Characterization of aerodynamic performance of vertical axis wind turbines: Impact of operational parameters

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1. Introduction

Vertical axis wind turbines (VAWTs) have received growing interest for off-shore applications and in the urban environments mainly due to their omni-directional capability, scalability, robustness, low noise and costs. However, their aerodynamic performance is still not comparable with their horizontal axis counterparts. To enhance their performance, the impact of operational parameters such as tip speed ratio (λ), Reynolds number (Re) and turbulence intensity (TI) on their power performance and aerodynamics needs to be deeply understood. The current study, therefore, intends to systematically investigate the effect of these parameters in order to provide a deeper insight into their impact on the aerodynamic performance of VAWTs. For this investigation, a Darrieus H-type VAWT has been employed. A wide range of the parameters is considered: λ = 1.2-6.0, Re = 0.3 x 10^5-4.2 x 10^6 and TI = 0%-30% to analyze the turbine performance, turbine wake and dynamic loads on blades. High-fidelity computational fluid dynamics (CFD), extensively validated with experimental data, are employed. The results show that (i) variable-speed operation maintaining the optimal λ, at different wind speeds improves the turbine power coefficient, e.g. up to 168% at 4 m/s, while keeping an almost constant thrust coefficient, (ii) the turbine performance and wake are Re-dependent up to the highest Re studied, (iii) large TI (> 5%) improves the turbine performance in dynamic stall by promoting the laminar-to-turbulent transition and delaying stall on blades, however it deteriorates the optimal performance by introducing extra skin friction drag. The findings of the current study can support more accurate performance prediction of VAWTs for various operating conditions and can help the improvement of the aerodynamic performance of VAWTs.

1.1. Advantages of VAWTs

- Omni-directional capability: no yaw system is needed.
- Very low noise: due to operating at relatively low tip speed ratios and small diameters, the blade tip speed is very low.
- Low manufacturing cost: due to simple blade profiles with no taper and twist as well as simplicity in the control system, i.e. no pitch and yaw control system.
- Low installation and maintenance costs: due to having the generator on the ground.
- Scalability: the turbine height can scale up with minimal effect on performance.
- Robustness and reliability.
- Very small shadow flickering.
- Birds safety: due to their shape and typically low installation height
- Visually attractive.
- Multifaceted installation tower, e.g. telecom towers
- High space efficiency: VAWTs have smaller plan area compared to HAWT of the same swept area.

However, the aerodynamic performance of VAWTs is currently lower than HAWTs [29-32]. Research on VAWTs, despite their complex aerodynamics, has been situated in the shadow of the studies on HAWTs and hence received comparatively little attention during the last decades [33]. The underlying physics behind the power generation of VAWTs is much more complex compared to HAWTs [34-40]. The complexity could be mainly attributed to the VAWT’s inherent unsteady power conversion due to the large variations of angle of attack and the...
relative velocity during each turbine revolution [23]. In addition, this can be accompanied by several complex flow phenomena such as dynamic stall [41,42], blade-wake interaction [43], flow curvature effects [44], Coriolis and centrifugal forces on the boundary layer of the rotating blades and the shed vortices [45]. In order to improve the aerodynamic performance of VAWTs, therefore, these flow complexities need to be well understood. In addition, the impact of various geometrical parameters and operational parameters on the aerodynamic performance of VAWTs needs to be comprehensively characterized. The geometrical parameters include number of blades [46–48], solidity [49–51], airfoil shape [52–54], blade pitch angle [23] and turbine shaft [55]. The operational parameters consist of tip speed ratio [56–61], Reynolds number [61–65] and turbulence intensity [58,66–68]. The focus of the present study is on the impact of the aforementioned operational parameters.

Tip speed ratio \( \lambda \) is one of the most important operational parameters of VAWTs.
parameters for VAWTs as it defines the range of variations of angle of attack (Δα) on blades during each turbine revolution. Low λ values correspond to large Δα (Fig. 1a) that could result in significant flow separation and the consequent power loss, if the stall angle is exceeded. On the other hand, high λ values correspond to small Δα (Fig. 1b), which could also mean that the blade is producing less power than its actual capability. Neither of the two cases are desired. Therefore, it is very important to deeply clarify the impact of λ on the aerodynamic performance of VAWTs. Note that the velocity triangle on a VAWT blade includes the induced velocity Uᵢ. The induced velocity, which is usually ignored for simplicity, will affect the calculated α and relative velocity Vᵣₑ₁ (see Fig. 1c and d) and consequently the loads on blades. The importance of considering the induced velocity in the aerodynamic performance calculations for VAWTs is further discussed in the Appendix A.

Numerous studies have been performed to provide insight on the impact of λ for VAWTs [56–61]. However, the vast majority of these studies focused on the impact of λ on power coefficient Cp, while less attention has been paid to the detailed analysis of aerodynamics and dynamic loads on turbine blades. In addition, these studies did not investigate the optimal turbine operation by maintaining the optimal λ versus wind speed. Such investigations could highlight the benefits of maintaining the optimal tip speed ratio for VAWTs.

The prime effect of Reynolds number (Re) on boundary layer events and the aerodynamic performance of static airfoils is well shown in the literature [69–75]. The performance of VAWTs highly depends on the flow development over the blades, which have airfoil cross section. However, the presence of the two sources of unsteadiness, α and Vᵣₑ₁ imposes significant differences in the boundary layer events compared to the static airfoils [23]. Therefore, the impact of Re on the dynamic

Table 1
Geometrical and operational characteristics of the reference turbine.

| Parameter                       | Value   |
|---------------------------------|---------|
| Number of blades, n             | 2       |
| Diameter, d [m]                 | 1       |
| Swept area, A [m²]              | 1       |
| Airfoil                         | NACA0018|
| Airfoil chord, c [m]            | 0.06    |
| Solidity, σ                     | 0.12    |
| Blade aspect ratio, h/c         | 16.67   |
| Shaft diameter [m]              | 0.04    |
| Tip speed ratio, λ              | 4.5     |
| Rotational speed, Ω [rad/s]     | 83.8    |
| Freestream velocity, Uᵢ [m/s]   | 9.3     |
| Chord-based Reynolds number, Reₜ | 1.76 × 10⁵|
| Freestream (approach-flow) total TI [%] | 5 |
| Turbulence length scale [m]     | 1       |
| Reduced frequency, K            | 0.06    |

Fig. 2. Schematic of (a) the reference turbine and (b) the computational domain (both not to scale); (c–h) computational grid near the (c) rotating core, (d) airfoil, (e) leading edge, (f) trailing edge; and along the span for the (g) airfoil and (h) shaft.
loads on blades and the turbine performance cannot be simply adopted from the knowledge on static airfoils and demands a dedicated investigation.

For wind turbines, mainly due to size limitations, experiments are typically performed at small scales. This is especially the case when the wake effects and optimal arrangement of multiple turbines are investigated. This further emphasizes that the impact of Re on both turbine performance and wake needs to be well understood in order to enable a realistic interpretation of the scaled experiments for full-scale prototypes.

The high sensitivity of the VAWT performance to Re has been studied by Blackwell et al. [62], Polagye et al. [63], Bravo et al. [64], Bachant and Wosnik [65], Araya and Dabiri [61] and Zanforlin and Deluca [76]. While these studies have provided valuable findings, they did not focus on the impact of Re on blade aerodynamics and dynamic loads.

The importance of freestream turbulence on the separation behavior and the overall performance of airfoils [77] and HAWTs [78] is well established. It should be noted that while numerical and experimental studies of wind turbines are typically performed at a fixed turbulence level, in a real operating condition, such as in the urban environment, freestream turbulence intensity is varies widely [70,79–81]. Research on the impact of turbulence intensity for VAWTs is scarce and limited to few studies [58,66–68], which narrowed their scope on variations in Cp. To the best of our knowledge, however, a comprehensive study on the impact of TI on the aerodynamics, power performance and wake of VAWTs has not yet been performed.

Therefore, the current study intends to address these gaps by probing into the impact of λ, Re, and TI on:

- Dynamic loads on blades: the variations of geometrical and experienced angle of attack, relative velocity, lift, drag and pressure coefficients and vorticity fields;
- Turbine performance: turbine power and thrust force, instantaneous tangential and normal loads on blades and the contribution of each turbine quartile in power production;
- Turbine wake: the instantaneous wake generation by a single blade and the mean velocity profiles in the wake.

The findings of this study are of paramount importance as they can significantly improve the accuracy of the performance predictions of VAWTs for different operating conditions. In addition, the results support the improvement of the design of VAWTs with respect to the target operating conditions.

The outline of the paper is: Section 2 describes the computational settings and parameters where the details of the studied turbine, the computational domain and grid and other numerical settings are presented. Section 3 briefly explains the verification and validation studies. The impact of tip speed ratio, Reynolds number and turbulence intensity are presented and discussed in Sections 4–6. The summary and conclusions are provided in Section 7.

2. Computational settings and parameters

A H-type vertical axis wind turbine with the geometrical and operational characteristics described in Table 1 is employed. The blade cross-section is the typical symmetrical NACA0018 airfoil. The geometrical and operational parameters of the reference turbine are selected with respect to the experimental study by Tescione et al. [82] employed for the validation (see Section 3). A schematic of the reference turbine is illustrated in Fig. 2a. The turbine and shaft rotate counter-clockwise with the same rotational velocity.

For the reference case, the approach-flow total TI is 5% (see Table 1), while the incident-flow total TI is 4.42%. It should be noted that for CFD simulations of VAWTs the incident-flow TI (the value at the location of the turbine), rather than the approach-flow TI (freestream), should be reported as it represents the level of turbulence that is actually experienced by the turbine blades. The decay of the turbulence in the computational domains has been already shown for the urban flows [83–86] and VAWTs [87]. The turbulence length scale at the inlet of CFD simulations describes the size of the large energy-containing eddies in a turbulent flow. For the flow around a wind turbine, the size of such eddies is found to be in the order of the turbine diameter [88]. Therefore, in the present study, the turbulence length scale is selected equal to the turbine diameter, i.e. 1 m.

