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Wind Tunnel Experimental Study of the Effects of Blade Number on the Performance and Starting Behavior of a Low Tip-speed Ratio and Micro-Scale Wind Turbine at Fixed Blade Geometry

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Abstract

The effects of the number of blades on the efficiency and starting behavior of low tip-speed ratio micro-scale wind turbines are controversial. In contrast to modern 3-bladed fast large-scale horizontal axis wind turbines, these runners are multi-bladed to increase torque and to perform efficiently in low wind speed conditions. While an optimal number of blades for large-scale wind turbines has been established, it is still under consideration for small wind energy harvesters. The aim of this research is to examine the influence of the number of blades, while maintaining a constant blade chord length, on the power and torque coefficients of micro-scale wind turbines that are specifically designed to work at low tip-speed ratio. Seven 200 mm high-solidity wind turbines with a number of blades varying from 4 to 16 were designed, manufactured, and tested in a wind tunnel to collect the full power and torque coefficients *vs.* tip-speed ratio characteristics. We found that turbines with a large number of blades are more efficient in low wind speed conditions and have a lower cut-in wind speed than turbines with fewer blades. The experimental results emphasize the existence of an optimal range of blade numbers for our specific blade geometry, between 12 and 14 blades, that decreases the cut-in wind speed while maximizing the power coefficient. Furthermore, we observed that the performance curves of the wind turbines change as the number of blades increases, emphasizing the existence of blade interactions that alter blade aerodynamic properties. In addition, this experimental study provides some guidelines for the development of efficient micro wind energy harvesters.

Keywords: Micro-scale Wind Turbines, Power and Torque Coefficients, Blade Solidity

1. Introduction

Micro-scale wind turbines are wind turbines with a diameter less than 200 mm. These rotors have the potential to harvest power from ambient wind resources and convert it into mechanical power. The mechanical energy of the blades is then transformed into electrical energy by a generator. Micro-scale wind turbines are typically designed to operate in low wind speed conditions, such as in metropolitan areas, and have a low power output, usually less than 10 W. Even though they have a limited capacity to generate electricity compared to large-scale wind turbines, they may be used in a variety of small-scale applications, such as powering autonomous sensors or charging batteries [1]. In particular, they are an attractive alternative technology to single-use batteries for providing electricity to electronic devices from a clean and renewable energy resource. In conjunction with other renewable energy technologies, such as solar panels, they can also provide energy independence

to electronic devices in remote locations that can reduce maintenance costs.

The blades of a wind turbine ensure the conversion of the kinetic power of the wind into mechanical power; hence, their design and performance play a critical role in the global turbine's efficiency. There are many physics and geometrics parameters to consider to design an optimal blade but the effects of each of these parameters on performance are not yet fully examined and understood. Among these factors the blade solidity σ is defined as the ratio of the blade chord length over the spacing between blades

$$\sigma = \frac{Nc}{2\pi r}. \quad (1)$$

The blade solidity of wind turbines can vary significantly depending on the intended application.

Windmills are among the oldest types of horizontal axis wind turbines, and they were traditionally employed for tasks that required mechanical energy, such as grinding grains and pumping water (windpumps). These runners are specifically designed to operate efficiently in low wind speed conditions and to turn slowly while producing a high amount of torque, which is required for the proper

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operation of piston pump, for example [2]. A high starting torque also reduces the windmill's cut-in wind speed, which is the wind speed at which the rotor begins to work and is often required to initiate a reciprocating water pump [3]. As a result, in order to maximize the torque, windmills are often made of numerous wide chord blades or, in other words, have a large blade solidity $\sigma \geq 0.5$. It should be noted that these machines often use non-optimized curved plates for blades rather than true airfoils [4]. Furthermore, they mostly operate at low tip-speed ratios $\lambda \leq 3$, where λ is the ratio of the tip velocity to the freestream wind velocity

$$\lambda = \frac{R_T \omega}{V_\infty}. \quad (2)$$

In addition, windmills, such as American windmills, are slow, high-solidity horizontal axis wind turbines with a large number of blades that perform well at low wind speeds.

Unlike, modern large-scale wind turbines, used to produce electricity, are fast and low-solidity turbines. As a high shaft rotational speed is required for the efficient operation of an electrical generator, these turbines are mainly designed to operate at high tip-speed ratios, from 5 to 9, and have a low blade-solidity $\sigma \leq 0.07$ [4]. Despite some doubts about the better efficiency of two-bladed wind turbines, the majority of large-scale wind turbines have three blades. This number of blades appears to be the best compromise between the aerodynamic efficiency, the structural integrity of the turbine, and the manufacturing costs [5]. Furthermore, the general momentum theory of horizontal axis wind turbines predicts that the highest power coefficient C_p , defined as the ratio of the rotor's mechanical power output to available wind power, increases with the tip-speed ratio, explaining why large-scale horizontal axis wind turbines are designed to operate at high tip-speed ratios [6].

$$C_p = \frac{P}{P_a} = \frac{\tau \omega}{0.5 \rho \pi R_T^2 V_\infty^3} \quad (3)$$

For modern large-scale horizontal axis wind turbines, the typical maximum power coefficient $C_{p,max}$ ranges between 0.4 and 0.5, whereas runners with a large number of blades, such as the American windmill, have a lower maximum power coefficient, around 0.3 [4, 7].

