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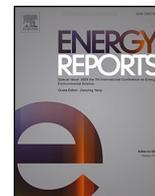
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Research paper

# Rotor solidity and blade pitch influence on horizontal axis small wind turbine performance – Experimental study

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## ABSTRACT

The urgent need to reduce greenhouse gas emissions has accelerated the adoption of renewable energy sources such as wind power. In this context, small wind turbines (SWTs) have emerged as a viable solution for decentralized electricity generation. This paper investigates the combined influence of rotor solidity and pitch angle variation on the performance of a small horizontal axis wind turbine through experimental analysis conducted in a wind tunnel. Results show that increasing rotor solidity generally improves  $C_{pmax}$ , particularly for shorter chord blades, with up to a 25–35 % increase observed by increasing the number of blades and a 10–15 % increase by employing longer chord blades compared to benchmark designs. Additionally, the study highlights the significant sensitivity of turbine performance to slight changes in pitch angle resulting in a 4–8 % rise in  $C_{pmax}$ . Higher solidity rotors exhibit reduced sensitivity to pitch angle changes and reference velocity variations, contributing to improved stability in varying environmental conditions. The study highlights the influence of aerofoil Reynolds number on turbine performance, underscoring the importance of careful aerodynamic design considerations. It provides valuable insights for SWT design to enhance energy efficiency and promote the widespread adoption of wind energy technology.

## 1. Introduction

The reduction of greenhouse gas emissions has been a significant challenge for several decades now, as witnessed for example by the European Union's plans for achieving climate neutrality in 2050. To attain this goal, the transfer from fossil fuels to renewable energy sources like wind needs to happen promptly. Aside from an increasing number of large-scale offshore- and onshore wind farms, a market for electricity generation by individual household owners (prosumers) is emerging. Small wind turbines (SWTs), operating usually at transitory Reynolds number ranges, are to be utilized, while remaining profitable. High efficiency can be provided by optimization of blade geometries, whereas the economic justification plays a major role in potential performance improvement. This can be achieved by a careful tuning of pitch angle, followed by an inspection of rotor solidity influence on the efficiency, at given environmental conditions.

## 1.1. Blade pitch

Proper control of pitch angle of small wind turbine blades may

facilitate the control of wind turbine rotational velocity. Chavero-Navarrete (Chavero-Navarrete et al., 2021) used a fuzzy logic controller in varying pitch and diminishing the necessity of exceeding the nominal generator rotational speed by even 20 %, resulting in 7 % gain of generated energy. Algorithms employing methods such as TLBO (teaching-learning based optimization) can work also for larger turbines – the improvement of control in different wind speed ranges was confirmed on 14 kW PMSG wind turbine (Chavero-Navarrete et al., 2019).

It was observed by Najafian Ashrafi et al. (2015), that the presence of pitch control mechanism enables augmentation of the efficiency of wind turbine, especially at off-design wind speeds. The blade pitch influence on efficiency is an even more important field of research when vertical axis wind turbines are analysed (Rezaeiha et al., 2017), particularly for the returning blade.

Sudhamshu et al. (2016) investigated numerically a two-bladed NREL Phase VI wind turbine. It was concluded that there is an optimum pitch angle, depending on a wind velocity, for which the attained power would be maximized. Increase in pitch angle results in decreased thrust. A field test performed by Rocha et al. (2018), resulted in following conclusions: the higher pitch angle (+6°) is appreciable to

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**List of symbols**

$B$	number of blades [dimensionless]
$C$	chord factor [dimensionless]
$c$	blade chord [m]
$C_d$	drag force coefficient [dimensionless]
$C_l$	lift force coefficient [dimensionless]
$C_p$	power coefficient [dimensionless]
$C_{p_{max}}$	maximum power coefficient [dimensionless]
$D$	wind turbine diameter [m]
$Q$	torque [Nm]
$R$	wind turbine radius [m]
$r$	wind turbine local radius [m]
$S$	solidity factor [dimensionless]
$TSR$	tip speed ratio [dimensionless]
$V_{ref}$	reference flow velocity [m/s]
$\alpha$	angle of attack [°]
$\beta$	blade pitch angle [°]
$\rho$	air density [kg/m <sup>3</sup> ]
$\sigma$	solidity [dimensionless]
$\varphi$	inflow angle [°]
$\omega$	wind turbine rotational velocity [rad/s]

start the turbine, while  $+3^\circ$  provides best efficiency for wide range of tip speed ratios (from 3 to 7). Carefully chosen and conditions-appropriate pitch angle can provide better starting torque (lower cut-in speed) and broader operating range of a unit.

### 1.2. Solidity

Small wind turbines of horizontal axis have a slightly different initial design requirements when compared to large ones. Low wind speed conditions imply that high torque is required for a turbine to start and operate effectively at low freestream velocities, as demonstrated by Refan and Hangan (2012). As the design tip speed ratio is relatively low, it is the high solidity that makes it possible to reduce the cut-in speed, as confirmed by Bourhis et al. (2023) and Eltayesh et al. (2021). However, one should have in mind that the optimum working conditions for wind turbine doesn't only mean maximized power coefficient, but can also refer to relatively wide range of velocities upholding the high-efficiency working regime. Most commercially available small horizontal axis wind turbines operate at tip speed ratios of 5 or greater and employ 2 or 3 blades with a total solidity of less than 7 %, similar to large, utility-scale HAWTs (Duquette and Visser, 2003).

Eltayesh et al. (2021) stated that the effect of the Reynolds number in case of small-scale HAWT is negligible for the ranges of wind speed not exceeding 10 m/s, what actually stood in contrast to the literature research – perhaps due to relatively low turbulence intensity of the study (0.5 %). An important aspect is controlling the rotational speed, which has to be fine-tuned based on the number of blades (to provide optimal turbine operation).

Duquette et al (Duquette and Visser, 2003; Duquette et al., 2003). utilized in their research the Blade Element-Momentum (BEM) theory. Increasing the blade number while maintaining the rotor solidity resulted in higher maximal power coefficient of the rotor. At the same time, more blades resulted in lowered optimal tip speed ratio (Duquette et al., 2003). The findings were confirmed by Mendonça and Azevedo (Mendonça and Azevedo, 2017), who compared three- and six-bladed configurations.

One of the most significant findings of Bourhis et al. (2023) is that an increase in the blade solidity results in increase of the power coefficient until a maximum value at a blade solidity  $\sigma = 1.25$ . Another important finding is that high-solidity rotors present a nearly linear decrease in

torque coefficient with tip speed ratio, while this relation for low-solidity rotors is not strictly linear. The analysis of the wake shows that the high-solidity turbine induces a highly stable and rotating wake, with lower wake expansion and deceleration than the conventional one (Bourhis et al., 2022).

Additional advantages over current 5–7 % solidity designs would include lower noise, lower cut-in wind speed, and less blade erosion (Duquette and Visser, 2003).

Typical environmental conditions observed by the real SWTs correspond mostly often to Reynolds number approximately in range  $10^4 - 10^5$ . At such conditions the transitory flow over the individual blade sections (aerofoils) may provoke separations and contribute to drag increase. This justifies the importance of small wind turbine performance assessment under the adverse conditions proposed in the current study.