A two-dimensional (2D) and a 2.5D computational domain, as shown in Fig. 2b, are employed. The three-dimensional (3D) simulation is not considered as the focus of the present study is on the flow in the mid-plane of a turbine with high blade aspect ratio (h/c > 10) where the flow is minimally influenced by the 3D tip effects on the blades.
The computational domain is $35d \times 20d$, where the distance from the turbine center to domain inlet and outlet are $10d$ and $25d$, respectively. The blockage ratio ($d/W$) is 5%. The diameter of the rotating core is $1.5d$. The computational domain is selected in line with the recently published guidelines for CFD simulations for VAWTs [87,90].

For 2.5D simulations, the sufficient spanwise domain size has been studied for the incompressible flows around airfoils and was found to be Re-dependent while for higher Re a smaller domain span would be required. For a NACA0012 airfoil at $10^\circ$ angle of attack and $Re_\infty$ = $10^4$ a domain span of 0.64$c$ was found to be sufficient [91] while for a NACA0015 airfoil at $16.6^\circ$ angle of attack and $Re_\infty$ = $8.96 \times 10^5$, a domain span of 0.2$c$ was proved to be adequate [92]. Therefore, for the present study on VAWTs, a larger spanwise domain length of 1$c$ is selected as a safe choice. The 2.5D domain is only employed for the solution verification study for the 2D domain (see Section 3). The comparison of the 2D and 2.5D results for the reference turbine are provided in Section 3.

The turbine revolution is divided into 4 quartiles as listed below [93] where $\theta$ is defined based on the position of the top blade in Fig. 2:

- Upwind: $45^\circ \leq \theta < 135^\circ$
- Windward: $315^\circ \leq \theta < 45^\circ$
- Leeward: $135^\circ \leq \theta < 225^\circ$
- Downwind: $225^\circ \leq \theta < 315^\circ$

In addition, the turbine fore half, $0^\circ \leq \theta < 180^\circ$, and the turbine aft half, $180^\circ \leq \theta < 360^\circ$, are used to further assist with the interpretation of the results.

The computational grid, as shown in Fig. 2c-h, consists of quadrilateral cells with maximum and average $y^+$ values of 3.8 and 1.8, respectively, on the airfoil and 1.4 and 1.0, respectively, on the shaft. The number of cells are approximately 400,000 in 2D and 28 million in 2.5D. The 2D grid is extruded in spanwise direction to generate the 2.5D grid. The spanwise grid spacing is 0.5 mm and 1 mm for the airfoil and the shaft, respectively. Boundary conditions are uniform velocity and the shaft, respectively. Boundary conditions are uniform velocity inlet, zero gauge static pressure outlet, no-slip walls for airfoil and shaft, symmetry sides, sliding grid interface between the rotating and fixed grids, and periodic boundary condition on the top and bottom sides of the 2.5D domain.

Incompressible unsteady Reynolds-averaged Navier-Stokes (URANS) are performed using the commercial CFD software package ANSYS Fluent 16.1 with 2nd order discretization in time and space and SIMPLE scheme for pressure-velocity coupling. The numerical settings and simulation procedure are selected following extensive solution verification and validation studies performed by Rezaeiha et al. [23,55,87,90].

Given the transitional nature of the flow on a VAWT blade, considering $Re_\infty$, the transition SST turbulence model is used. This model is a 4-equation model [94] developed based on the 2-equation k-$\omega$ SST turbulence model [95,96], which additionally solves two more equations for momentum-thickness Reynolds number $Re_\theta$ and intermittency $\gamma$. The model, also known as $\gamma$-SST model, is an intermittency-based model. Intermittency-based models have been successfully used to improve the prediction of laminar-to-turbulent transition for flows on airfoils [97–101].

The simulations are initialized with steady RANS. The transient simulations are performed with azimuthal increment of 0.1° for 20 revolutions of the turbine. The 20 turbine revolutions are to ensure the results reach a statistically steady state condition. 20 iterations per time step is used to ensure scaled residuals drop below $10^{-5}$. The results are sampled at the 21st turbine revolution.

To calculate the dynamic loads on blades, namely lift and drag, the experienced values of angle of attack and relative velocity, rather than the typically-used geometrical values, are employed. There exist noticeable differences between the geometrical and experienced values of the angle of attack, the relative velocity and their resultant loads on the blades. The calculation method for the experienced values and a comparison with the geometrical values are presented and discussed in the Appendix A.

3. Solution verification and validation

Extensive solution verification and two sets of validation have been performed to ensure the accuracy of the present CFD results. The results have been published in Ref. [87,90]. For solution verification studies:

- Grid dependence is analyzed using three uniformly doubled grids where the refinement factor in each directions is $\sqrt{2}$. The Grid Convergence Index (GCI) [102] for the coarse-medium grid pair, calculated for the turbine $C_p$ using a safety factor $(F_\omega)$ of 1.25, is GCI$\text{coarse} = 0.0061$ (1.48% of the $C_p$ value) and GCI$\text{fine} = 0.0035$ (0.85% of the $C_p$ value), respectively. The medium grid, also shown in Fig. 2c-f, is selected for the rest of the study.
- A detailed sensitivity analysis is performed for time step and convergence criterion [87,90]. The analysis shows that an azimuthal increment of 0.1° is the minimum requirement. In addition, a minimum of 20 turbine revolutions is required to reach a statistically steady state condition.
- The power and thrust coefficients for 2D and 2.5D simulations are compared [87] (shown in Fig. 3a and b). The comparison reveals a systematic but small overestimation of the turbine power performance for the 2D simulations. The 2D $C_p$ and $C_t$ values are $\pm 6\%$ and $\pm 2\%$ higher than that of the 2.5D simulations due to neglecting the three-dimensional effects in the boundary layer, which affect the transition and separation onsets on blades [103]. The analysis shows that the difference between the 2D and 2.5D simulations is weakly dependent on the operating conditions of the turbine. Note that that small difference between the 2D and 2.5D ($< 6\%$) is in spite of the fact that the number of cells for the 2.5D simulations is approximately 28 million, which is 70 times more than that of the 2D grid, i.e. approximately 400,000 cells. Therefore, to minimize the computational cost, which is essential for extensive parametric studies such as the present study including 300 transient simulations each employing a fine azimuthal increment of 0.1° and continuing for minimum 20 turbine revolutions, the 2D simulations are selected to predict the turbine performance.

Two separate sets of validation studies have been performed where the CFD results have been compared against the experimental data by

### Table 2
Comparison of power coefficient from experiment by Castelli et al. [104] and the present CFD and their relative deviation.

| $\lambda$ | 2.04 | 2.33 | 2.51 | 2.64 | 3.08 |
|----------|------|------|------|------|------|
| $C_p$ (exp.) | 0.137 | 0.259 | 0.300 | 0.312 | 0.284 |
| $C_p$ (present CFD) | 0.142 | 0.231 | 0.299 | 0.333 | 0.350 |
| $\mid \Delta C_p \mid$ [%] | 3.42% | 10.7% | 0.5% | 6.8% | 23.2% |

[82,89]. The h/c for the reference turbine is 16.67.

- Upwind: $45^\circ \leq \theta < 135^\circ$
- Windward: $315^\circ \leq \theta < 45^\circ$
- Leeward: $135^\circ \leq \theta < 225^\circ$
- Downwind: $225^\circ \leq \theta < 315^\circ$

In addition, the turbine fore half, $0^\circ \leq \theta < 180^\circ$, and the turbine aft half, $180^\circ \leq \theta < 360^\circ$, are used to further assist with the interpretation of the results.

The results are

| $U_\infty$ [m/s] | 18.6 | 16.275 | 13.95 | 11.625 | 11.625 |
| $\Omega$ [rad/s] | 93 | 97.65 | 97.65 | 93 | 104.625 |
| $TI$ [%] | 5 | 5 | 5 | 5 | 5 |
| $TL$ [%] | 4.42 | 4.42 | 4.42 | 4.42 | 4.42 |
| $Re_\theta (\times 10^5)$ | 2.06 | 2.11 | 2.09 | 1.97 | 2.2 |
| $K$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |

| $\lambda$ | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.5 |
|----------|------|------|------|------|------|------|

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Castelli et al. [104] and Tescione et al. [82]. Note that the turbines employed in the two experiments have different airfoil shape, number of blades, solidity and tip speed ratios. In addition, the parameters employed for the two validations are also different. The turbine for the first validation is a 2-bladed H-type turbine with NACA0018 airfoil, a solidity of 0.12 and a tip speed ratio of 4.5 (reference turbine). For this validation, the time-averaged normalized lateral and streamwise velocities at different downstream locations ($x/R = 2.0–3.0$) in the near wake of the turbine along the lateral direction are compared with the experimental results by Tescione et al. [82]. The deviation from the experiment is $2.3–2.5\%$ and $8.6–11.8\%$ for the lateral and streamwise velocity components, respectively. Further details and possible explanations for the observed deviation are comprehensively presented in Ref. [55,87]. The turbine for the second validation is a 3-bladed H-type turbine with NACA0021 airfoil, a solidity of 0.25 and tip speed ratios from 2.04 to 3.08. For this validation, the turbine power coefficients at 5 different tip speed ratios (i.e. 2.04, 2.33, 2.51, 2.64 and 3.08) are compared with experimental and numerical data by Castelli et al. [104] (see Fig. 3c). An overall good agreement is observed between the CFD results and the experiment where the quantitative differences, presented in Table 2, are found to be the largest for the highest $\lambda$ of 3.08. The observed deviations could be explained to be a result of:

- The uncertainties associated with the experimental data: several important geometrical characteristics of the turbine, e.g. the blade surface roughness and the location of the blade-spoke connection, and the boundary conditions, e.g. the turbulence intensity and length scale, are not clearly mentioned in the experiment. For
instance, the impact of the location of the blade-spoke connection on the turbine $C_p$ is known to be more pronounced at higher tip speed ratios [105]. This could somehow explain the larger deviation at higher $\lambda$.