The design of an efficient micro-scale wind turbine is a challenging task since these machines must combine the benefits of both windmills and large-scale horizontal axis wind turbines. On one hand, as micro-scale wind turbines are designed to operate in low wind speed conditions, they require a high starting torque to overcome the frictional resistance of the mechanical parts included in the nacelle and begin rotating. Hence, most micro-scale wind turbines, like windmills, are multi-bladed, have a large blade solidity, and have a low design tip-speed ratio to increase the amount of torque, *i.e.*, the torque coefficient C_τ . The

torque coefficient is a dimensionless measure of the amount of torque generated by a wind machine

$$C_\tau = \frac{\tau}{0.5 \rho \pi R_T^3 V_\infty^2}. \quad (4)$$

Despite existing research recognizing the critical role of blade solidity in wind turbine performance and wake, to date, no consensus on optimal N and σ for high-solidity micro-scale wind turbines operating at low tip-speed ratios has been reached, as it is the case for fast and large-scale wind turbines [5].

Blade solidity effects can be explored in two distinct ways (please see Eq. 1):

- 1 by changing the blade chord length c of the turbine at a fixed number of blades N (first approach¹) or,
- 2 by varying the number of blades N at a fixed blade geometry, *i.e.*, at a fixed blade chord length c (second approach²).

Since the number of blades in the first approach¹ is equal, the Reynolds number based on blade chord length and freestream wind velocity, varies from runner to runner while the blade tip-losses remain relatively constant. In the second case², the situation is the opposite.

Some experimental studies have explored the impact of the blade solidity and number of blades on wind turbine's characteristics by mixing the 2 approaches. Eltayesh et al. investigated experimentally the effects of the number of blades ($N = 3 - 5 - 6$) on the power and torque coefficient curves of a 2 m diameter low-solidity ($\sigma \leq 0.5$) and fast ($\lambda_{opt} \geq 4$) wind turbine [8]. Their results showed that increasing the number of blades leads to a decrease in C_p , an increase in C_τ and a shift of the $C_p - \lambda$ curves towards lower tip-speed ratios. A similar pattern is depicted in the work of Zhang et al. [9] and Vedovelli et al. [10]. Eltayesh et al. reported also that increasing the number of blades implies narrower $C_p - \lambda$ and $C_\tau - \lambda$ curves. Moreover, they recommended the use of high-solidity runners in low wind speed conditions due to their smaller cut-in wind speed. On the other hand, using a similar experimental approach, Brasil et al. [11], Zawadzki et al. [12] and Duquette and Visser [13] reported that increasing the turbine blade solidity by adding blades increases the power coefficient. According to Zawadzki et al., this growth is only true up to a certain point, after which further increases in N cause a C_p decay. In addition, some authors found that increasing the blade solidity and the number of blades increases the efficiency, or in other words, the power coefficient of the turbine [11, 12, 14] but others have drawn opposite conclusions [3, 8, 10, 15–17].

The majority of the wind turbines investigated in these studies were not specifically designed for micro-scale applications. The turbines feature a relative geometry that is similar to that of large-scale horizontal axis wind turbines. They have a low blade solidity $\sigma \leq 0.5$, a low number of

blades, and a high optimum tip-speed ratio $\lambda \geq 3$. Moreover, the range of blade numbers explored, from $N = 3$ to $N = 5$, is restricted in contrast to the high number of blades on high-solidity runners such as American windmills. Even though these studies provide interesting data on blade number effects for low-solidity runners, it is unclear whether these effects are equivalent for high solidity and low tip-speed ratio runners. Moreover, it is hazardous to compare wind turbines from different studies as many geometric parameters change.

In our previous work [18], we proposed a flow deflection-based method to design turbines with a low tip-speed ratio of $\lambda = 1$. In a subsequent experimental investigation, we examined the effects of the blade solidity on the performance and wake of 200 mm diameter horizontal axis wind turbines, using the first approach¹ [19]. The number of blades was kept constant while the blade chord length varied from one rotor to another to modify the blade solidity. Five 8-bladed runners with similar blade angle distributions and different blade solidities from $\sigma = 1.5$ to $\sigma = 0.5$ were designed and tested in a wind tunnel. We found that a blade solidity larger than $\sigma \geq 1$ was advantageous for low tip-speed ratio wind turbines for the following reasons. Firstly, high solidity micro-scale runners have a higher power coefficient across the entire tip-speed ratio range and a higher maximum power coefficient, of the order of $C_{p,max} = 0.3$, than low-solidity rotors. Secondly, their torque coefficient C_τ varies linearly with tip-speed ratio, which can be useful for regulating their angular velocity with a torque-resisting control strategy, and they have a low cut-in wind speed. On the other hand, $C_\tau - \lambda$ curves of low-solidity runners were not strictly linear, and we reported significant stall effects, *i.e.*, a significant drop in C_τ . This effect could be attributed to both low solidity and a transition resulting from a lower Reynolds number with the first approach¹. We found also that increasing the blade solidity from $\sigma = 1.25$ to $\sigma = 1.5$ leads to a drop in the maximum power coefficient from $C_{p,max} = 0.3$ to $C_{p,max} = 0.28$.