### 1.3. Contribution of the performed study to the overall knowledge

The above considerations point to the aim of the current research: to investigate the influence of the rotor solidity combined with varying pitch angle on the performance of a small horizontal axis wind turbine. The solidity was subjected to change by different number of blades (two vs. three vs. four) and chord (standard vs. increased to 1.33 of its original dimension). The experimental analysis was performed in a wind tunnel located at the LIFSE laboratory in ENSAM, Paris, France.

## 2. Methods

This Chapter describes the experimental methods used in the research, including the tested win turbine configuration and measurement apparatus.

### 2.1. Theoretical background and principal notions

The number of blades  $B$  and the chord distribution have a direct influence on the blade solidity  $\sigma$ , which is defined as ratio of the rotor planform area to the rotor swept area  $A$ . Solidity at the blade local radius  $r$  is described by the following mathematical formula (Hansen, 2008):

$$\sigma(r) = \frac{c(r)B}{2\pi r} \quad (1)$$

The initial results predicted by the numerical software QBlade have given a new insight on the issue of an optimal solidity. In order to choose the best configuration of the rotor and the chord of blades, the series of numerical simulations and experiments in wind tunnel were performed (including small scale tests (Zawadzki et al., 2021)). The combination of S826 and S834 aerofoils (Fig. 1) was utilized to construct the blade.

In the performed study, the following parameters were defined and changed:

- Chord factor  $C$ , defined as 1 for original chord and 1.33 for chord scaled up by 33 %,
- Solidity factor  $S$ , based on number of blades  $B$  and  $C$ , defined as  $S = B \cdot C$  (see Table 1),
- Pitch angle  $\beta$ , set to  $-4^\circ$ ,  $-2^\circ$ ,  $0^\circ$  (design configuration),  $2^\circ$  and  $4^\circ$ ,
- Reference wind velocity  $V_{ref}$ , set to 4.0 m/s, 4.5 m/s, 5.0 m/s, 5.5 m/s and 6.0 m/s,
- Wind turbine rotational velocity  $\omega$ .

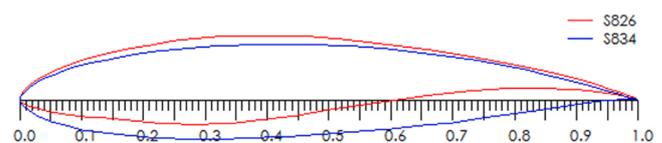


Fig. 1. Outlines of aerofoils used in the study.

**Table 1**

Tested values of solidity factor  $S$ , depending on number of blades  $B$  and chord factor  $C$ .

		C		
		1	mix	1.33
B	2			2.66
	3	3.00		3.99
	4	4.00	4.66	5.32

While pitch change in itself also influences the projected front area of the rotor, this factor is deemed negligible, compared to changes in  $B$  and  $C$ .

Fig. 2 shows the used pitching notion convention. Since the literature is not always coherent in the matter, the current research assumes that increasing the pitch angle  $\beta$  means increasing the angle between chord line and rotation plane (equivalent to turning the blade clockwise in Fig. 2).

## 2.2. Experimental setup

The experimental study was carried out in the Prandtl type wind tunnel of the LIFSE facilities (Fig. 3).

The closed loop system is powered by an axial fan with a rotor diameter of 3 m powered by asynchronous motor. Downstream the fan, the flow is decelerated and straightened in a settling chamber equipped with honeycomb straightener. The tests are conducted in a return channel of dimensions 3 m x 3 m x 6 m, carried out with a turbine subjected to wind velocities  $V_{ref} = 4$  m/s, 4.5 m/s, 5 m/s, 5.5 m/s and 6 m/s.

The flow uniformity in wind tunnel may be estimated at a level of 1–3 %, while turbulence intensity at a level of 5–10 %. Although the precise values cannot be confirmed by any recent study (rare usage of large test section), these values seem fair when compared with similar wind tunnel concepts. While  $TI = 5$  % may seem exaggerated for the wind tunnel conditions, the study in general concentrates on the strength analysis, also in the extreme actual operating conditions, much closer to the value of 5 %.

Fig. 4 illustrates the configuration of the experimental test stand used in the research. The examined blade geometries were affixed to a hub with two, three or four blades (1). To start up the wind turbine a 300 W motor was used (4). During the tests, the rotor tip speed ratio was varied to obtain different points on the aerodynamic characteristics. This was achieved by adjusting the turbine's braking torque, accomplished using an eddy current brake (3). Torque measurements were conducted using a test bed and a strain gauge positioned behind the brake (out of sight in the photo). The rotational velocity of the rotor was monitored using an additional sensor of a torque meter (2).

The three- and four-bladed rotor configurations are visible in Fig. 5, which also presents a zoomed view onto the trapezoidal cross-section inserts placed between the blade(s) and the hub to set up the pitch

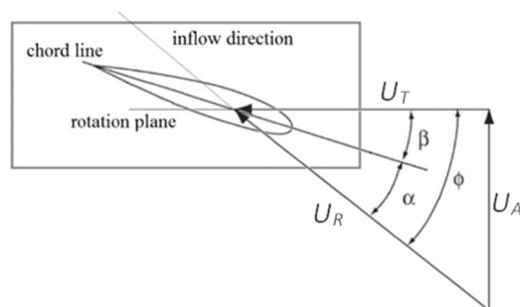


Fig. 2. Local velocity triangle on a wind turbine blade section,  $U_A$  – axial velocity,  $U_T$  – tangential velocity, based on (Hansen, 2008).

angle. The inserts, 3D printed in plastic (ABS), were blocked between the two surfaces and fixed with screws, ensuring a safe and repeatable mounting process.

The test stand operated in an open-loop configuration. A data acquisition system in LabView software allowed one to collect all data from the test stand (torque  $Q$  and rotational speed  $\omega$ ), wind velocity readings from a Pitot probe and input parameters related to the rotor geometry, specifically the rotor diameter ( $D = 1.6$  m).

The results analysis is done based on the dimensionless parameters: power coefficient ( $C_p$ ), relating wind turbine power to available wind stream power; and tip-speed ratio (TSR), relating the rotational and axial velocity components (with  $\rho$  – flow density) (Burton et al., 2013):

$$C_p = \frac{Q\omega}{0.5\rho\pi R^2 V_{ref}^3} \quad (2)$$

$$TSR = \frac{\omega R}{V_{ref}} \quad (3)$$

## 3. Results and discussion

This Chapter presents the results of experimental campaign and performance analysis of tested rotors. These include a discussion of rotor solidity effects on the wind turbine operation, supplemented with study of blade pitching influence on wind turbine efficiency. Eventually, the combined effect of solidity and pitch alterations is discussed.