- Lack of error analysis for the experiment: the experiment has not provided an error analysis of the data, therefore, the error associated with the measurement is not known. For instance, the blockage ratio for the experiment is considerable large (approximately 10%) while the measured values were not corrected for the blockage effects.
- Geometrical simplifications: ignoring the turbine spokes and connections in the CFD modeling is possibly contributing to the observed deviation. As these less-aerodynamic structural components typically result in considerable drag, their impact will be more pronounced at higher relative velocities, i.e. higher tip speed ratios. This could also justify the larger deviation at higher $\lambda$.
- The two-dimensional modeling: because the turbine is modeled in 2D, the blade tip effects are not considered in the simulations where ignoring them also partly contributes to the deviation.
- The RANS modeling: the limitations of RANS modeling in predicting complex flows around VAWTs could be another contributor to the observed deviation, esp. at lower $\lambda$ where the flow becomes more complex due to dynamic stall.

Further information about this validation study with further explanations for the observed deviation is presented in detail in Refs. [23,90]. The two validation studies performed confirm that the CFD results can provide accurate predictions of the turbine performance and wake for different operating conditions.

4. Impact of tip speed ratio

This section provides an extensive analysis of the impact of $\lambda$ on the dynamic loads on turbine blades, the turbine performance and the
Fig. 7. Contours of non-dimensionalized z-vorticity with superimposed streamlines for different tip speed ratios during the last turbine revolution at azimuthal positions set in Fig. 5. (Reₙ ≈ 2.0 × 10⁵).
wake. Table 3 lists the operational parameters used to study the impact of $\lambda$. The tip speed ratios are selected to range from low, $\lambda = 2.5$, to moderately high, $\lambda = 5.5$, values for the given solidity of the reference turbine. The analysis is performed at a fixed $Re_\infty$ of approximately $2.0 \times 10^5$, as a representative value for small- to medium-scale urban VAWTs [12]. The fixed $Re_\infty$ avoids Reynolds number effects and facilitates a detailed analysis of the impact of tip speed ratio. To keep a fixed $Re_\infty$ for different tip speed ratios, both freestream velocity and turbine rotational velocity are inevitably adjusted. The turbulence intensity and reduced frequency are kept the same as in the reference case. The approach-flow (incident-flow) total TI is 5% (4.42%) and the reduced frequency (defined as $K = \Omega c/(2V_\infty)$) is 0.06 for all cases.

4.1. Loads on blades

Fig. 4 shows the variations of $\alpha$, normalized $V_{rel}$, lift and drag coefficients, $C_l$ and $C_d$, during the last turbine revolution for $2.5 \leq \lambda \leq 5.5$. Two sources of flow unsteadiness on VAWT blades, namely unsteady $\alpha$ and $V_{rel}$, are shown in Fig. 4a and b where the values are calculated following the method described in the Appendix A. The following observations are made for the angle of attack $\alpha$:

- In the turbine fore half, almost a half-cycle sinusoidal variation is observed for all cases.
- In the turbine aft half, the trend deviates from a sinusoidal trend and becomes nearly flat with increasing $\lambda$. The different trend in the turbine aft half is because the flow in this region is significantly affected by the blades passing in the turbine fore half and slowed down due to the turbine thrust force. The increase in flatness can also be explained by the increase in the thrust force for higher $\lambda$ (see Section 4.2).
- A negative non-zero value of $\alpha$ occurs at $\theta = 0^o$ and $180^o$ due to the lateral deviation of the incoming flow at the turbine incidence (streamtube expansion).
- Decreasing $\lambda$, as expected, is found to increase the amplitude of variations of $\alpha$ throughout the revolution. This is simply explained by comparing the velocity triangles shown in Fig. 1a and b. For $\lambda > 3.0$, the variation of $\alpha$ remains below the static stall angle $\alpha_{st} = 17.5^\circ$, which is calculated from Xfoil [106] at $Re_\infty = 2.0 \times 10^5$. Further reduction in $\lambda$ results in $\alpha$ reaching and exceeding $\alpha_{st}$ both in fore and aft halves. A deep stall happens for $\lambda = 2.5$ in both halves.
- For $\lambda = 2.5$, the ripples observed at $\theta = 225^\circ$ are due to blade-wake interactions which will be later discussed in this section.
- The ratio of the magnitude of the negative peak, in the turbine aft half, to that of the positive peak, in the turbine fore half, decreases from 90% for $\lambda = 2.5$ to 54% for $\lambda = 5.5$.
- In the turbine aft half, the effect of the turbine shaft wake on $\alpha$ is also apparent as a sudden reduction near $\theta = 270^\circ$. The impact of the VAWT turbine shaft is extensively discussed in Ref. [55].

Fig. 4b depicts the other source of flow unsteadiness for VAWT, i.e. unsteady inflow to the blades. In the turbine fore half, the normalized $V_{rel}$ oscillates sinusoidally where the amplitude of the oscillations increases from 17.5% at $\lambda = 5.5$ to 36.7% at $\lambda = 2.5$. In the turbine aft half, similar to $\alpha$, a different trend is observed.

The two co-occurring sources of unsteadiness for VAWTs, namely unsteady $\alpha$ and $V_{rel}$, are known to have a different impact on boundary layer events, namely laminar-to-turbulent transition and separation, on airfoils [103], which further highlights the complexity of the dynamic loads on VAWTs. Fig. 4c and d show the dynamic lift and drag coefficients ($C_l$ and $C_d$) versus azimuth $\theta$ for the last turbine revolution. The impact of $\alpha$ on $C_l$ is similar to that of $\lambda$ on $C_l$ although the peak for $C_l$ occurs earlier for $C_l$. For $\lambda = 2.5$, the fluctuations in $C_l$ and the large

![Fig. 8. Coefficients of (a) tangential force, (b) normal force, (c) power and thrust and (d) the normalized cumulative sum of moment coefficient during the last turbine revolution for different tip speed ratios. ($Re_\infty = 2.0 \times 10^5$).](image-url)
jump in $C_D$ at $90° \leq \theta \leq 170°$ clearly signal the stall on blades. The blade-wake interactions can be distinguished as large fluctuations in $C_L$ and $C_D$ at $220° \leq \theta \leq 260°$. The effect of the shaft wake is also observed around $\theta = 270°$.

Fig. 4e and f show the dynamic $C_L$ and $C_D$ versus $\alpha$ for the last turbine revolution. Note that for better visualization of the impact of $\lambda$, the case of $\lambda = 2.5$ is not shown in these figures. The following observations can be made:

- The upwind quartile is shown using full circles (○) and diamonds (◊) signaling $\theta = 45°$ and $135°$, respectively. It is clearly seen that this quartile is where the blades operate near $C_{L,max}, C_{d,max}$. The importance of this quartile will be more elaborately discussed in Section 4.2.
- Decreasing $\lambda$ increases $C_{L,max}, C_{d,max}$ and the respective $\alpha$ for each.
- Decreasing $\lambda$ marginally influences the hysteresis in the polars of both $C_L$ and $C_D$ prior to stall while near the stall, i.e. $\lambda = 3.0$, the hysteresis significantly increases. The hysteresis prior to stall is due to the presence of the unsteady separation on blades and the different resistance of the boundary layer to separation in the upstroke and downstroke [103]. The observations are in line with the experimental observations on pitching airfoils by Lee and Gerontakos [107].

To further analyze the impact of $\lambda$, the pressure coefficient on the blade and the flowfield at different azimuthal positions are compared for three different $\lambda$: 2.5, 3.5 and 4.5. The schematic shown in Fig. 5 illustrates the selected azimuthal positions. The respective positions along the $\alpha, C_L$ and $C_D$ curves for the three $\lambda$ can be found in Fig. 4a, c and d. The focus is on $70° \leq \theta \leq 150°$, which corresponds to the regime where the blade experiences the maximum $\alpha$ during the upstroke and downstroke.

Pressure coefficients (CoP) on the blade and contours of non-dimensionalized vorticity with superimposed streamlines are compared for different tip speed ratios in Figs. 6 and 7, respectively. It should be noted that the pressure distribution on the blade suction side (in the turbine fore half corresponding to the inner side of the blade) can be employed to identify the boundary layer events: (i) the sudden change in the rate of pressure recovery typically signals the beginning of a laminar separation bubble (LSB), (ii) the follow-up abrupt increase in pressure prompts laminar-to-turbulent transition onset (triggered by the Kelvin-Helmholtz instabilities in the shear layer of LSB) and (iii) the second sudden change in rate of pressure recovery shows the end of LSB, from which the length of LSB can also be estimated [108,109]. For further clarification, the aforementioned boundary layer events are highlighted with arrows for $\lambda = 4.5$ at $\theta = 100°$ (see Fig. 6d). The results show that:

- Laminar-to-turbulent transition onset occurs earlier for lower $\lambda$ due to their higher $\alpha$. This is in agreement with the experimental data for pitching airfoils where the transition onset is found to move towards the leading edge when $\alpha$ increases [107]. Previous CFD simulations of VAWTs also confirmed similar occurrence, e.g. [23].
- The length of laminar separation bubble is shorter for lower $\lambda$ due to higher $\alpha$.
- For $\lambda = 2.5$, the increase of flatness in the CoP curve, which extends from $X/c \geq 0.6$ at $\theta = 70°$ to $X/c \geq 0.1$ at $\theta = 120°$, implies the growth of the turbulent trailing edge separation over the blade. The
growth of the trailing edge separation from $\theta = 70'$ to 120' can also be distinguished from the vorticity field (Fig. 7). For $\lambda = 3.5$ and 4.5, the extent of trailing edge separation is limited to $X/c \geq 0.6$ and $0.8$, respectively. The smaller separation for higher $\lambda$ is due to their lower $\alpha$.

- For $\lambda = 2.5$, from $\theta = 120'$ to 140', a small bump is found to grow near the trailing edge on the $CoP$ curve. This could be due to the clockwise vortices rolled up from the pressure side towards the suction side.