The objective of this study is to further explore the impact of blade solidity on the performance characteristics of these low tip-speed ratio 200 mm wind turbines. This time, we aim to investigate the effects of blade solidity by keeping the blade chord length constant and varying the number of blades², in order to obtain a comprehensive evaluation of this parameter.

2. Materials and Methods

2.1. Wind turbines design

The turbines under consideration in this research are designed with a blade geometry that has been previously studied and tested [18, 19]. In this preliminary work, we designed and tested several 200 mm diameter high-solidity runners with 8 blades, and we proved experimentally that the runner with a constant blade solidity $\sigma = 1$ obtained

a high degree of performance $C_{p,max} = 0.293$ at its design tip-speed ratio, $\lambda = 1$. Additionally, compared to low-solidity wind turbines, it has a very low cut-in wind speed, making it an attractive candidate for use in low wind speed conditions. As a result, we decided to investigate the effects of the number of blades using the blade geometry of this particular turbine.

Seven micro-scale wind turbines with different blade numbers, equal to $N = 4 - 6 - 8 - 10 - 12 - 14 - 16$, were designed, manufactured, and tested in a wind tunnel. All turbines have the exact same blade geometry. Their tip radius and hub radius are respectively equal to $R_T = 100$ mm and $R_H = 30$ mm and they are designed to achieve maximum efficiency at a low tip-speed ratio $\lambda = 1$. Blade angle distributions are computed according to a design methodology described in Ref. [18] and their spanwise variations are displayed in Fig. 1b. The major purpose of the design procedure is to achieve the appropriate torque by controlling the flow deflection into a high-solidity blade cascade arrangement. In the design methodology, the blade is divided into eleven blade elements from the root to the tip of the blade (Fig. 1a). A polynomial mean camber-line tangent to the blade angles at the input β_1 and output β_2 of the blade cascade is drawn for each blade element using the following equation:

$$y(x) = \frac{\tan(\beta_2) - \tan(\beta_1)}{2}x^2 + \tan(\beta_1)x \quad (5)$$

with $x \in [0; 1]$ and thickened according to the thickness distribution of the symmetric NACA10 airfoil. The geometry is then upscaled according to the blade solidity distribution. The blade solidity is assumed to be constant along the span and varies from one rotor to the next as the blade number changes, from $\sigma = 0.5$ to $\sigma = 2$ in 0.25 steps (please see Tab. 1 for $N - \sigma$ relationships). It results in a fan type blade geometry that appears better suited for micro-scale wind turbines [20, 21].

The hub is 42.5 mm long, and the fillet radius of the runners' nose is 5 mm. Fig. 1c shows 3D models of 4, 8 and 14 bladed wind turbines. All turbines were manufactured by fused material deposition with a 3D printer CREALITY CR-10 MAX and with the same 3D printing machine parameters (polyactic acid filament for print material, 20% fill density, grid infill pattern).

2.2. Experimental setup and procedure

The experimental campaign aimed to collect power coefficient C_p and torque coefficient C_τ vs. tip-speed ratio characteristics for all seven rotors.

The experiments were carried out in the closed wind tunnel of the *LIFSE* facilities. The semi-open test section is 1.80 m long and has a rectangular cross-section of 1.35 m \times 1.65 m, resulting in a very low blockage ratio of less than 2%. Fig. 2 shows a schematic diagram of the experimental setup inside the test section.

The dynamic pressure in the wind tunnel was measured using a Pitot probe placed in the settling chamber.