### 3.1. Influence of chord length and number of blades

In the presented study two different factors influenced the solidity factor  $S$ , that is  $B$  (number of blades) and  $C$  (blade chord length factor). Fig. 6 shows the variation of the power coefficient  $C_p$  as a function of TSR for five different small-scale wind turbines (of different solidities). The tip speed ratio range of operation is nearly the same for all rotors ( $4 < TSR < 8$ ) and is resulting from the wind turbine aerodynamic design and the capabilities of experimental test stand: due to controlling of the torque by the brake, it is not possible to collect the complete (i.e. including TSR lower than that for the maximum allowable braking torque)  $C_p$  characteristic. Marker types in Fig. 6 distinguish series with same blade chord length (circles for  $C = 1.33$  and triangles for  $C = 1.00$ ), while colours denote consecutive numbers of blades  $B$ . It is worth noting that chord elongation leads to a significant improvement in power production (compared to  $C = 1.00$ ), which additionally is attained at slightly lower (by approximately 1) TSR values. It also seems that the plateau of high efficiency is slightly wider for  $C = 1.33$ . The right-hand sides of the  $C_p$  characteristics are very alike for rotors of both  $C$ , for ranges of  $TSR > 6$  – in such conditions the unit performance differences become negligible. The rotors of various number of blades  $B$  operate with a clear tendency – more blades produce more power, indicating that the original design may not be optimal for a 3-bladed solution. Higher  $B$  results in higher values of power coefficient (analogically for both lengths of chords) obtained at slightly lower TSRs. This is in agreement with Duquette and Visser (2003) and Rector et al. (2006), who proved similar trends both experimentally and numerically. The relative difference of obtained  $C_p$  can reach up to even 20 % (when comparing 4-bladed rotors with elongated chord with 3-bladed one).

To make the abovementioned relationships even more apparent, the results of maximum  $C_p$  obtained by variously pitched rotors ( $\beta = -4^\circ, -2^\circ, 0^\circ$  - design configuration -  $2^\circ$  and  $4^\circ$ ) at different freestream velocities (4 m/s - 6 m/s) were grouped with respect to three combinations of  $B$  and  $C$  (Fig. 7, where the same colour and marker schemes were used, as in Fig. 6). Two of these cases are comparable in terms of the same rotor solidity  $S = 4$  (see Table 1). The first observation is the clear, linear trend between  $C_{p_{max}}$  for different pitch values at the same  $V_{ref}$  values. Regardless of the solidity and freestream velocity, all pitch variants present the similarly-sloped linear dependence between

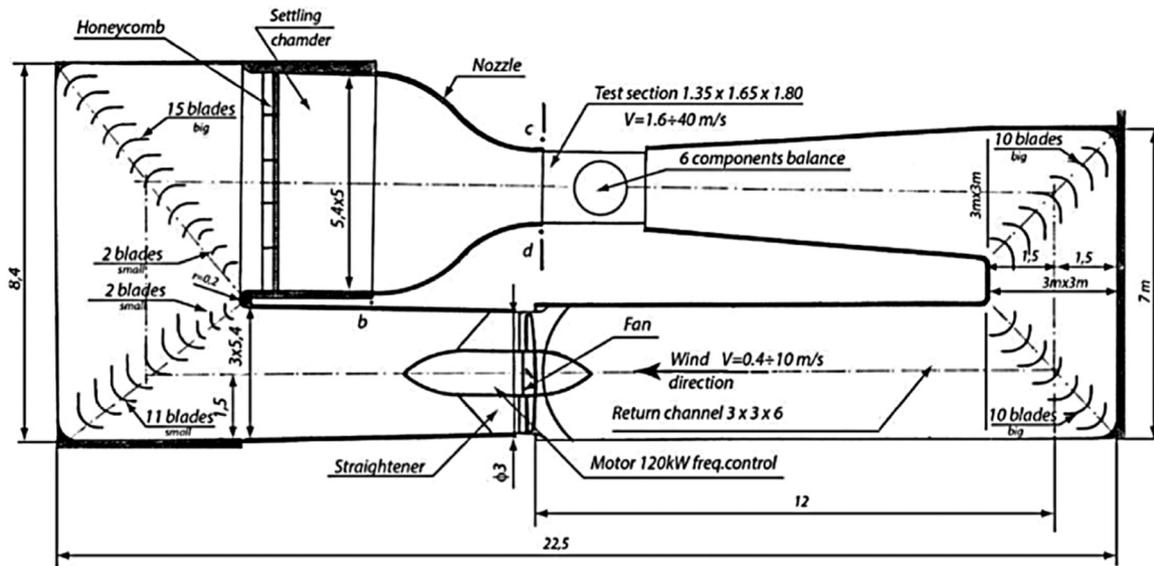


Fig. 3. Scheme of the LIFSE wind tunnel.

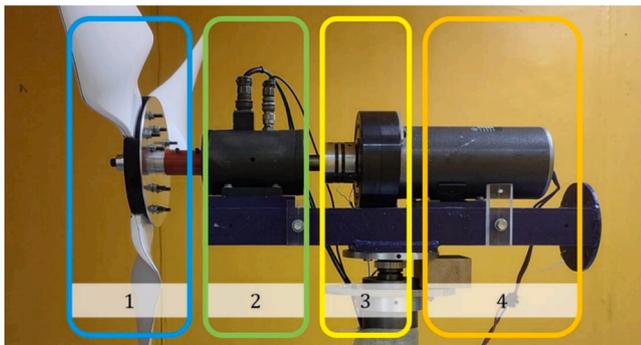


Fig. 4. General view of the wind turbine test stand: (1) rotor, (2) torque sensor (used for rot. velocity measurement only), (3) brake with strain gauge (not visible), (4) motor.

maximum obtained power coefficients  $C_p$  and TSR. Another notable finding is that four-bladed rotor ( $B = 4, C = 1.00$ ) performs better than the three-bladed one ( $B = 3, C = 1.33$ ) of an equivalent solidity. It reaches higher power (by about 0.025) at consecutive tip speed ratios. The range of TSRs for which the maximum  $C_p$  is obtained is similar for

the rotors with blades of the same chord length  $C = 1.00$ , regardless of the number of blades, and is in range from  $TSR = 4$  to  $TSR = 5.5$ .

The abovementioned results confirm the known relationship between rotors of the same blade geometry but different number of blades: the more blades, the higher obtained power coefficient (for respective tip speed ratios). From the point of view of wind turbine overall efficiency, the recommendation is to consider replacing the configuration of blades of given chord with an alternative rotor with increased number of blades of diminished chord (preserving the same rotor solidity). This can be confirmed by comparing the maximum  $C_p$  values for  $S \approx 4$  at pitch angle  $\beta = 0^\circ$  (see Fig. 8). It is evident that, to a limited extent, the higher  $\sigma$  results in higher obtainable efficiency. Increasing the number of blades from 3 to 4 raises the  $C_{p_{max}} = 0.27$  at  $TSR = 5.25$  raised to  $C_{p_{max}} = 0.36$  at  $TSR = 4.95$  (increase in  $C_{p_{max}}$  by more than 30%). Similar tendency (refer to grey trend lines) can be observed for rotors with  $C = 1.33$ . What is most noticeable is the difference between three- and four-bladed rotor variants with similar solidities – the increase in  $C_{p_{max}}$  is by ca. 15% (from 0.31 to 0.36 for  $TSR = 4.8$  and  $4.95$ , respectively). Further increase of  $S$  (4 blades with extended chord) results in just slightly higher efficiency, possibly close to the attainable limit ( $C_{p_{max}} = 0.38$  at  $TSR = 4.6$ ).