- For $\lambda = 2.5$, from $\theta = 100'$ to 150', vortex shedding occurs from the blade. This results in oscillations in loads as shown already in Fig. 4c and d for $C_l$ and $C_D$. The interaction of such shed vortices with the boundary layer on the blades passing downstream (220' $\leq \theta \leq 260'$) causes oscillations in loads as already shown in Fig. 4c and d for $C_l$ and $C_D$. The downwind region influenced by the blade-wake interactions is not straitly downstream of the stalled region but is slightly drifted towards the center of rotation. This is attributed to the impact of the Coriolis force on the shed vortices, which is consistent with the finding of Tsai and Colonius [45].

### 4.2. Turbine performance

The instantaneous tangential $C_{l_{\text{t}}}$ and normal $C_{D_{\text{n}}}$ force coefficients on the blades and the power $C_P$ and thrust coefficients $C_T$ during the last turbine revolution for different tip speed ratios are shown in Fig. 8a-c. It can be seen that:

- Changing $\lambda$ results in a rather complex change in tangential loads for both fore and aft turbine halves. In contrast, higher $\lambda$ simply results in higher positive normal loads in the turbine fore half. In the turbine aft half, the effect of $\lambda$ on normal loads is much less noticeable except for $\lambda = 2.5$ where the flow is dominated by the occurrence of dynamic stall and blade-wake interactions.

- At the beginning of the revolution ($0' \leq \theta \leq 75'$), decreasing $\lambda$ results in higher tangential loads. This is a result of higher $\alpha$ and $C_l$ for lower $\lambda$ as shown in Fig. 4a and b.

- For 75' $< \theta \leq 170'$, the occurrence of a deep stall is observed for $\lambda = 2.5$ where $C_{D_{\text{n}}}$ suddenly drops. This associates with the sudden drop in $C_l$ and the jump in $C_D$ as shown in Fig. 4c and d. The occurrence of stall is clearly seen as fluctuations in $C_{D_{\text{n}}}$ and $C_{D_{\text{t}}}$. A negligible difference is observed in the tangential loads for $3 < \lambda < 5.5$.

- In the turbine aft half, and for 220' $\leq \theta \leq 260'$, the blade-wake interactions can be distinguished as fluctuations in $C_{l_{\text{t}}}$ and $C_{D_{\text{n}}}$, especially for $\lambda = 2.5$.

- The effect of the shaft is seen as a drop in $C_{D_{\text{n}}}$ and a jump in $C_{D_{\text{t}}}$ in $\theta = 270'$.

- An optimum $\lambda$ of 4.0 is found to maximize $C_P$.

- $C_T$ grows with increasing $\lambda$. The trend is linear up to $\lambda = 3.5$ while it becomes asymptotic for $\lambda > 3.5$. This is in line with the experimental observations by Bachant and Wosnik [110].

The normalized cumulative sum of the instantaneous moment coefficients $C_{m_{\text{t}}}$ during the last turbine revolution is shown in Fig. 8d. The values are employed to calculate the contribution of each turbine quartile in total power production, which is shown in Fig. 9. The contribution is calculated as the difference between the normalized cumulative sum of $C_{m_{\text{t}}}$ at the end of each quartile and that at the beginning of that quartile. For a given $\lambda$, for example, if the cumulative sum at the beginning of a quartile has a negative value, due to prior negative moment, while high positive value exists at the end of the quartile, the difference (the contribution of that quartile) can be close to 100% or even more. In addition, if one quartile has a negative total contribution, the sum of contribution of the other three quartiles needs to be more than 100% so that the total contribution of all 4 quartiles is 100%.

- In the windward quartile, the contribution is very small and decreases from 12.7% to $-9.9\%$ when $\lambda$ increases from 2.5 to 5.5. A negative contribution is observed for $\lambda = 5.5$ which simply means that the flow is tending to rotate the turbine in the opposite direction.

- In the upwind quartile, for all cases, more than 50% of the total power is produced. The contribution increases from 52.5% to 103.7% for $\lambda$ from 2.5 to 5.5. The contribution higher than 100% for $\lambda = 5.5$ is due to the negative contribution of the windward quartile for this $\lambda$. For the optimal $\lambda$ (= 4.0), the contribution of the upwind quartile is $\approx 68\%$.

- In the leeward quartile, the contribution is less than 10% for all cases. The highest contribution is 9.8% at the optimal $\lambda$.

- In the downwind quartile, the contribution decreases from 28.7% to 1.9% at the optimal $\lambda$ (2.5 to 5.5). The trend is reverse of that in the upwind. This is because the flow reaching the downwind quartile is not fresh as it already passed the blades in the upwind region. Therefore, if higher energy is extracted from the flow upstream, less is remained to be extracted downstream.

The analysis reveals a very important fact regarding the power production of VAWTs. The upwind quartile is contributing the most to the total power production and is by far the most important region for the turbine operation. As highlighted in Section 4.1 and 4.2, the operation of VAWTs is highly variable during the revolution due to the unsteady $\alpha$ and $V_{\text{rad}}$, and this inherent unsteadiness occurs for all $\lambda$. From a practical point of view, given the unsteady aerodynamics, it is extremely difficult to improve the performance during the whole revolution. This analysis shows the local power enhancement strategies functioning in the upwind quartile can grant the maximum benefit, compared to the other quartiles, because any small improvement in this region can have large influences on the total power production due to the significant contribution of this quartile.

### 4.3. Turbine wake

The turbine wake is generated from the vortices shed from the blades during the revolution. Based on Kelvin’s circulation theorem [111], when the strength of the bound vortices along the blade alters, a new vortex is shed, with the same strength but the opposite sign, which travels downstream with the incoming flow. The change in the bound
Fig. 11. Time-averaged (over the last turbine revolution) normalized (with freestream velocity) streamwise velocity along lateral lines $-0.75 \leq y/d \leq 0.75$ at several downstream locations for different tip speed ratios ($Re_c \approx 2.0 \times 10^5$).
vortex system could be due to variations in angle of attack and/or incoming flow that both simultaneously occur for VAWTs during each revolution. This results in a continuous vortex shedding and the following generation of wake. The strength of the shed vorticity by a single blade can be calculated using Eq. (1) defined as the gradient of circulation per each azimuthal increment. Based on the Kutta–Joukowski theorem, a positive value denotes counter-clockwise circulation. Eq. (2) presents a non-dimensional form of Eq. (1).

**Table 4**

Turbine wake length vs. tip speed ratio for the reference turbine.

| \( \lambda \) | 1.5 | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.5 |
|---|---|---|---|---|---|---|---|
| \( L_w/d \) | 40 | 23 | 19 | 16 | 14 | 13 | 10 |

The following observations are made:

- In the turbine fore half, during the upstroke where the circulation around the blade and consequently \( C_l \) increase, clockwise vortices (negative sign) are shed. Conversely, during the downstroke where the circulation around the blade and consequently \( C_l \) decrease, counter-clockwise (positive sign) vortices are shed. The signs reverse in the turbine aft half.
- The impact of stall on the blade and blade-wake interactions, for \( \lambda \leq 3.0 \), are apparent as large oscillations in the strength of shed vorticity.
- Decrease of \( \lambda \) increases the strength of the shed vorticity which is in line with the higher slope of \( C_l-\alpha \) curve for lower \( \lambda \). This is clearly shown for \( 0^\circ \leq \theta \leq 135^\circ \).
- Increase of \( \lambda \) decreases the magnitude of oscillations in the strength of the shed vorticity. This is due to smaller \( \Delta \alpha \) and subsequently more limited separation on the blade. Therefore, for larger \( \lambda \ (\geq 3.0) \) where the occurrence of stall is avoided, the variations in the strength of the shed vorticity is mostly due to the unsteadiness in the angle of attack and the incoming flow while for lower \( \lambda \ (\leq 3.0) \) stall and the blade-wake interactions also have noticeable effects.

\[
\frac{\partial \Gamma}{\partial \theta} = -0.5U_\infty \frac{\partial C_l}{\partial \theta}
\]

\[
\frac{2\pi \frac{\partial \Gamma}{\partial \theta}}{cU_\infty} = -\frac{\partial C_l}{\partial \theta}
\]

**Table 5**

Operational parameters to find the optimal \( \lambda \) at different \( U_\infty \).

| \( \lambda \) | 1.2 – 6.0 |
|---|---|
| \( U_\infty \) [m/s] | 2.3 – 22.3 |
| \( \Omega \) [rad/s] | 11.6 – 204.6 |
| TI [%] | 5 |
| \( Re_c \ (\times 10^5) \) | 0.3 – 4.3 |

**Fig. 11** shows profiles of the time-averaged (over the last turbine revolution) streamwise velocities (normalized with respect to the freestream velocity) along the lateral line, \(-0.75 \leq y/d \leq 0.75\), at different downstream locations in the turbine wake with \( x/d = 1.0, 1.5, 2.0, 2.5, 3.0, 4.0 \), for various tip speed ratios. It can be seen that:

- For all downstream locations, the velocity deficit in the turbine wake grows as \( \lambda \) increases. This is because the turbine thrust force gets larger when \( \lambda \) increases resulting in further velocity
deceleration (see Fig. 8c). This is in agreement with the experimental observations by Araya and Dabiri [61].

- Increasing $\lambda$ is found to increase the wake expansion and streamwise asymmetry which is in line with the wind-tunnel measurements by Araya and Dabiri [61].

- The wake self-induction is found to occur for all $\lambda$ where this is more noticeable for higher $\lambda$. The wake self-induction refers to reduction in the streamwise velocity as the wake travels downstream. This is consistent with the experimental observations by Teschine et al. [82].

- For $\lambda = 2.5$, the impact of large oscillations, already observed in the strength of the shed vorticity for $220^\circ \leq \theta \leq 260^\circ$ (see Fig. 10), is also seen in the streamwise velocity for $x/d \leq 1.5$. This fades out as the wake travels further downstream.