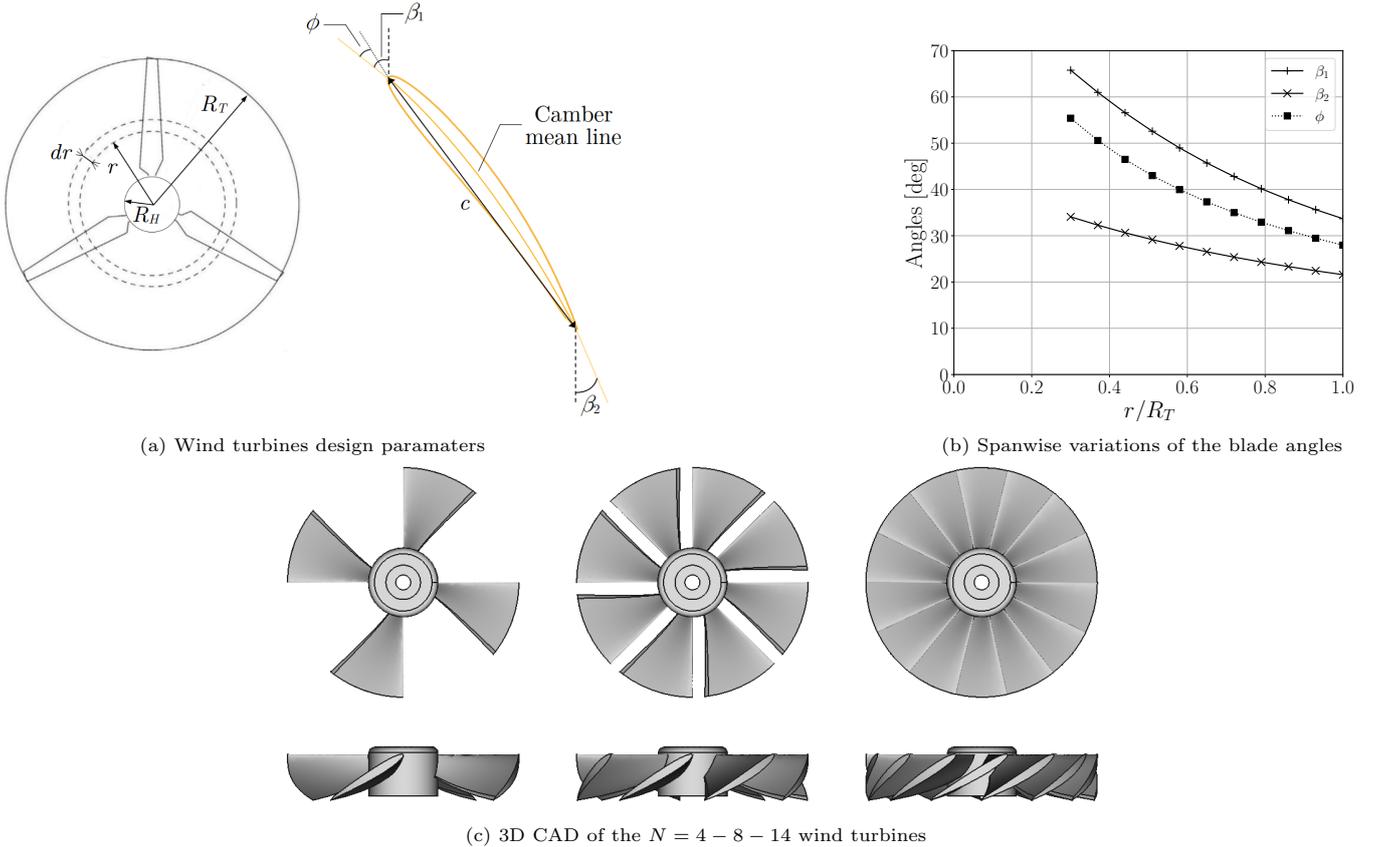


Figure 1: Wind turbines design

Table 1: Wind turbines $N - \sigma$ relationships with experimental maximum mechanical power P_{max} and initial torque τ_0 for $V_\infty = 15 \text{ m.s}^{-1}$

N	σ	P_{max} [W]	τ_0 [N.m]
4	0.5	13.0	0.09
6	0.75	16.8	0.15
8	1	18.7	0.23
10	1.25	19.3	0.23
12	1.5	19.7	0.24
14	1.75	19.7	0.24
16	2	18.6	0.22

The air temperature and atmospheric pressure were also monitored to compute the air density and to adjust the freestream wind velocity in the wind tunnel. The measurement series presented in this paper were performed at a constant wind speed of $V_\infty = 15 \text{ m.s}^{-1}$, corresponding to a tip-Reynolds number of $\text{Re} = 99100$. Although this high wind speed is not representative of typical wind energy harvesting conditions, it was required in order to obtain the power and torque coefficients for the full range of tip-speed ratios. While a lower wind velocity may result in reduced power and torque coefficients, it is expected that this decrease will be consistent across all seven runners.

During a measurement session, the wind turbine was

mounted on a shaft housed inside a 700 mm long nacelle. The nacelle was installed at the top of a 530 mm tall tower in the center of the test section. The torque τ and the angular velocity ω of the rotor were measured by a rotating torque meter HBM-TW20 connected to the rotor's shaft on one side and to a MAXON DC motor on the other. The motor was wired to a variable resistor and was used as a brake system. As the wind velocity was kept constant during a measurement session, the tip-speed ratio was altered by changing the angular velocity of the rotor. This was accomplished using a resistive torque control strategy. A variation in the voltage at the generator terminal changes the resistive torque applied to the wind turbine and its angular velocity. As a result, the electrical resistance was changed across samples to move to a different steady-state tip-speed ratio.

For every sample, *i.e.*, for every steady-state tip-speed ratio, the electrical signals generated by torque, temperature, and pressure transducers were acquired by a National Instruments NI-USB6229 card during 50 s. The acquisition frequency was set at $f = 1000 \text{ Hz}$.

2.3. Repeatability and propagation of uncertainties

For each sample, the arithmetic average of torque, angular velocity, dynamic pressure, and temperature were computed from the 50 s acquisitions. Average tip-speed

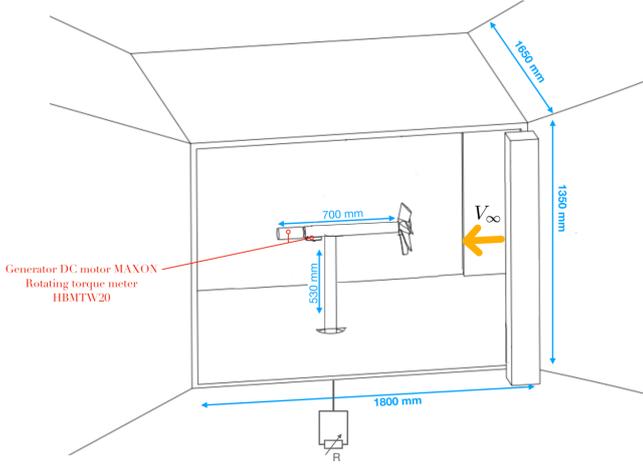


Figure 2: Schematic diagram of the closed wind tunnel of the *LIFSE* facilities with the experimental setup

ratios, power coefficients, and torque coefficients were then calculated according to Eqs. 2, 3, and 4 for each steady-state operating point. The experimental procedure was repeated twice on different days for all seven runners to ensure that the measurements were reliable and reproducible. The results of these two acquisitions are gathered and plotted on two graphs that show the variations in the torque and power coefficients with the tip-speed ratio for all seven runners.

