistance.

The electric generator of the turbine is a three-phase generator that provides 12 V at 1200 rpm. The number of rotations per minute is measured with a tachometer. The voltage and the current provided by the electric generator are measured and the electric power is calculated. The electric power obtained serves as the performance indicator of the turbine. For easier measurement, the alternating current obtained is transformed into direct current by using a diode bridge.

As for the electric generator a large number of rotations per minute is needed, to the generator's shaft a multiplying gear was mounted. The transmission ratio of the gear is 3.41.

The blades are attached to the rotor's axle through the supporting struts, which are made from plywood (figure 5).

Figure 4. The experimental VAWT.

Figure 5. Supporting struts.

For an easier replacement, the blade is mounted to the strut in one spot and not two as it is usually done. A rigid belt holds the blade and connects it with the strut. The attachment is done through a special made fixator.

The blades are made by 3D printing. As the work volume of the 3D printer is limited and does not allow the printing of the whole blade at once, separate blade segments were printed. Then the segments were glued so that the desired length of the blade is obtained. When operational, the blades are subject to large and variable loads, especially bending. For better structural performance, they were taped in a way that preserves the originally printed aerodynamic shape (figure 6). The whole experimental setup is presented in the figure 7.

Figure 6. 3D printed blades.

Figure 7. The experimental setup.

4. Results and discussions

First, the three rotors have undergone different wind speeds without being coupled to the electric generator. The results are presented in graph of the figure 8. Unlike rotor one, the second and the third rotors were not tried under high wind speeds because there was a risk of harming the blades. However, the tendency is clear, which is: the bigger the aspect ratio, the more rotations per minute.

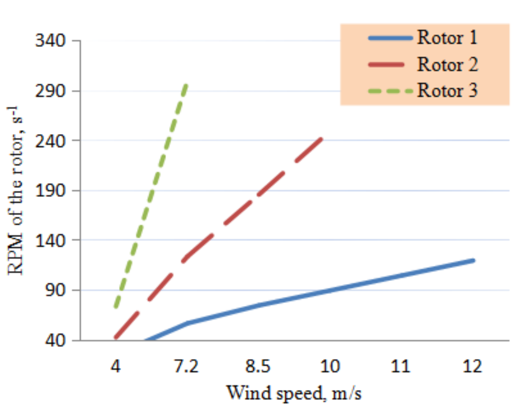

Figure 8. Rotors' performance when uncoupled to the generator.

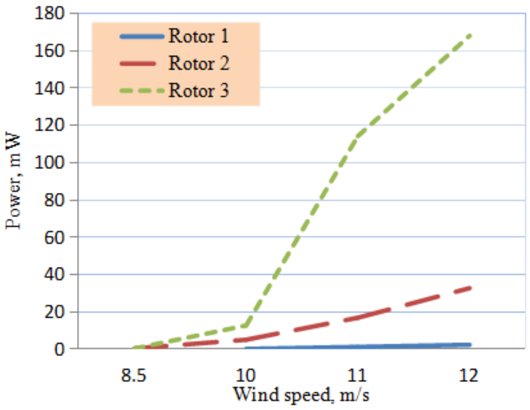

Figure 9. Rotors' performance when coupled to the generator with an external load of 200 Ω.

Secondly, the three rotors have undergone the same wind speeds but coupled to the electrical generator. The external load applied is equal to 200 Ω. The voltage and the current obtained are used to calculate the power output of the turbine. The values obtained at specific wind speeds are presented in the figure 9. As for small wind speeds the wind turbines present poor or no performance at all, only data at higher wind speeds is shown. The difference between the three rotors is obvious for high wind speeds, the tendency being that: the higher the aspect ratio value the higher the performance in terms of power output. The tendency is the same regardless of the wind speeds with little exception: at the speed of 8.5 m/s the rotor 2 shows slightly better performance which is barely noticeably in the graph. The difference is about 15 % which is insignificant for the small wind turbines but can be important for big wind turbines when operating at relatively low wind speeds.

The results could be explained in two ways. First: because the 3rd rotor has a higher solidity, much more lift force is developed on its blades. For even higher solidities though, the performance is expected to decrease. For VAWTs the optimum solidity ranges between 0.2 – 0.6 [9] whereas the solidity of the most efficient rotor, that is the 3rd one is 0.5.

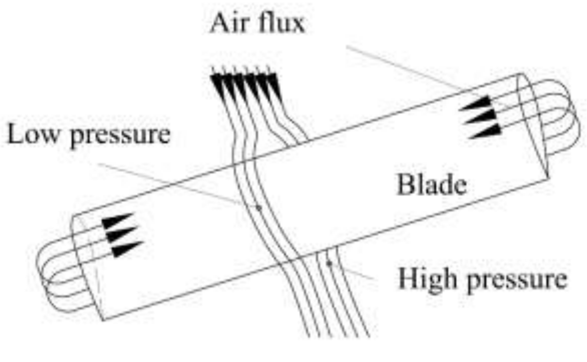

Figure 10. Tip blade losses.

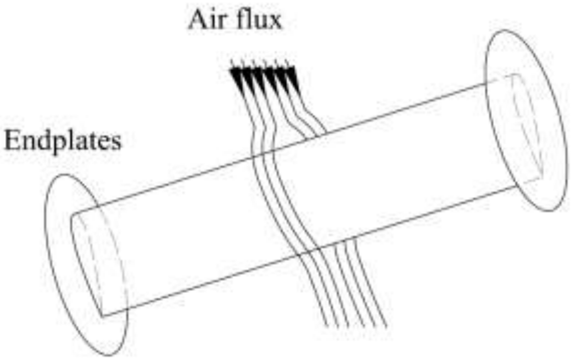

Figure 11. Endplates.

Second is the tip blade loss phenomenon. When a finite length blade undergoes an air flux, a pressure difference is developed between the two sides (figure 10) which is considered a positive effect as it causes the lift force. The same pressure difference is causing an additional flow over the tip of the blade. This is an undesired effect for a wind turbine as it causes an efficiency loss. This effect is more pronounced for blades with a small aspect ratio. The blade aspect ratio is the defined as the ratio between blade height and the chord length. Kirke [9] recommends a blade aspect ratio higher than 7.5 while Ahmadi [10] between 10 and 20. For partially overcoming this problem there are several technical solutions like winglets or endplates (figure 11).

5. Conclusions

For a constant swept area of the rotor, by keeping the blades chord length constant, a turbine with a higher aspect ratio provides a higher power output. In general, each wind turbine provides a maximum efficiency for a specific wind speed. The rotor 1 and 2 might have their efficiency peak at higher wind speeds, but for practical wind speeds, under which these rotors have been analyzed, the tendency is: the higher the aspect ratio value, the higher the power output.

In the future more research is to be done on the same rotors when the blades are provided with endplates. Also, rotors with a different set of blades will be analyzed. In this case the blades will be based on a different chord length to see if the tendencies remain the same. Research is to be done on the aspect ratio for the case when the solidity of all the rotors remains the same.

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