- The influence of the shaft is distinguished as a larger velocity deficit at $y/d = 0$. This is more pronounced for lower $\lambda$ values at $x/d < 2.0$, which also fades out as the wake travels further downstream.

- Tip speed ratio is also found to significantly influence the length of the turbine wake $L_w$, which is defined from the turbine center to a downstream location along the turbine centerline, $y/d = 0$, where the normalized velocity magnitude $V/U_\infty = 0.97$. $L_w$ is found to asymptotically decrease from 40d to 10d when $\lambda$ increases from 1.5 to 5.5 for the reference turbine (see Table 4). The earlier breakdown of the wake for higher $\lambda$ is attributed to the closer distance between the shed vortices in the wake, which eventually amplifies the wake instabilities and results in an earlier wake structure breakdown. More detailed results on the impact of $\lambda$ on $L_w$ and comprehensive discussions are provided in Ref. [90]. The trend is in line with the experimental observations for HAWTs [112].

4.4. Optimal tip speed ratio

Unlike HAWTs, VAWTs are currently designed to operate at constant rotational velocity mainly due to simplicity and costs [12,113,114]. This means that for a wide range of freestream velocities, their operation is not optimal and they operate optimally only at a specific wind speed. Two series of simulations are performed for the reference turbine covering a wide range of wind speeds ($2.3$–$22.3$ m/s), rotational velocities ($11.6$–$204.6$ rad/s) and tip speed ratios ($1.2$–$6.0$) in order to investigate the optimal operation of the reference turbine. The two series include simulations at fixed rotational velocities and at fixed freestream velocities. Table 5 lists the operational parameters used to find the optimal tip speed ratio for different freestream velocities.

Fig. 12 shows the turbine power and thrust coefficients versus tip speed ratio and freestream velocity for different fixed rotational velocities $46.5$ rad/s $\leq \Omega \leq 102.3$ rad/s. Fig. 13 shows the turbine power and thrust coefficients versus tip speed ratio and rotational velocity for different fixed freestream velocities $2.3$ m/s $\leq U_\infty \leq 18.6$ m/s.

At low $\lambda$, the turbine has very low $C_P$. Increasing $\lambda$ results in a growth of $C_P$ to a maximum value with a high slope. $C_P$ gradually decreases with further increase of $\lambda$. This trend is similarly observed at both fixed rotational and freestream velocities, which implies that based on $\lambda$ three operating regimes for VAWTs are typically defined as follows:

- High wind speed regime: this regime corresponds to low $\lambda$ where the flow is largely separated on blades at high $\alpha$ (see Section 4.1) and the performance is adversely affected by dynamic stall.

- Optimal regime: this regime associates with where the turbine is producing the maximum $C_P$.

- Low wind speed regime: this regime refers to high $\lambda$ where the variations of $\alpha$ on blades are very small, therefore, the blade is operating inefficiently (see Section 4.1).
The aforementioned regimes can also be shown when considering the $C_P-U_\infty$ ($C_T-\Omega$) curve (Figs. 12c and 13c):

- At low $U_\infty$ (high $\Omega$), the turbine is performing sub-optimal.
- Increasing $U_\infty$ (decreasing $\Omega$) improves the turbine performance where for each fixed $\Omega$ ($U_\infty$), there exists a specific $U_\infty$ ($\Omega$) where the turbine is operating optimally.
- Further increase of $U_\infty$ (decrease of $\Omega$) deteriorates the performance due to the growth of separations on blades and the subsequent stall.

$C_T$ asymptotically grows as $\lambda$ increases. This occurs at both fixed rotational and freestream velocities. This can also be shown by $C_T-U_\infty$ ($C_T-\Omega$) curves where increasing $U_\infty$ (decreasing $\Omega$) reduces $C_T$. Increase of $C_T$ by increasing $\lambda$ is in line with the increase of normal forces on blades shown in Fig. 8b. At high $\lambda$ due to small $\alpha$ on blades, the generated force is more contributing to thrust force than the tangential force, which is responsible for power generation.

Increasing either the freestream or rotational velocity is found to shift upward the $C_P-\lambda$ curve. This improvement in turbine performance is attributed to Reynolds number effect which is extensively discussed in Section 5.

To further generalize the findings and to derive the optimal operating condition of the turbine, the results presented in Figs. 12 and 13 are employed to construct contours of $C_P$ and $C_T$ in $\lambda-U_\infty$ space as shown in Fig. 14a and b. Fig. 14a clearly suggests that to keep the optimal operation of the turbine at different wind speeds, the turbine needs to maintain a constant $\lambda$, which is 4.0. Note that the optimal value of $\lambda$ is dependent on the turbine characteristics and will be different for a turbine of different solidity and/or airfoil shape. Therefore, such analysis will need to be repeated for that case to identify the optimal $\lambda$. Based on that, the turbine optimal $\Omega$ versus $U_\infty$ is derived and depicted in Fig. 14c. Therefore, $\Omega$ needs to increase linearly with $U_\infty$. A comparison of the turbine performance operating at the optimal $\lambda$ of 4.0 against the operation at a constant $\Omega$, i.e. 55.8 rad/s, is shown in Fig. 14d.

Table 6 presents the improvement in $C_P$ due to maintaining the optimal $\lambda$. $\Omega$ and fixed $\Omega$ of 55.8 rad/s versus freestream velocity.

### Table 6

| $\Omega$ [rad/s] | $U_\infty$ [m/s] | $\Delta C_P$ [%] | $\Delta C_P$ [%] |
|-----------------|-----------------|-----------------|-----------------|
| 46.5 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 4.0 | 24 | 11 | 5 | 11 | 46 | 124 | 220 | 351 | 549 |
| 55.8 | 145 | 63 | 11 | 1 | 4 | 21 | 54 | 122 | 211 |
| 65.1 | 168 | 116 | 42 | 8 | 5 | 4 | 13 | 28 | 57 |

To further analyze the findings and to derive the optimal operating condition of the turbine, the results presented in Figs. 12 and 13 are employed to construct contours of $C_P$ and $C_T$ in $\lambda-U_\infty$ space as shown in Fig. 14a and b. Fig. 14a clearly suggests that to keep the optimal operation of the turbine at different wind speeds, the turbine needs to maintain a constant $\lambda$, which is 4.0. Note that the optimal value of $\lambda$ is dependent on the turbine characteristics and will be different for a turbine of different solidity and/or airfoil shape. Therefore, such analysis will need to be repeated for that case to identify the optimal $\lambda$. Based on that, the turbine optimal $\Omega$ versus $U_\infty$ is derived and depicted in Fig. 14c. Therefore, $\Omega$ needs to increase linearly with $U_\infty$. A comparison of the turbine performance operating at the optimal $\lambda$ of 4.0 against the operation at a constant $\Omega$, i.e. 55.8 rad/s, is shown in Fig. 14d.

### Table 7

| $\lambda$ | $\Delta C_P$ [%] | $\Delta C_P$ [%] |
|-----------|-----------------|-----------------|
| 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.5 |
| 2.3 | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| 3.0 | 3.25 | 2.79 | 2.5 | 2.3 | 2.3 |
| 3.5 | 2.8 | 2.3 | 2.3 | 2.3 | 2.3 |
| 4.0 | 2.8 | 2.3 | 2.3 | 2.3 | 2.3 |
| 4.5 | 2.8 | 2.3 | 2.3 | 2.3 | 2.3 |
| 5.5 | 2.8 | 2.3 | 2.3 | 2.3 | 2.3 |

- $\Delta C_P$ [%] = $\frac{C_P - C_P\text{opt}}{C_P\text{opt}} \times 100$
- $\Delta C_P$ [%] = $\frac{C_T - C_T\text{opt}}{C_T\text{opt}} \times 100$

The aforementioned regimes can also be shown when considering the $C_P-U_\infty$ ($C_T-\Omega$) curve (Figs. 12c and 13c):

- At low $U_\infty$ (high $\Omega$), the turbine is performing sub-optimal.
- Increasing $U_\infty$ (decreasing $\Omega$) improves the turbine performance where for each fixed $\Omega$ ($U_\infty$), there exists a specific $U_\infty$ ($\Omega$) where the turbine is operating optimally.
- Further increase of $U_\infty$ (decrease of $\Omega$) deteriorates the performance due to the growth of separations on blades and the subsequent stall.

The $C_T$ for the turbine operating at the optimal $\lambda$ is found to stay...
almost constant with small increase due to Reynolds number effects (see Section 5). This can reduce the flapwise fatigue loads on the turbine blades which are caused by the fluctuations in the thrust force. Such fluctuations occur due to the unsteady incoming flow.

5. Impact of Reynolds number

The current section investigates the impact of Re_{\text{c}}, based on the blade chord length, on the dynamic loads on turbine blades, turbine performance and wake at different tip speed ratios. A wide range of
Rec = 0.3 × 10^5 – 4.3 × 10^5 is considered where the range covers the values corresponding to small- to medium-scale urban VAWTs [12]. The turbulence intensity and the reduced frequency are kept the same as in the reference case. The other main operational parameters are presented in Table 7. An overall analysis is performed for 2.5 ≤ λ ≤ 5.5 covering low to moderately high tip speed ratios while a more detailed analysis focuses on the optimal λ of 4.0 and λ = 2.5, where the blade is in dynamic stall. It should be noted that the two selected λ will cover the two distinctive turbine operation regimes based on the flow physics: the former corresponds to the regime when the flow is mostly attached while the latter corresponds to the regime that includes strong separation from the blades. Therefore, these two deserve a dedicated analysis.

5.1. Loads on blades

The variations of α, V_{rel}, dynamic C_L and C_D during the last turbine revolution for different Rec are compared in Fig. 15 for λ = 4.0 and λ = 2.5. The Rec ranges between 0.79 × 10^5 –3.15 × 10^5 and 0.51 × 10^5–2.06 × 10^5 for λ = 4.0 and 2.5, respectively.