The experimental uncertainties associated with C_p , C_τ , and λ at each data point are calculated by utilizing the standard deviation **SD** of the measured values and applying the appropriate formula for error propagation :

$$\mathbf{SD}_{C_p} = C_p \sqrt{\left(\frac{\mathbf{SD}_\tau}{\tau}\right)^2 + \left(\frac{\mathbf{SD}_\omega}{\omega}\right)^2 + \left(\frac{3\mathbf{SD}_{V_\infty}}{V_\infty}\right)^2} \quad (6)$$

$$\mathbf{SD}_{C_\tau} = C_\tau \sqrt{\left(\frac{\mathbf{SD}_\tau}{\tau}\right)^2 + \left(\frac{2\mathbf{SD}_{V_\infty}}{V_\infty}\right)^2} \quad (7)$$

$$\mathbf{SD}_\lambda = \lambda \sqrt{\left(\frac{\mathbf{SD}_\omega}{\omega}\right)^2 + \left(\frac{\mathbf{SD}_{V_\infty}}{V_\infty}\right)^2} \quad (8)$$

The length of the error bars in the figures represents the standard deviation of uncertainty at every experimental point.

3. Results and Discussion

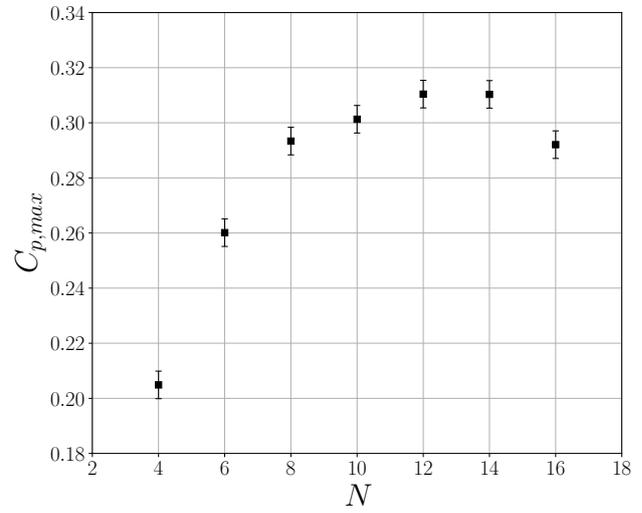
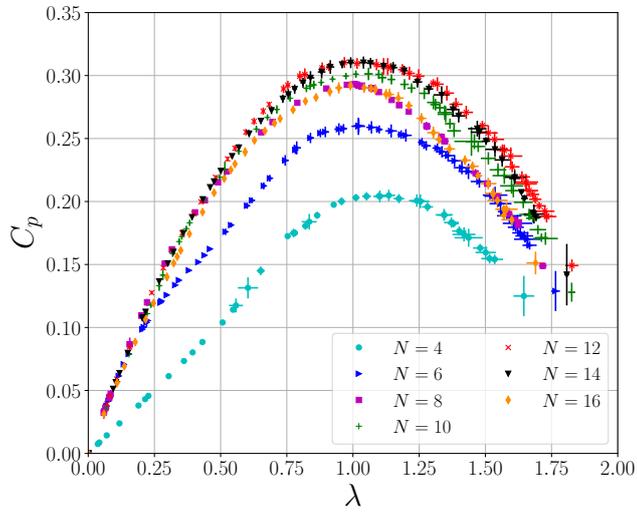
3.1. $C_p - \lambda$ characteristics

Fig. 3 illustrates the effects of the blade number on the power characteristics, *i.e.*, on the efficiency of the kinetic to mechanical power conversion. Experimental $C_p - \lambda$ characteristics for all seven turbines are displayed in Fig. 3a and Fig. 3b shows the variations of the maximum power coefficient $C_{p,max}$ with the number of blades.