The typical, practical limitation of increasing number of blades is the economic justification. In the context of design considerations, the

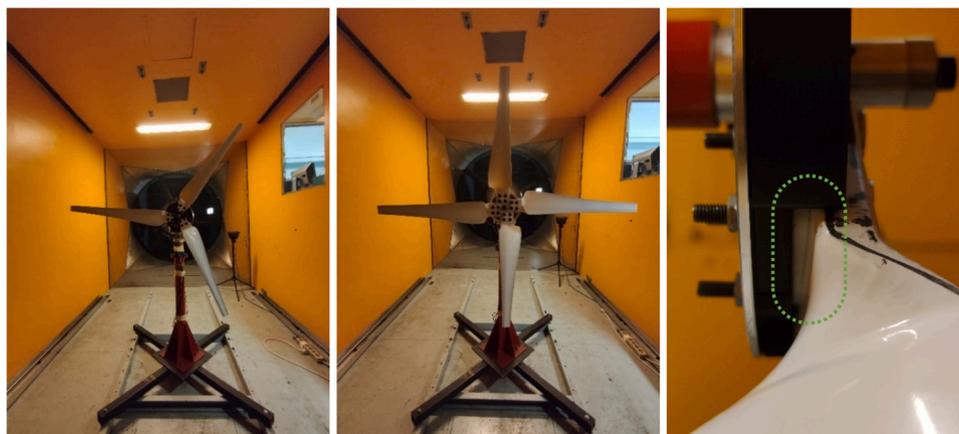


Fig. 5. Wind turbine configuration: (left) 3-bladed rotor, (middle) 4-bladed rotor and (right) pitch modification realised with use of 3D-printed inserts [green] between hub [black] and blade [white].

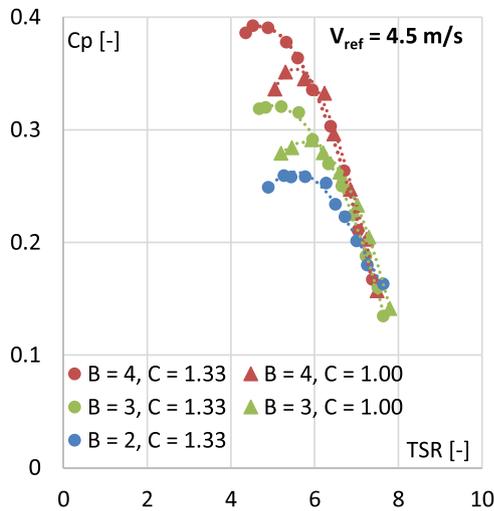


Fig. 6.  $C_p$  vs. TSR at constant  $V_{ref} = 4.5$  m/s and pitch maximizing performance ( $\beta = -2^\circ$  for  $C = 1.00$ ,  $\beta = -4^\circ$  for  $C = 1.33$ ).

significant impacts should be studied: different distribution of loads, more sophisticated construction of hub, larger number of sub-assemblies, etc. Similarly, the operation (along with proper unit control) would be affected considerably.

### 3.2. Width of the $C_p$ curve

Having the collection of wind turbine performance data for various rotor pitch angles at different wind speed velocities enables one to estimate the operational envelope of a unit (Fig. 9). This “high performance region” was defined as TSR values for which the wind turbine operates at or above 99 % of maximum  $C_p$  at TSR lower than optimal, and 95 % of maximum  $C_p$  at TSR higher than optimal. Presumption of particular, limited range of acceptable generated power levels can indicate the breadth of TSR values for which the turbine can operate optimally.

A composition of operational envelopes obtained for all investigated wind turbine units (Fig. 10) allows one to compare their performance easily. General trends can be quickly identified. Two units with lowest solidity ( $B = 2$ ,  $C = 1.33$  and  $B = 3$ ,  $C = 1.00$ ) are characterised by a significantly wider TSR operation range, at the same time achieving globally lower  $C_p$ . Gradual increase of solidity results in the raise of power coefficient together with slight shift of performance regions towards lower values of tip speed ratio. Finally, total area of presented

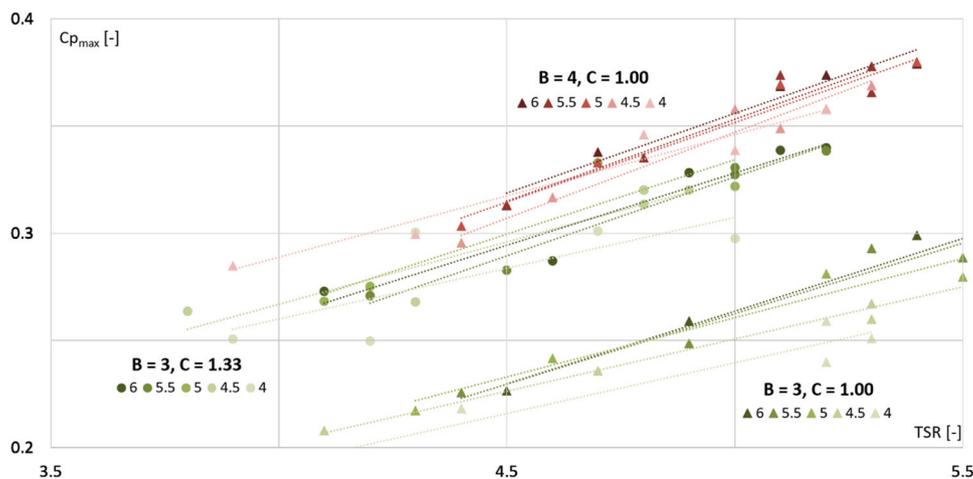


Fig. 7.  $C_{p_{max}}$  vs. TSR for three rotor families: 3- (green) and 4-bladed (red) with basic (triangles) and elongated chord (circles).

envelopes drops for higher solidity. This can be interpreted as lower sensitivity of higher solidity units to changes of investigated parameters: pitch and reference velocity.

### 3.3. Blade pitching influence on wind turbine performance

Assuming that the inflow angle  $\varphi$  remains constant, decreasing  $\beta$  results in increase of the angle of attack  $\alpha$ . If the blade is designed to operate well before stall conditions, this may be a good way to increase  $Cl/Cd$ .

In turn, at specific  $V_{ref}$ , if constant  $\alpha$  is assumed, decreasing  $\beta$  results in increasing the tangential velocity vector  $U_T$  and consequently – tip speed ratio TSR. This means that the rotational velocity giving a prescribed  $\alpha$  increases, resulting in rise of the inflow velocity  $U_R$  and consequently – local Reynolds number  $Re$ . In case of small wind turbines, whose blades often work in transitory regime, increasing  $Re$  normally permits one to stabilise the machine and obtain higher  $C_p$  by increasing  $Cl/Cd$  – see e.g. the experimental data for S826 airfoil in Fig. 11.