For λ = 4.0 (optimal performance), in the turbine fore half:

- Rec has a negligible influence on α during the upstroke (0° ≤ θ ≤ 45°).
- Normalized V_{rel} is Re-independent.
- During the upstroke, Rec has negligible effect on C_L, especially for Rec ≥ 10^5.
- Near C_L,max and during the downstroke, 45° < θ ≤ 180°, increasing Rec increases C_L and C_L,max, slightly postpones α_{c,max} to higher θ and marginally reduces C_D. Given the constant value of α for different Rec, these are associated to the delay in trailing-edge separation, which will be discussed later in this section. This is in agreement with earlier studies on airfoils in similar Re regime [70].
- C_L is more sensitive to Rec for Rec ≤ 1.58 × 10^5. This threshold is consistent with the findings for static airfoils reported by Lissaman [74].

In the turbine aft half:

- Rec has noticeable influence on α and C_L mainly in two regions, (i) 235° ≤ θ ≤ 265° where the flow has already slightly lower velocity due to the improved blade performance and more efficient energy extraction (less energy is remained in the flow) at higher Rec. The lower velocity results in lower α and C_L for higher Rec, (ii) θ ≈ 270°
where increasing $Re_c$ noticeably diminishes the sudden change in all parameters in the shaft wake. This is due to the strong Reynolds number effects on shaft, where increasing $Re$ significantly delays the separation and reduces the wake width. Note that the $Re$ corresponding to the shaft is defined based on its diameter and solely the incoming flow, which therefore, will be significantly lower than $Rec$.

An extensive discussion on the effect of the turbine shaft for VAWTs is provided by Rezaeiha et al.\[55\].

Increasing $Rec$ is found to significantly reduce $Cd$, especially for $Rec \leq 1.58 \times 10^5$. Note that given the small variations of $\alpha$, the flow on the blade is mostly attached in this region. For attached flows on flat plates and airfoils, increasing $Re$ effectively reduces the turbulent shear stress, and consequently the skin friction drag, while such an effect becomes less strong by increasing $Re$ above $10^5$\[72\].

For $\lambda = 2.5$ (dynamic stall), similar observations as the optimal $\lambda$ are made while the following points are also noteworthy. In the turbine fore half, the delay in stall by increasing $Rec$ is evident from the postponement of $C_{d,max}$. While increasing $Re_c$ visibly increases $C_{d,max}$, no monotonic trend is found for $C_{d,max}$. The complexities associated with the impact of $Re_c$ on dynamic stall has also been already reported by Singleton and Yeager Jr. \[115\]. In the turbine aft half, for $235^\circ \leq \theta \leq 265^\circ$, increasing $Rec$ is found to reduce fluctuations in $\alpha$, $C_l$ and $C_d$ which occurs due to the blade-wake interactions as explained in Section 4.1.

Plotting the lift and drag coefficients versus angle of attack, which for brevity is not shown here, implies that the hysteresis in dynamic loads is marginally increased by $Re_c$ prior to stall, i.e. $\lambda = 4.0$, while is weakly influenced by $Re_c$ post-stall, i.e. $\lambda = 2.5$. This is in line with the experimental results of Bousman \[116\], which showed weak $Re$-dependency for dynamic stall at $Re_c 1 \times 10^5 - 2.5 \times 10^5$.

The pressure coefficients on the blade are shown in Fig. 16. Note that in this figure the azimuthal positions, and $\lambda$ and $Rec$ are corresponding to those values already employed in Figs. 5 and 15, respectively. It can be seen that:

- An increase in $Re_c$ promotes laminar-to-turbulent transition on the blade suction side. This is in agreement with the studies on airfoils and flat plates \[72,74,103\]. Similar to observations in Section 4.1, the transition occurs earlier and the length of LSB is shorter for lower $\lambda$ due to higher values of $\alpha$.
- An increase in $Re_c$ delays the separation on the blade. For $\lambda = 2.5$, at $\theta > 90^\circ$ the blade has already stalled for the lowest $Rec$ of $0.51 \times 10^5$ while this occurs at $\theta > 110^\circ$ for the highest $Re_c$ of $2.06 \times 10^5$. The delay in separation is associated to the promotion in laminar-to-turbulent transition. The turbulent boundary layer has higher energy, thus, is more resistant to adverse pressure gradient and will separate later.
- Increasing $Re_c$ also slightly increases the pressure difference on the blade which explains the improvement in $C_l$ shown in Fig. 15. The increment in pressure difference is found to be present both in laminar and turbulent regions of the blade. This can be associated to the reduction in skin friction by increasing $Re_c$ \[74\].

\[Fig. 17. Power and thrust coefficients versus tip speed ratio (2.5 \leq \lambda \leq 5.5) and chord-based Reynolds number (0.4 \times 10^5 < Rec < 4.0 \times 10^5).\]
5.2. Turbine performance

Fig. 17a and b show the turbine power and thrust coefficients versus tip speed ratio for different freestream chord-based Reynolds numbers $0.4 \times 10^5 \leq \text{Re}_c \leq 4.0 \times 10^5$. The range is selected corresponding to very small to moderate size VAWTs operating in the urban environment. Increasing Re$_c$ is found to significantly improve the turbine performance while the optimum $\lambda$ is Re-independent. The enhancement in $C_p$ at $\lambda = 2.5$ (dynamic stall) and the optimal $\lambda$ of 4.0 is 682% and 77%, respectively, when Re$_c$ increases from approximately $0.4 \times 10^5$ to $4.0 \times 10^5$.

As already shown in Section 5.1, increasing Re$_c$ results in two effects on the blade, i.e. increase in the pressure difference and the promotion of laminar-to-turbulent transition which eventually delays the separation. For a given geometrical design and operating condition, Re$_c$ will be fixed. Therefore, if any method can mimic the two effects of Re$_c$, it could also significantly improve the turbine performance. Flow control methods have emerged as promising options to introduce the two effects. For example, circulation control methods can be employed to increase the pressure difference on airfoils [117]. Separation control methods have also been shown to successfully delay the blade stall to higher $\alpha$ [103].

By increasing $\lambda$, the effect of Re$_c$ on $C_p$ becomes less pronounced. As Re$_c$ increases from $0.4 \times 10^5$ to $4.0 \times 10^5$, $C_p$ increases by 30.5% and 4.7% at $\lambda = 2.5$ and 4.0, respectively.

In order to further clarify the impact of Reynolds number, the

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Fig. 18. Coefficients of tangential and normal forces and the normalized cumulative sum of the moment coefficient during the last turbine revolution for different Re$_c$ for (a–c) $\lambda = 4.0$ and (d–f) $\lambda = 2.5$. 

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A. Rezaeiha et al. Energy Conversion and Management 169 (2018) 45–77
The impact of Re on CT is also clearly seen in Fig. 17d. For (which is more relevant for hydro turbines). The comparatively small solidity of 0.12 while in the experiment they had a large solidity of 0.42. The variation in Re-independence regime is limited to Re > 2 × 10^5.

Fig. 19. Shed vorticity by a single blade during the last revolution for different Re, at λ: (a) 4.0, (b) 2.5. Positive values denote counter-clockwise circulation based on the Kutta-Joukowski theorem [111].

Increasing Re is found to significantly increase the tangential loads on turbine blades in the turbine fore half. The increment was already shown to be due to the promotion in laminar-to-turbulent transition, delay in separation and reduction in drag for higher Re. The sudden drop in tangential loads in the turbine fore half occurs later for higher Re. This prompts the delay in stall.

A reduction in tangential and normal load fluctuations, by increasing Re, is noticeable. This occurs due to stall in the turbine fore half and the blade-wake interactions in the turbine aft half.

Unlike the optimal λ, increasing Re notably affects the contribution of different quartiles to the total power production where the contribution of the upwind quartile lessens and that of the downwind quartile increases. This is associated to the significant influence of Re on delaying the stall and remarkably diminishing the strength of shed vorticity from the blades, thus weaker blade-wake interactions at higher Re (see Section 5.3). As a result, at higher Re, the downstream region is still capable of extracting energy from the flow and contributing to the total power.

5.3. Turbine wake

Fig. 19 shows the strength of the shed vorticity by a single blade during the last turbine revolution for the λ = 4.0 (optimal value) and 2.5 (dynamic stall). It can be seen that at the optimal λ = 4.0, the strength of the shed vorticity by a single blade is insignificantly affected by Re. Small differences by increasing Re correspond to three regions: (i) delay in separation on the blade in the turbine fore half; (ii) consequent reduction in fluctuations of the strength of the shed vorticity due to smaller blade-wake interactions in the turbine aft half; and (iii) diminishing of the impact of the shaft wake.

At λ = 2.5 (dynamic stall), the influence of Re is apparent in the same three regions while the impact is much more pronounced, especially when increasing Re from 0.51 × 10^5 to 1.03 × 10^5 where stronger vortex shedding and larger instability in the strength of the shed vortices are found to occur at the lower Re. This is in agreement with the experimental results by Yoon et al. [118].

Fig. 20 presents the time-averaged (over the last turbine revolution) streamwise velocity (normalized with respect to the freestream velocity) along the lateral line, −0.75 ≤ y/d ≤ 0.75, at different downstream locations in the turbine wake with x/d = 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, for λ = 4.0 (optimal) and 2.5 (dynamic stall) at various Re are shown in. It can be seen that:

- The turbine wake mean velocity profile is much less sensitive to Re than λ.
- The sensitivity of the wake mean velocity to Re does not reduce with traveling further downstream from x/d = 1.0 to 4.0.
- The velocity deficit and the mean velocity profile in the wake of the
Fig. 20. Time-averaged (over the last turbine revolution) normalized (with freestream velocity) streamwise velocity along the lateral line $-0.75 \leq y/d \leq 0.75$ at several downstream locations for different $Re_c$ at $\lambda = 2.5$ and 4.0.
Table 8
Operational parameters to study the impact of freestream turbulence.

| λ  | 2.5 | 3.0 | 3.5 | 4.0 | 4.5 | 5.5 |
|----|-----|-----|-----|-----|-----|-----|
| U_∞ [m/s] | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 |
| Ω [rad/s]  | 46.5 | 55.8 | 65.1 | 74.4 | 83.7 | 102.3 |
| TI [%]  | 0 – 30 | 0 – 30 | 0 – 30 | 0 – 30 | 0 – 30 | 0 – 30 |
| Reₜ (× 10⁴) | 1.03 | 1.21 | 1.39 | 1.58 | 1.76 | 2.14 |

Table 9
Incident total turbulence intensities.

| TI [%] | 0 | 5 | 10 | 15 | 20 | 25 | 30 |
|-------|---|---|----|----|----|----|----|
| TI [%] | 1e-6 | 4.42 | 7.99 | 11.01 | 13.64 | 15.98 | 18.09 |

VAWT are Re-dependent within the range studied both for λ = 4.0 and λ = 2.5. For HAWT, Re-independency for the wake mean velocity is found to occur already at an approximate blade tip Reₜ of 2.0 × 10⁴ [119].