Both figures show that an increase in the number of blades from $N = 4$ to $N = 12$ leads to an increase in

the maximum power coefficient, from $C_{p,max} = 0.205$ to $C_{p,max} = 0.310$. Highly-bladed wind turbines ($N = 12 - 14$) achieve a high level of performance in comparison with other low tip-speed ratio micro-scale wind turbines available in the literature. The greatest increase in $C_{p,max}$ occurs when the number of blades increases from $N = 4$ to $N = 8$ (30% growth), while it only increases by 5% from $N = 8$ to $N = 14$. It confirms that high-solidity and multi-bladed wind turbines are better suited for micro-scale applications than low-solidity wind turbines. The existence of an optimal range of blade numbers, between $N = 12$ and $N = 14$ for our specific blade geometry that maximizes the power coefficient is an interesting result that has been sparsely experimentally determined in the literature. As shown in Fig. 3b, the turbine with 16 blades performs less well than the turbines with $N = 12$ and $N = 14$ blades for the entire range of tip-speed ratio and achieves a lower $C_{p,max} = 0.292$. A similar pattern of results was obtained in our previous study on the impacts of blade solidity at a constant number of blades, where we observed that increasing the blade solidity excessively, from $\sigma = 1.25$ to $\sigma = 1.5$, results in a 5% decline in $C_{p,max}$ [19]. This decline in performance could be the result of excessive drag or fluid blockage effects. The maximum mechanical power for all turbines are displayed in the Tab. 1. The mechanical power values are considerably high due to the strong wind speed, which does not accurately reflect the wind conditions in energy harvesting operations. However, if we assume a constant maximum power coefficient, we can estimate that the typical maximum power output will be about 0.7 W at $V_\infty = 5 \text{ m.s}^{-1}$.

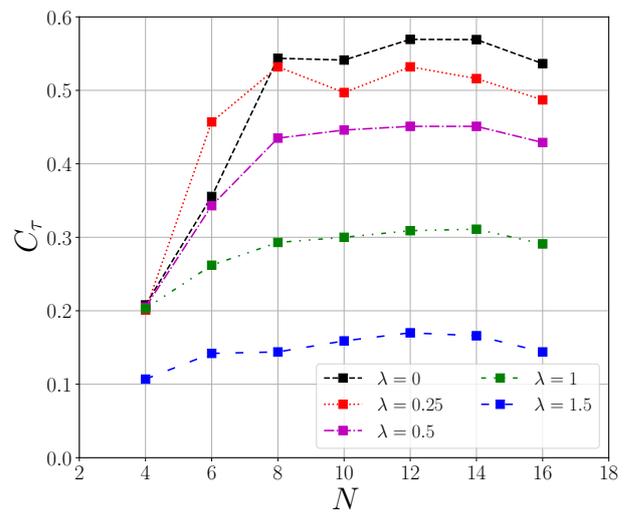
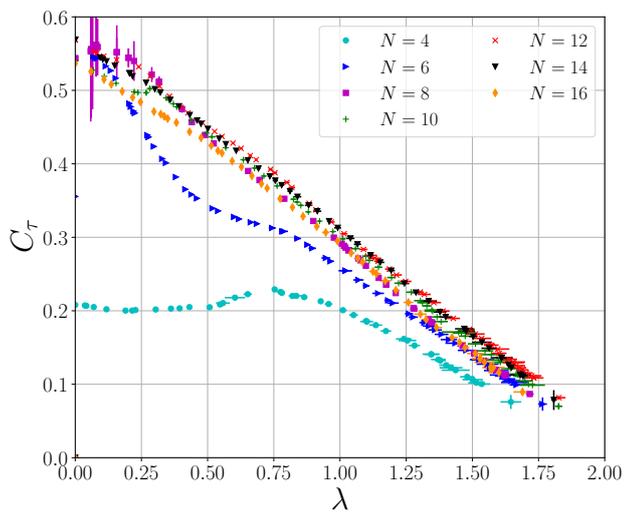
Closer inspection of Fig. 3a shows that increasing the number of blades shifts the $C_p - \lambda$ curves towards the lower tip-speed ratios and makes the curves wider, except for the turbine with $N = 16$ blades. The 4-bladed wind turbine's optimum tip-speed ratio is around $\lambda_{opt} = 1.1$, whereas highly-bladed turbines achieve $C_{p,max}$ at lower tip-speed ratios, around $\lambda_{opt} = 1$. Lower optimal tip-speed ratios are also advocated to reduce blade erosion and noise levels [4]. One can also notice that there are only a few differences in λ_{opt} from $N = 8$ to $N = 16$. Similar variations in λ_{opt} between low- and high-solidity wind turbines are reported in Refs. [8, 19], even though Eltayesh et al. added that increasing N produces narrower curves as well. These data suggest that the optimal angle of attack of a blade cascade arrangement, defined as the angle of attack α at which the maximum lift-to-drag C_l/C_d ratio occurs, decreases with the number of blades until a certain value is reached. It is commonly recognized that the optimal angle of attack of a two-dimensional and isolated airfoil depends on the Reynolds number, the turbulence ratio, the blade roughness and the aspect ratio. As all these parameters were identical for all seven turbines in our experiments, the current data suggest that the blade solidity, *i.e.*, the space between blades, affects the aerodynamic characteristics of an airfoil: the optimal angle of attack, the maximum lift to drag ratio, and more broadly the lift and drag properties.



(a) Variations in the power coefficient C_p with the tip-speed ratio λ for all seven rotors

(b) Variations in the maximum power coefficient $C_{p,max}$ with respect to the number of blades N

Figure 3: Power coefficient characteristics



(a) Variations in the torque coefficient C_t with the tip-speed ratio λ for all seven rotors

(b) Variations in the torque coefficient C_t with respect to the number of blades N for five different tip-speed ratios. The lines have been added for visualization purposes only. The length of the error bars is smaller than the size of the markers

Figure 4: Torque coefficient characteristics

3.2. $C_\tau - \lambda$ characteristics

Fig. 4 depicts the influence of the blade number on the torque coefficient C_τ of a wind turbine. Experimental $C_\tau - \lambda$ curves for all seven turbines are displayed in Fig. 4a and Fig. 4b shows the variations of the torque coefficient C_τ with the number of blades for five different tip-speed ratios. Typical values for the torque at $\lambda = 0$ are displayed in Tab. 1.