Fig. 12 shows how the analysed wind turbine efficiency varies with TSR and pitch angle. In all analysed cases increasing the pitch decreases the optimal rotational velocity and consequently - the optimal TSR. The corresponding decrease of  $C_p$  may be associated with the drop in  $Re$  and subsequently  $Cl/Cd$ . The  $C = 1.00$  blades are characterised by a saddle-like shape, where a local  $C_{p_{max}}$  is attained for  $\beta = 0^\circ$  and approximately  $TSR = 5$ ; while the rotor performance is poorer for  $\beta = -2^\circ$ , it increases importantly for  $\beta = -4^\circ$ , with optimum TSR shifting towards 5.5 – 6 (depending on the number of blades  $B$  and reference wind speed  $V_{ref}$ ).

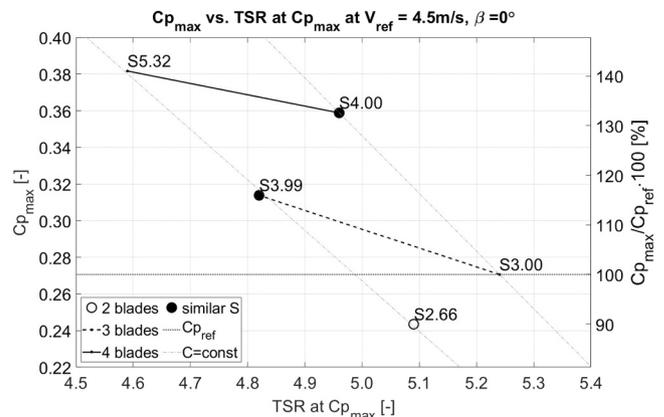


Fig. 8.  $C_{p_{max}}$  vs. TSR at pitch angle  $\beta = 0^\circ$ .

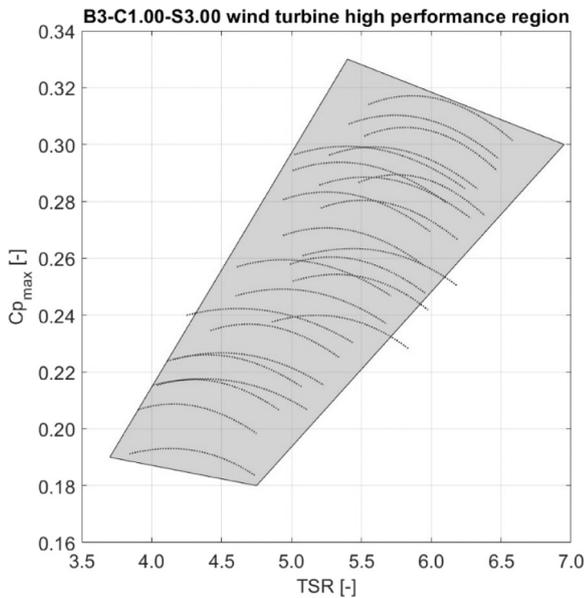


Fig. 9.  $C_p$ (TSR) curves for wind turbine ( $B = 3, C = 1.00$ ) constructing the quadrilateral “high performance region”.

An analogous behaviour is not observed for the  $C = 1.33$  blades, which exhibit a stable increase of characteristics with pitch drop, or a maximum for pitch  $\beta = -2^\circ$ . This behaviour could be attributed to the characteristic of the S826 aerofoil, in this case operating at Reynolds number range  $0.5 - 1.0 \times 10^5$ . These conditions are highly unfavourable for this aerofoil, in that the optimal angle of attack and the overall shape of the  $Cl/Cd$  curve in the normal operating range (until approx.  $\alpha = 9^\circ$ , see Fig. 11) changes drastically depending on the Reynolds number. In the said Re range, at a constant angle of attack, the  $Cl/Cd$  may rise by as much as 200–500 % as Re increases from  $0.5 \times 10^5$  to  $1.0 \times 10^5$ . Consequently, even small local disturbances in flow velocity or angle of attack may result in relatively high changes in the aerofoil and blade performance.

### 3.4. Maximum $C_p$ and optimal TSR

The study on the blade pitch influence on wind turbine performance can be deepened by investigating the relationship between maximum power coefficient  $C_{p_{max}}$  for different pitch angles  $\beta$ . Such comparison is presented in Fig. 13, where six variants of rotors are presented separately as a function of pitch angle values  $\beta$  (grouped by various free-stream velocities  $V_{ref}$ ; the same ranges of Y-axis were preserved for easy comparison between different rotor variants). In Fig. 14, on the other hand, the rotors are grouped by  $\beta$ , where  $C_{p_{max}}$  is presented as a function

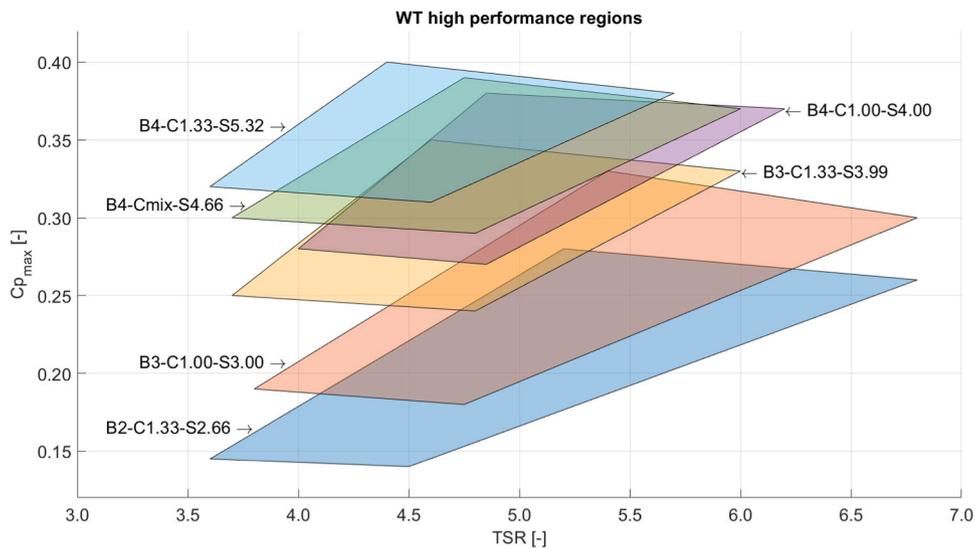


Fig. 10. All tested wind turbines “high performance regions”.

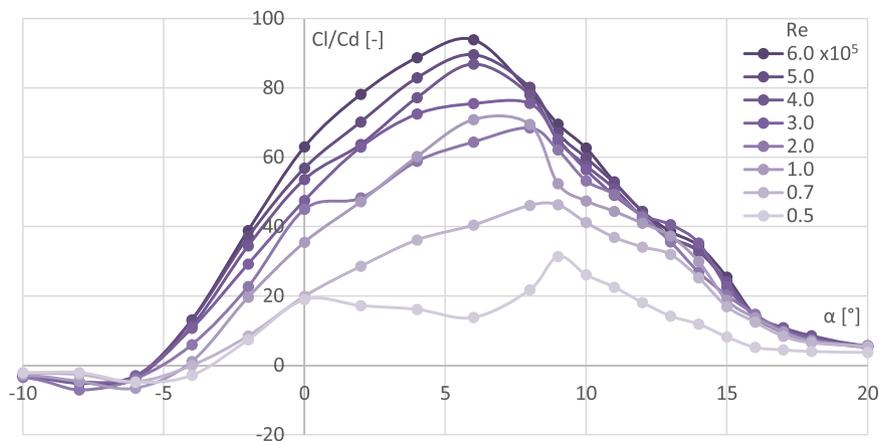


Fig. 11. Typical change in  $Cl/Cd$  characteristics of an asymmetric profile at low Re: S826 experimental data by Bartl et al. (2019).