- Increasing Reₜ increases the velocity deficit for x/d > 1.0. This corroborates the observations by Bachant and Wosnik on hydro turbines [65].
- Increasing Reₜ expands the turbine wake. Similar observations are reported for HAWTs by McTavish et al. [120].
- The influence of Reₜ is more prominent for λ = 2.5, compared to λ = 4.0, and the impact is larger for Reₜ, increasing from 0.51 × 10⁵ to 1.03 × 10⁵. This is consistent with the comparatively large impact of Reₜ on the strength of the shed vorticity for the lower λ, at the same Reₜ as shown in Fig. 19. As the turbine wake is generated by the shed vorticity from the blades, therefore, the larger influence of the Reₜ on the strength of the shed vorticity will also result in a larger difference in the velocity profiles in the wake.
- For λ = 2.5, at downstream positions x/d < 2.0, the impact of the local blade aerodynamics (vortex shedding due to stall on blades) is strongly distinguished as fluctuations in the mean velocity profile in y/d < 0. The local blade effect fades away as the wake travels further downstream.

The above findings highlight the facts that (i) there exist important differences in Re-dependency of wake characteristics for VAWTs and HAWTs; (ii) in the study of array of reduced-scale VAWTs, Re-dependency of the wake mean velocity and turbulence intensity needs special attention to avoid wrong conclusions for the full-scale turbines.

6. Impact of turbulence intensity

In this section, the impact of freestream turbulence intensity on the dynamic loads on blades, the turbine performance and the wake is systematically investigated. Table 8 lists the operational parameters employed. TI is selected to vary within 0 to 30%, covering a wide range from very low values relevant to low turbulence wind tunnels to moderately high turbulence in the real operating conditions such as urban environments. An overall analysis is performed for 2.5 ≤ λ ≤ 5.5 covering low to moderately high tip speed ratios while a more detailed analysis focuses on the optimal λ of 4.0 as well as λ = 2.5 where the blade is in dynamic stall. Table 9 presents the incident-flow total turbulence intensities for all the cases. The reduced frequency is kept the same as the reference case.

6.1. Loads on blades

Fig. 21 compares the variations of α, Vrel, dynamic C₄ and C₅ during the last turbine revolution for different TI for λ = 4.0 (optimal) and λ = 2.5 (dynamic stall). For λ = 4.0, the following observations are made:

- α is found not to be affected by TI except in the shaft wake where the magnitude of the sudden change in α abates by increasing TI. This is because increasing TI promotes laminar-to-turbulent transition on bluff bodies [121], which consequently delays the flow separation and reduces the shaft wake width [55].
- At TI = 0%, fluctuations are present in both C₄ and C₅ which could be associated to the long laminar separation bubble (LSB) existing on the airfoil suction side [109]. Increasing TI damps out such load fluctuations.
- In the turbine fore half, very small differences in C₄ are observed for TI = 5% and 30%.
- In the turbine fore half, C₄ is highest for TI = 30%. In the turbine aft half, C₄ is higher for TI = 30% compared to 5% while strong fluctuations, due the blade-wake interactions and shaft wake, are present for TI = 0%.

For λ = 2.5 (dynamic stall), it can be seen that:

- Fluctuations of α corresponding to the blade-wake interactions downstream of the stall region, already identified in Section 4.1, reduce as TI increases.
- Increasing TI remarkably reduces the load (C₄ and C₅) fluctuations due to the stall, the blade-wake interactions and the shaft wake where the difference is much more pronounced from TI of 0% to 5%.
- In contrary to λ = 4.0, increasing TI notably reduces C₄ where the minimum C₄ corresponds to TI = 30%.
- The minimum C₄, occurring due to the stall and the blade-wake interactions occurs at TI = 30%.
- By increasing TI, stall is delayed. This is apparent from the postponement in C₄, occurring in the turbine fore half.
- C₄ is found not to be affected by TI.

In addition, plotting the lift and drag coefficients versus angle of attack, which for brevity is not shown here, implies that the asymmetry (hysteresis) in the dynamic loads is barely influenced by TI.

The pressure coefficients on the blade are compared in Fig. 22. The following observations are made:

- Similar to observations in Sections 4.1 and 5.1, the transition occurs earlier and the length of LSB is shorter for lower λ due to higher values of α.
- At TI = 0%, a long LSB is present, where the length of the bubble is shorter for λ = 2.5 due to higher α, which is thought to be causing the notable load fluctuations shown in Fig. 21.
- Increasing TI from 0 to 5% significantly decreases the length of LSB.
- The reduction in the bubble length has been experimentally shown to be associated to the stronger velocity fluctuations, at higher TI, entering the separated boundary layer which tends to reattach the boundary layer and close the bubble [122].

At TI = 30%, bypass transition occurs for all cases for λ = 4.0. This is limited to θ < 90° and > 130° for λ = 2.5. While for other θ, an early transition within a short LSB at 0 < x/c < 0.1 happens.

- For λ = 2.5 (dynamic stall), the delay in stall by increasing TI is clearly visible. At TI = 0%, the blade stalls at θ = 80°. This is postponed for θ = 100° at TI = 5%. This is further postponed at TI = 30% where separation extends over almost 90% of the blade at θ = 120°.
- For the optimal λ = 4.0 where the flow is mostly attached, TI = 0% has the minimum pressure difference on the blade. A slight increase of pressure difference on the blade by increasing TI from 5 to 30% is present for θ > 100°.

6.2. Turbine performance

Fig. 23 shows C₆ and C₇ versus λ for 0% ≤ TI ≤ 30% and versus TI for 2.5 ≤ λ ≤ 5.5. It can be seen that C₆ is strongly sensitive to TI for all
λ. For low tip speed ratios (λ ≤ 3.0), the sensitivity for TI < 10% is substantial while it quickly decreases for 10% ≤ TI ≤ 30%. Within the studied range of TI, this sensitivity becomes comparatively small for moderate to high tip speed ratios, 3.5 ≤ λ ≤ 4.5, while again increases for higher λ of 5.5. The optimum λ has a small dependence on TI where it slightly decreases from 4.0 to 3.5 by increasing TI from 0% to 30%.

For λ = 2.5, where the flow is strongly separated and dynamic stall is present, increasing TI from 0% to 30% dramatically improves the turbine performance (249%). The improvement is shown to be associated with the promotion in laminar-to-turbulent transition and

Fig. 21. Variations of experienced angle of attack, normalized relative velocity, lift and drag coefficients during the last turbine revolution for different TI at λ: (a–d) 4.0, (e–h) 2.5.
considerable delay in stall on blade (see Section 6.1).

For $\lambda > 2.5$, where the blade is operating prior or near stall, an initial increase of TI from 0% improves the $C_p$ by promoting laminar-to-turbulent transition (happening within a shorter LSB) and increasing the pressure difference on the blade. There exists an optimal TI which grants the maximum $C_p$. The optimal TI is 15% and 10% for $\lambda = 3.0$ and 3.5, respectively, while this reduces to TI = 5% for $\lambda \geq 4.0$. The optimal $C_p$ compared to that of TI = 0% is 87%, 25%, 7%, 6% and 7% higher for $\lambda = 3.0, 3.5, 4.0, 4.5$ and 5.5, respectively. This highlights significant influence of TI especially for TI $\leq 15%$. Further increase of TI deteriorates the CP due to massive increase of $C_d$ as a result of large growth of skin friction in the attached boundary layer along the blade.

For the optimal $\lambda = 4.0$, the maximum $C_p$, which occurs at TI = 5%, drops by 9% at TI = 30%. The reduction grows to 23% for $\lambda = 5.5$. The comparatively high reduction at $\lambda = 5.5$ could be explained as for higher $\lambda$, flow is attached over a larger part of the blade, therefore, friction drag is playing a more important role. For $\lambda \geq 4.0$, $C_p$ at TI = 30% is lower than that of TI = 0%. $C_f$ can be considered almost TI-independent.

Fig. 24 presents the instantaneous tangential $C_{Ft}$ and normal $C_{Fn}$ force coefficients on the blades and the normalized cumulative sum of instantaneous moment coefficient $C_m$ during the last turbine revolution for the optimal $\lambda$ of 4.0 and $\lambda = 2.5$ (dynamic stall) for different TI values. For the optimal $\lambda$ of 4.0, it can be seen that:

- Increasing TI from 0% to 5% improves the tangential loads in the turbine fore half while further increase of TI to 30% decreases the tangential loads. The explanation is provided in Section 6.1.
- The loads in the shaft wake behave differently where TI = 30% shows the least reduction in loads. This is because the flow over a bluff body, namely the shaft, is driven by large separation and friction drag plays a minimal role to the total drag. Therefore, increase of TI delays the separation and reduces the shaft wake, which consequently improves the tangential loads in this region.
- Normal loads are less sensitive to TI. In the turbine fore half, the normal loads slightly increase due to higher TI, especially during the downstroke while the reverse occurs in the turbine aft half.
- The contribution of different quartiles are minimally affected by TI (Fig. 24c).