Firstly, it is clear from both figures that increasing the number of blades from $N = 4$ to $N = 14$ increases the torque coefficient for the entire range of tip-speed ratio. However, this rise is limited and not straightforward. The greatest increase in C_τ occurs when the number of blades grows from $N = 4$ to $N = 8$, 62% at $\lambda = 0$ and 31% at $\lambda = 1$, while the increase from $N = 8$ to $N = 12$ is just 4% at $\lambda = 0$ and 15% at $\lambda = 1$. Moreover, we found that beyond $N = 12$, adding more blades does not significantly affect the torque characteristic ($N = 14$) or badly affect it ($N = 16$). Indeed, the 16-bladed wind turbine has a lower starting torque coefficient $C_{\tau,0}$ or, in other words, a higher cut-in wind speed than the $N = 12$ and $N = 14$ wind turbines as well as lower torque coefficients throughout the operating range. These results are particularly interesting because it is commonly known that increasing the blade solidity (by increasing either the number of blades [8, 9, 15] or the blade chord length [19]) increases the torque coefficient and the starting torque coefficient, but the existence of an optimal number of blades is rarely mentioned and even less experimentally determined. With the current blade geometry, adding more blades after $N = 12$ does not result in increased torque output, even though there are more blades able to capture wind energy. The additional blade area does not compensate for the increased drag and fluid slowing.

Secondly, a closer look at Fig. 4a reveals that the $C_\tau - \lambda$ characteristics change significantly as the number of blades changes. It is clear that the more the number of blades increases, the more the $C_\tau - \lambda$ characteristics get linear. The turbines with $N = 14$ and $N = 16$ blades have a linear variation of their torque coefficient with the tip-speed ratio for their entire range of operation, and despite little variations at very low tip-speed ratios $\lambda \leq 0.25$, the $N = 8 - 10 - 12$ wind turbines also. Furthermore, the torque coefficients of highly-bladed turbines vary widely. The 12- and 14-bladed turbines have the highest range of torque coefficients, from $C_\tau = 0.57$ at $\lambda = 0$ to $C_\tau = 0.08$ at $\lambda = 1.8$. As a result, these turbines are well suited to provide electricity to electronic devices at a constant voltage since they have a sensitive and linear response of their angular velocity while using a resistive torque control technique.

In comparison, the torque coefficient of low-solidity turbines ($N = 4 - 6$) varies non-linearly with the tip-speed ratio. For example, the torque coefficient of the 4-bladed wind turbine increases linearly from $\lambda = 1.6$ to $\lambda = 0.75$, drops at $\lambda = 0.75$ and then remains almost constant at

low tip-speed ratios (read Fig. 4a from right to left, *i.e.*, from high to low tip-speed ratios). The $C_\tau - \lambda$ variation pattern of the 4-bladed wind turbine is similar to the $C_l - \alpha$ variation pattern of an isolated 2D airfoil, where C_l is the lift coefficient. If we consider a singular blade of the turbine, a decrease in the tip-speed ratio corresponds to an increase in the angle of attack. For an isolated 2D airfoil, before the stall, as the angle of attack increases, so do the lift coefficient and the lift force acting on the blade. As a result, the linear increase in C_τ from high to low tip-speed ratios is explained by the increase in C_l with increasing angle of attack. The decline in C_τ at $\lambda = 0.75$ with the 4-bladed wind turbine is significant of the blade stall, which is characterized by a fall in the lift coefficient. Even though it is clearly visible with the 4-bladed turbine, the drop in C_τ becomes less apparent as the number of blades grows and happens at lower tip-speed ratios, *i.e.*, at higher angles of attack. Moreover, it is clear from the Fig. 4a that the shape of $C_\tau - \lambda$ characteristics differs significantly when the number of blade increases from $N = 4$ to $N = 6$ and from $N = 6$ to $N = 8$. Above $N = 8$ ($\sigma = 1$), only few differences are observed at very low tip-speed ratios. It emphasizes that the interactions between the airflow and the wind turbine change mainly when the number of blades grows from $N = 4$ to $N = 8$, *i.e.*, when the blade solidity increases from $\sigma = 0.5$ to $\sigma = 1$.

In addition, these results show that above a particular number of blades, *i.e.*, a particular blade solidity, the blades no longer work independently but interact among themselves. The pressure side of a blade may interact with the suction side of the next blade, influencing boundary layer separation, the formation of laminar separation bubbles, and stall effects. As a result of the mutual blade interactions, the existing aerodynamic data, the polar plots, are unreliable and become useless for the design and the analysis of high solidity wind turbines [22] and as stated by Hau “*When rotor solidity is very high, the aerodynamic flow conditions become more complicated (cascade flow) and cannot be described by the theoretical model concepts.*” [7]. Although the aerodynamic flow conditions at the blade level are difficult to describe, the turbine’s global performance or, in other words, the $C_\tau - \lambda$ curves, highlight the presence of blade interactions. The containment of the flow into a high-solidity blade cascade may restrict the formation of large laminar separation bubbles and mitigate the stall effects [19]. However, excessive blade solidity reduces the amount of torque produced by the turbine due to increased fluid obstruction and excessive drag forces.