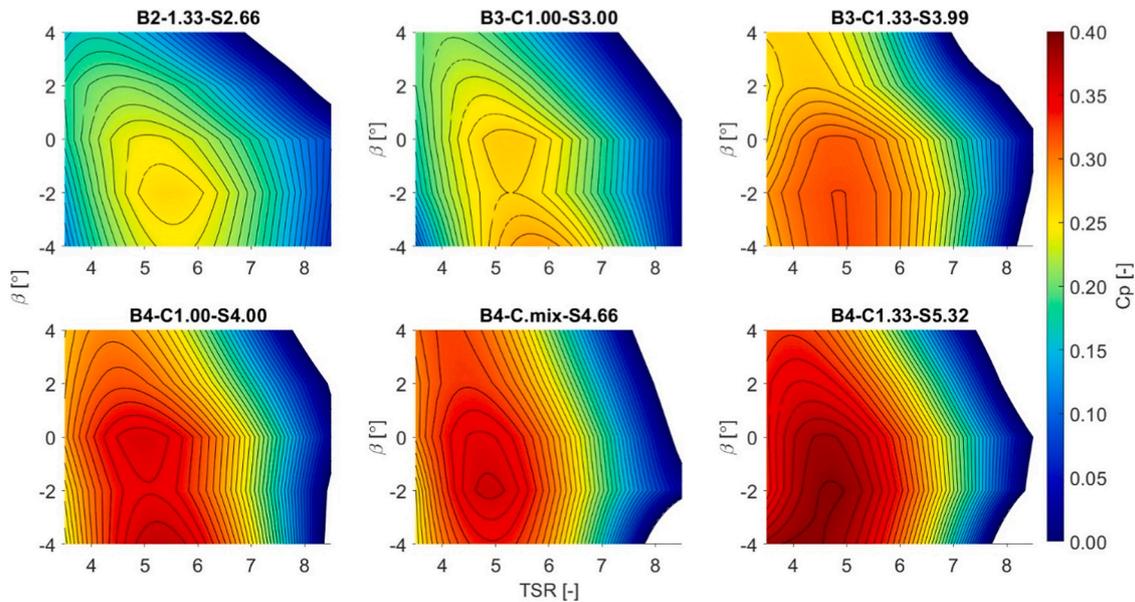


Fig. 12.  $C_p$  as function of pitch  $\beta$  and TSR for different blade configurations,  $V_{ref} = 4.5$  m/s.

of  $V_{ref}$ .

Apart from the local minimum (saddle-like shape at  $\beta = -2^\circ$  in cases with original  $C = 1.00$ ), all cases present consistent behaviour. Negative pitch angles for a distinct number of cases result in the highest efficiency, which confirms the proclamation that the original blade was not optimised to operate at  $\beta = 0^\circ$ . Moving further on with increasing the pitch angle (towards positive values, up to  $4^\circ$ ), the efficiency drops down for all rotor variants and all  $V_{ref}$  values. Naturally, the lower values of freestream velocity result in lower turbine efficiency, with a difference in  $C_{p_{max}}$  values fading for the highest  $V_{ref}$  cases (negligible variations of maximum efficiency for  $V_{ref} > 5$  m/s).

Together with increased solidity one can observe higher values of obtained  $C_{p_{max}}$ . Regardless of the blade pitch angles  $\beta$ , there is also a clear tendency for asymptotical rise of power coefficient along with increase of  $V_{ref}$ . This suggests that further increment of wind velocity would not cause any additional gain in power retrieved from the flow. It is evident that the original blade pitch angle  $\beta = 0^\circ$  is not optimal – its slight adjustment towards negative angles improves the wind turbine performance for most of the examined solidities. In turn, the positive blade pitch angles slightly deteriorate the operational efficiency for all investigated wind velocities and rotor solidities.

Finally, Fig. 15 shows the maximum power coefficient as a function of rotor solidity factor and Fig. 16 presents the optimum TSR at which this maximum power is attained. For both figures two freestream velocities  $V_{ref}$  were chosen as representative examples: 4.5 m/s (left) and 5.5 m/s (right).

It is somehow evident that negative pitch angles could result in attaining highest possible power coefficients, along with further increase of rotor solidity. However, the experimental campaign was constrained to compare two-, three- and four-bladed hubs, even though it would be beneficial to continue the tests in the future with five-bladed rotors. It is striking that the rise of  $C_{p_{max}}$  for  $C = 1.00$  is more steep than for  $C = 1.33$ . Was it not for the limitations of the test stand, one could possibly increase the solidity further on to find the limit of obtainable power for this particular blade geometries. Also, the absolute values of  $C_{p_{max}}$  are generally higher for shorter chord blades ( $C = 1.00$ ) than for longer chord blades ( $C = 1.33$ ). This observation is valid for all pitch angles and flow velocities (refer to corresponding sets of two-point and three-point data sets plotted for the same pitch angles in Fig. 15). More noticeable influences of pitch angle choice are visible when optimal TSR values are plotted as a function of solidity (Fig. 16). Here,

one can observe that  $\beta = 4^\circ$  for  $C = 1.00$  results in reversed tendency (higher solidity, thus more blades -  $C_{p_{max}}$  reached at higher TSR). This implies that, although the negative  $\beta$  angles confirms that the originally defined blade pitch angle ( $\beta = 0^\circ$ ) left room for improvement, it was clearly towards the negative  $\beta$  angles. In that manner, even lower pitch angles ( $\beta < -4^\circ$ ) might be worthy of investigation. Such behaviour is confirmed at lower  $V_{ref}$ , where the increase of solidity continuously concludes in highest turbine efficiencies obtained at lower TSR values.

#### 4. Conclusions

The presented research aims at investigation of the influence of the rotor solidity combined with varying pitch angle on the performance of a small horizontal axis wind turbine. Two ways to vary the solidity factor were examined: different number of blades (either two, three or four) and chord (standard/benchmark chord length, and an increased one: 1.33 of its original dimension). The following conclusions were formulated in terms of interpreting the impact of various rotor solidities:

- Generally,  $C_{p_{max}}$  reaches higher values with the solidity factor increase. Such effect is more evident, however, for shorter ( $C = 1.00$ ) blades.
- The increase of solidity results in slight shift of  $C_{p_{max}}$  towards lower TSRs (from applicational point of view – improving the wind turbine responsiveness to lower wind velocities).
- Observation of results obtained for rotors with similar solidity factor  $S \approx 4$  leads to conclusion that a four-bladed rotor ( $B = 4$ ,  $C = 1.00$ ,  $S = 4.00$ ) performs better than the “solidity-equivalent” three-bladed one ( $B = 3$ ,  $C = 1.33$ ,  $S = 3.99$ ). By increasing number of blades, a raise of maximum power coefficient by up to 25 % - 35 % was observed, whereas application of longer chord blades resulted in 10 % - 15 %  $C_{p_{max}}$  raise with respect to the benchmark rotor ( $B = 3$ ,  $C = 1.00$ ,  $S = 3.00$ ).
- It has been proven that higher solidity rotors are considerably less sensitive to changes of pitch angle and variations of reference velocity. This might be treated as a benefit in terms of more stable turbine operation in unsteady weather conditions.

Along with the above findings (all with agreement with reported literature data), the influence of pitching the original blade (both into negative and positive angles) was studied:

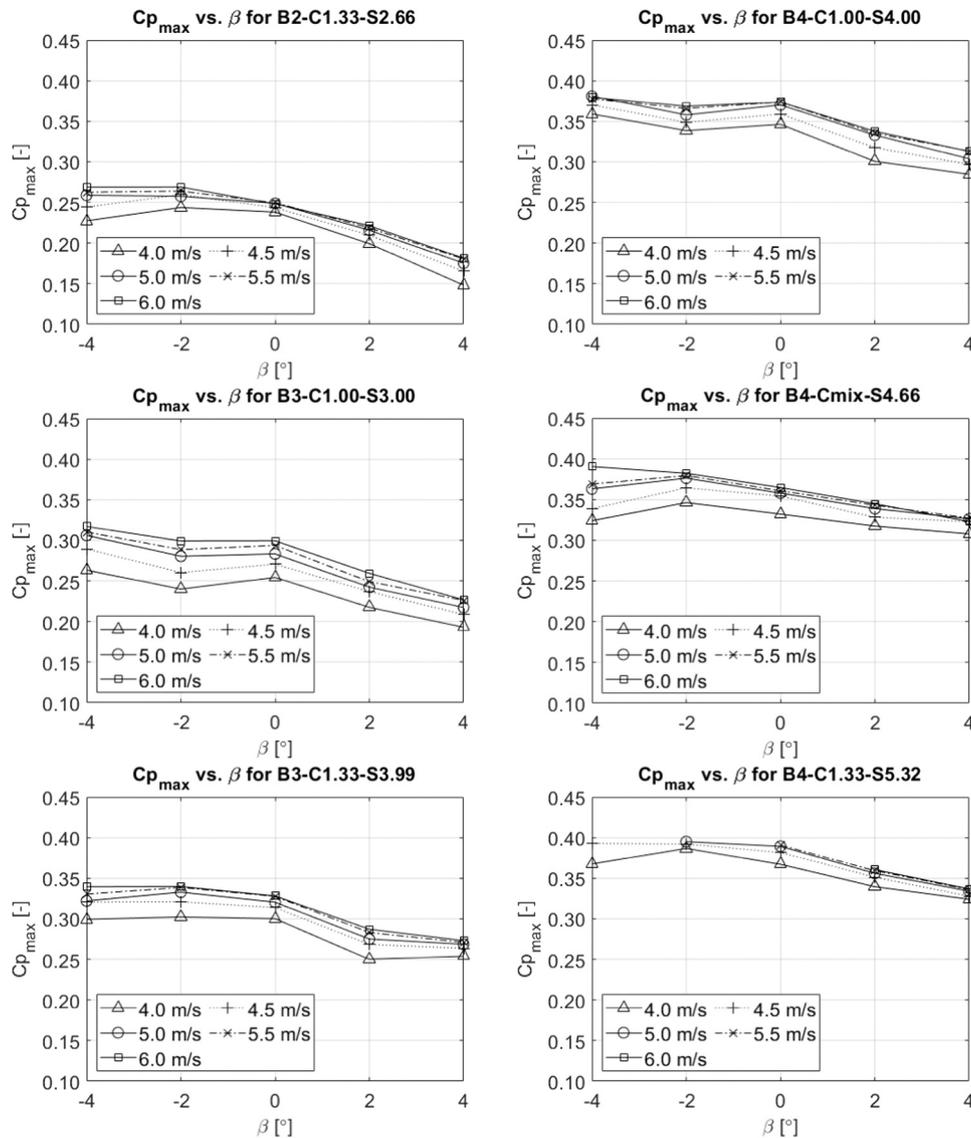


Fig. 13.  $C_{p_{max}}$  attained at various pitch angles for different wind speeds: 2- and 3-bladed rotors (left) and 4-bladed rotors (right).

- In present study the original, benchmark pitch angle  $\beta = 0^\circ$  resulted in non-optimal rotor performance. Fixing pitch angles to different values showed the significant sensitivity of the turbine to even slight changes of pitch angle: negative angles ( $\beta = -2^\circ$  and  $\beta = -4^\circ$ ) resulted in a rise of maximum power coefficient by 4% - 8%, especially in original three bladed rotor ( $B = 3$ ,  $C = 1.00$ ,  $S = 3.00$ ).
- In opposition to solidity change effect mentioned above (higher  $C_{p_{max}}$  obtained at lower TSR), decrease of pitch angle results in optimum TSR shifting towards higher values (higher  $C_{p_{max}}$  obtained at higher TSR).

The current study has also pointed out up to what degree the aerofoil Reynolds number effects may influence the overall performance of a small wind turbine. The use of S826 aerofoil, of very particular aerodynamic performance at the Reynolds number range below  $10^5$ , resulted in a relatively high vulnerability of  $C_p$  to the wind speed and pitch change, particularly for the  $C = 1.00$  blades; and was most probably responsible for the drop of  $C_p$  at pitch angle  $-2^\circ$  for that set of blades. Negative influence of too low reference velocity and thus the Reynolds number was observed only to a limited extent. Plots of  $C_{p_{max}}$  as a function of reference velocity reveal an asymptotic character. Increment of wind velocity above 5–5.5 m/s resulted in no significant gain in

power coefficient.

On a more practical note, the research leads to following guideline: the lower the wind speeds and the smaller the wind turbine, the more prone it will be to transitory Reynolds flow regimes. This is pronounced in wind turbine sensibility to small variations in pitch and need for careful adjustment to particular wind conditions, if the maximum efficiency is to be ensured. Therefore, the designer should be well informed and aware of the wind conditions on site to adjust the design (including the proper tweaking of pitch angles) to a given location.

#### CRediT authorship contribution statement

**Michal Lipian:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Krzysztof Olasek:** Writing – review & editing, Writing – original draft, Visualization, Validation, Data curation. **Michael Pereira:** Writing – review & editing, Supervision, Resources. **Florent Ravelet:** Writing – review & editing, Supervision, Resources. **Michal Kulak:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization.