4. Conclusion

The design of an efficient micro-scale wind turbine is a complex challenge, as there are many factors to consider and the impact of each of these factors on performance is not yet fully investigated and understood. Among these variables, the blade solidity plays a key role in determining the performance of micro wind turbines. Prior research

has largely concentrated on the effects of blade solidity and number of blades on low-solidity horizontal axis wind turbines that share similar geometric features with large-scale wind turbines, rather than on high-solidity and low tip-speed ratio wind turbines that are specifically engineered for micro-scale applications. Additionally, there has been limited research that investigates the effect of blade solidity across a broad spectrum and independently, and it is also challenging to compare wind turbines from different studies as many geometric parameters change. The absence of extensive experimental data and design guidelines results in a wide diversity of micro-scale wind turbine geometries, with significant variations in blade solidity and blade number.

Therefore, the purpose of this work was to isolate and analyze the effect of blade solidity on the performance curves of micro-scale wind turbines, over a wide range of blade solidities. In our previous study, we looked into the influence of blade solidity while keeping the number of blades constant, which is equivalent to changing the blade chord length [19]. In this current study, we aim to examine the effects of blade solidity by keeping the blade chord length constant and varying the number of blades, in order to comprehensively evaluate this parameter using our micro-scale wind turbine.

Seven 200 mm turbines, each possessing identical blade geometry in terms of chord length, airfoil, and blade angles were manufactured using Fused Deposition Modeling (FDM) technology. To focus exclusively on the impact of blade solidity, all geometric parameters were kept the same, with the exception of the number of blades, which varied from 4 to 16, resulting in blade solidities ranging from 0.5 to 2. The turbines are designed with a low tip-speed ratio of $\lambda = 1$ and feature larger blade solidities compared to standard large-scale wind turbines, allowing them to start rotating even in low wind speed conditions.

Through series of experiments in a wind tunnel, we found that high-solidity wind turbines with a large number of blades ($N \geq 8$ or $\sigma \geq 1$) were favorable for micro-scale applications. With the current blade geometry, we found that the 12-bladed wind turbine achieves the highest power coefficient $C_{p,max} = 0.310$ and the highest starting torque coefficient $C_{\tau,0} = 0.57$. However, an excessive number of blades ($N > 14$) decreases both torque and power coefficients due to excessive fluid obstruction, while a low number of blades ($N < 8$) decreases the area swept by the blades and thus reduces the amount of wind power that the turbine is able to convert. Moreover, we found a change in the shape of the torque characteristic as the number of blades increased, indicating a blade interaction and raising the question of the applicability of the airfoil polar plots for the design of micro-scale wind turbines. The classical design methodology, which is based on airfoil polar plots and is commonly used for the design and analysis of large-scale wind turbines (the Blade Element Momentum Theory), does not appear to be applicable at the micro-scale, where a design methodology based on blade cascade and

flow deflection might be more appropriate [18].

The generalisability of these results is subject to certain limitations. The optimal range of number of blades and blade solidities found are specific to the turbine blade geometry. For example, a higher tip-speed ratio would likely result in a lower optimal blade solidity and number of blades. Additionally, we did not examine in this study how changes in blade angles or blade profile impact the overall mechanical performance. Given the limited number of studies that independently examine these parameters over a sufficient range, it is challenging to provide definitive design recommendations. Further research would be valuable in achieving a more comprehensive understanding of micro-scale wind turbine operation. Despite these limitations, this study offers some experimental evidence on the impact of blade solidity on the performance and startup behavior of low tip-speed ratio and micro-scale wind turbines, which could aid in the design of more efficient wind energy harvesting systems.

Nomenclature

Dimensionless groups

C_d	Drag coefficient
C_l	Lift coefficient
C_p	Power coefficient, P/P_a
C_τ	Torque coefficient, C_p/λ
x	Dimensionless radial coordinate, r/R_T
Re	Reynolds number, $\rho c V_\infty / \nu$

Greek letters

α	Angle of attack [deg]
β	Relative angle [deg]
λ	Tip-speed ratio, $R_T \omega / V_\infty$
ν	Dynamic viscosity [Pa.s]
ω	Angular velocity [rad.s ⁻¹]
ϕ	Pitch angle [deg]
ρ	Density [kg.m ⁻³]
σ	Blade solidity, $Nc/2\pi r$
τ	Torque [N.m]

SD Standard Deviation

Roman letters

dr	Infinitesimal radial coordinate [m]
N	Number of blades

P	Mechanical power, $\tau\omega$ [W]
P_a	Available power, $1/2\rho\pi R_T^2 V_\infty^3$ [W]
r	Radial coordinate [m]
R_H	Hub radius [m]
R_T	Tip radius [m]
V_∞	Freestream wind velocity [m.s ⁻¹]
c	Chord length [m]
0	Value for $\lambda = 0$
1	Inlet
2	Outlet
max	Maximum value
opt	Optimal value

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