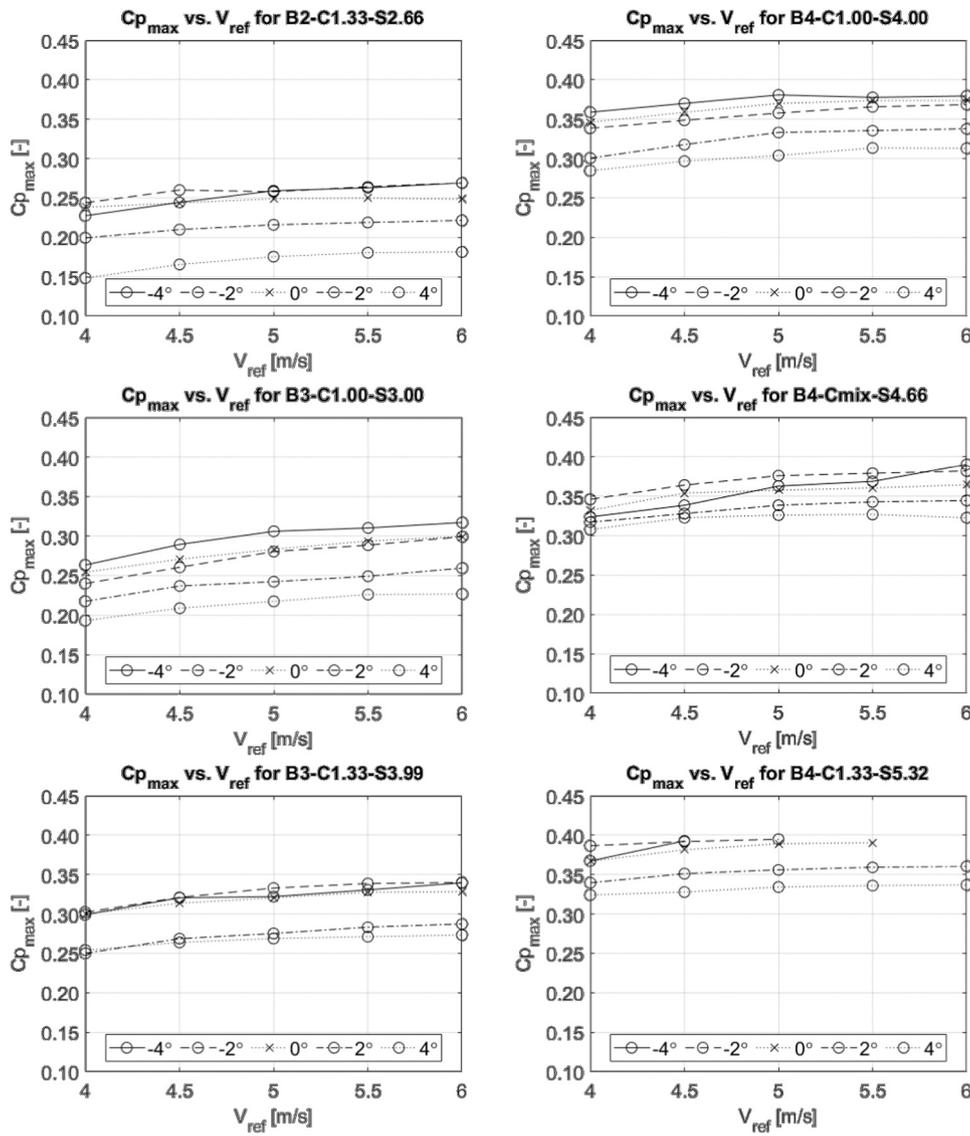


Fig. 14.  $C_{p_{max}}$  attained at different wind speeds  $V_{ref}$  for various pitch angles  $\beta$ : 2- and 3-bladed rotors (left) and 4-bladed rotors (right).

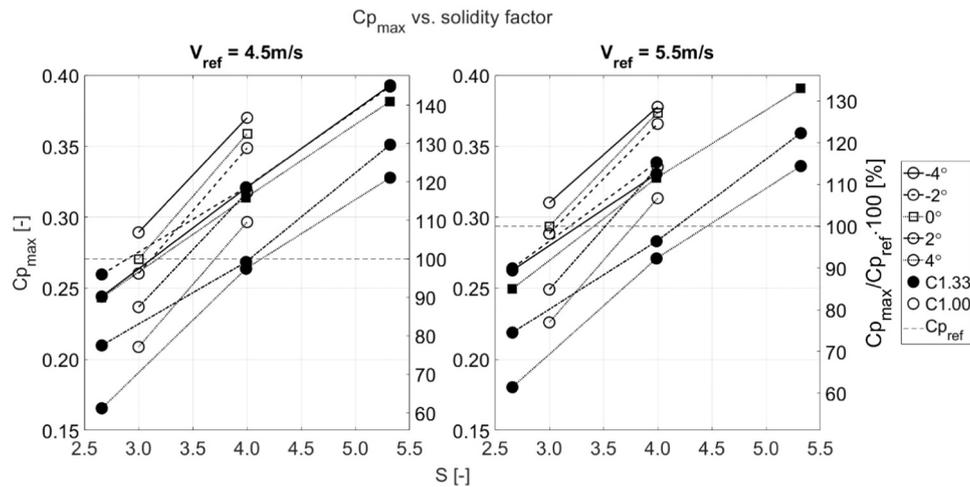


Fig. 15. Maximum  $C_p$  at wind velocities  $V_{ref} = 4.5$  m/s (left) and 5.5 m/s (right).

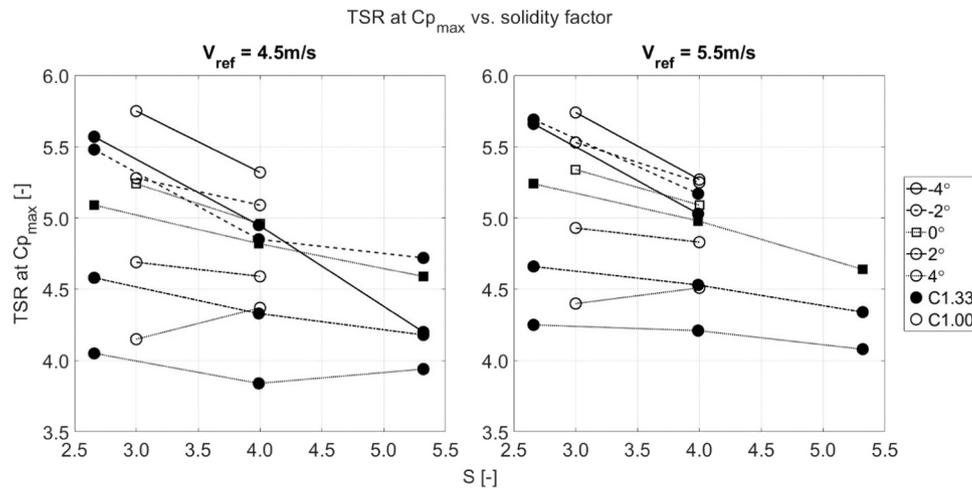


Fig. 16. Optimal TSR at wind velocities  $V_{ref} = 4.5$  m/s (left) and  $5.5$  m/s (right).

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## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michal Lipian reports financial support was provided by National Agency for Academic Exchange. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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