For $\lambda = 2.5$ (dynamic stall) it can be observed that:

- Increasing TI monotonically improves the tangential loads in dynamic stall by dramatically delaying the stall. This is clearly
distinguished from the postponement in the abrupt drop in tangential loads for higher TI.

- Increasing TI significantly diminishes the fluctuations in tangential and normal loads.
- Due to the considerable changes in the flow by delaying stall in the turbine fore half, the contribution of different quartiles to the total power production is altered.

6.3. Turbine wake

Fig. 25 shows the strength of the shed vorticity by a single blade during the last turbine revolution for $\lambda = 4.0$ (optimal value) and 2.5 (dynamic stall). It can be seen that:

- At the optimal $\lambda$ of 4.0, increasing TI from 0 to 5% diminishes the fluctuations in the strength of the shed vorticity while further increase of TI yields to less significant impact.
- At $\lambda = 2.5$, the similar observation is made while the impact of TI in reducing the fluctuations in the strength of the shed vorticity is much more pronounced.

Fig. 26 indicates the time-averaged (over the last turbine revolution) streamwise velocity (normalized with respect to the freestream velocity) along the lateral line, $-0.75 \leq y/d \leq 0.75$, at different downstream locations in the turbine wake with $x/d = 1.0, 1.5, 2.0, 2.5, 3.0, 4.0$, for $\lambda = 4.0$ (optimal) and 2.5 (dynamic stall) at various TI. It can be seen that:

- The sensitivity of the mean velocity in the turbine wake to TI is less than $\lambda$, but more than $\text{Re}_e$.
- The large fluctuations in the strength of the shed vortices for TI = 0%, shown in Fig. 25, are also clearly distinguished at $x/d \leq 1.5$ where the wake is strongly influenced by the local aerodynamic of blades.
- The fluctuations in the mean velocity are more significant for $\lambda = 2.5$ due to dynamic stall on the blades and stronger fluctuations in the strength of the shed vorticity.
- As the wake travels further downstream, such fluctuations are damped out.
- The influence of TI on the mean velocity in the wake is very prominent for both optimal and dynamic stall cases. This remains non-negligible for downstream locations as far as $x/d = 4.0$.
- Increasing TI reduces the impact of the shaft on the mean velocity in the turbine wake. This is attributed to the considerable delay in separation over the shaft and the subsequent reduction of the shaft wake.
- By increasing TI, the velocity deficit in the wake and the wake expansion reduce while the wake recovery increases. The findings are in line with the role of the turbulence level on the wake of HAWTs [123].

7. Summary and conclusions

High-fidelity computational fluid dynamics (CFD) simulations, extensively validated with experiments, are performed to systematically investigate the impact of operational parameters, i.e. tip speed ratio ($\lambda$), Reynolds number ($\text{Re}_e$) and turbulence intensity (TI), on the power performance and aerodynamics of vertical axis wind turbines. The study investigates a wide range of the parameters: $1.2 \leq \lambda \leq 6.0$, $0.3 \times 10^5 \leq \text{Re}_e \leq 4.2 \times 10^5$ and $0\% \leq \text{TI} \leq 30\%$ to comprehensively
clarify their impact on dynamic loads on blades, turbine performance and wake. The findings from the study can be summarized as follows:

(1) Tip speed ratio:
- In the turbine fore half, the variation of $\alpha$ is half-cycle sinusoidal, while in the turbine aft half it is notably different due to the strong impact of the turbine induction, the blade-wake interactions and the shaft wake. Increase of $\lambda$ also increases the flatness in $\alpha$ curve in the turbine aft half.
- The amplitude of the oscillations in the normalized relative velocity increases from 17.5% at $\lambda = 5.5$ to 36.7% at $\lambda = 2.5$.
- For $\lambda < 3.0$, the variations of $\alpha$ exceed $\alpha_{ss}$ which leads to dynamic stall. This is accompanied by strong fluctuations in $C_t$ and $C_p$ and a dramatic jump in $C_p$. The consequent blade-wake interactions also result in strong load fluctuations in the downwind quartile. Reducing $\lambda$ significantly increases $C_{l_{max}}$ and $C_{d_{max}}$.
- Reducing $\lambda$ promotes laminar-to-turbulent transition, decreases the length of the laminar separation bubble and moves the trailing edge separation towards the leading edge. These occur due to the higher $\alpha$ of the blades.
- An optimal $\lambda$ exists for $C_p$ while $C_t$ asymptotically increases with $\lambda$. For the studied turbine, the optimal $\lambda$ is 4.0. The optimal $\lambda$ stays constant with Re and reduced frequency, within the studied range.
- The contribution of different turbine quartiles to the total power production is strongly $\lambda$-dependent.
- Increasing $\lambda$ increases the velocity deficit, wake expansion and streamwise asymmetry in the wake.
- The length of the turbine wake, defined at $V/U_\infty = 0.97$, decreases asymptotically by increasing $\lambda$. The decrease in the wake length is thought to be due to the amplification of instabilities due to the closer spacing of the shed vortices in the wake which could lead to an earlier break down of the wake structure.

(2) Reynolds number:
- $\alpha$ and normalized $V_{sec}$ are almost Re-independent, esp. in the fore

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Fig. 24. Coefficients of tangential and normal force coefficients and the normalized cumulative sum of moment coefficient during the last turbine revolution for different TI at (a–c) $\lambda = 4.0$, (d–f) $\lambda = 2.5$. 

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turbine half.

- Increase of Re: (i) promotes the laminar-to-turbulent transition and postpones the separation on blades, (ii) reduces the fluctuations in $C_t$ and $C_d$ associated with the dynamic stall and the blade-wake interactions, (iii) reduces the impact of the shaft on turbine loads, (iv) improves $C_l$ by increasing $C_{l_{max}}$ and delaying stall where the sensitivity of $C_t$ to Re decreases for $Re > 10^5$, and (v) reduces $C_d$, especially in the turbine aft half, and $C_{d_{max}}$, occurring due to the blade-wake interactions.

- Within the studied range, $C_p$ is strongly Re-dependent where the sensitivity decreases by the increase of Re, $C_l$ is much less Re-dependent. For high $\lambda$, $C_T$ is almost Re-independent.

- The optimum $\lambda$ is Re-independent.

- Unlike the optimal $\lambda$ of 4.0, in dynamic stall ($\lambda = 2.5$) the contribution of different quartiles to the total power production is TI-dependent.

- Mean velocity in the wake is strongly influenced by TI. The sensitivity is less than that to $\lambda$ but more than that to Re.

- Increase of TI decreases the velocity deficit and the wake expansion while increases the wake recovery.

The main conclusions are:

- Two co-occurring sources of unsteadiness, $\alpha$ and $V_{rel}$, complicate the aerodynamics of VAWTs.

- Neglecting the induced velocity, via using the geometrical angle of attack, can lead to an overestimation of the variations of $\alpha$ up to 8.3° and the magnitude of $C_d$ and a shift in the $C_p$$\alpha$ and $C_{T_{max}}$-$\alpha$ curves, which could result in a large uncertainty in the turbine power prediction.

- Maintaining the optimal $\lambda$ (at different freestream velocities) via a variable-speed VAWT substantially improves $C_p$ compared to a fixed-speed VAWT. The improvement is 168%, for example, at 4 m/s compared to a turbine operating at a fixed rotational speed of 65.1 rad/s.

- The upwind quartile is the major contributor to the total power production with more than 50% contribution in all $\lambda$ studied.

- Given the inherent unsteady nature of VAWTs, which is due to the continuous and substantial variations of angle of attack and relative velocity during each revolution, power enhancement methods such as individual blade dynamic pitching, trailing edge flaps, microtabs and other flow control methods, can hardly be made effective during the whole revolution due to practical difficulties. Therefore, because the upwind quartile plays the most important role in the turbine total power production, the use of such power enhancement methods for this quartile, rather than the whole revolution, would be less challenging and more practical in terms of energy input, system complexity and time response.

- Within the range studied, $0.3 \times 10^5 \leq Re \leq 4.3 \times 10^5$ and $0 \leq TI \leq 30\%$, the turbine power coefficient $C_p$ and wake characteristics (i.e. mean velocity profile, velocity deficit and wake expansion) are strongly sensitive to Re and TI. Therefore, any experimental/numerical VAWT study performed for a scaled model (lower Re,) or at a different turbulence level needs to consider the strong sensitivity to Re and TI of any measured/calculated turbine power and wake data. The influence of these parameters on the power measurements would lead to unrealistic performance prediction for the full-scale turbine while their influence on the wake measurements would play a role when the effect of the turbine wake

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Fig. 25. Shed vorticity by a single blade during the last revolution for different TI at $\lambda$: (a) 4.0, (b) 2.5. Positive values denote counter-clockwise circulation based on the Kutta-Joukowski theorem [111].

- Increase of TI: (i) reduces the impact of the shaft on the turbine loads, (ii) promotes laminar-to-turbulent transition, and (iii) reduces the fluctuations in $C_t$ and $C_d$ associated with the dynamic stall, the blade-wake interactions and presence of the long laminar separation bubble on the blade at TI = 0%.

- At optimal $\lambda$ ($\lambda = 4.0$), an increase of TI from 0% to 5%, reduces $C_d$ while further increase of TI to 30% results in a significant growth in $C_d$ due to the increased skin friction in the attached boundary layer on the blade.

- At $\lambda = 2.5$ (dynamic stall), an increase of TI to 30% reduces the $C_{d_{max}}$ associated with the dynamic stall and the consequent blade-wake interactions, while $C_{l_{max}}$ is not affected.

- $C_p$ is strongly TI-dependent while $C_T$ is almost TI-independent.

- The optimum $\lambda$ slightly decreases by increasing TI.

- At $\lambda = 2.5$ (dynamic stall), increasing TI from 0% to 30% dramatically improves $C_p$ by 249%. The improvement is associated to the delay in stall. For higher $\lambda$, an optimal value of TI exists. The optimal TI reduces from 15% to 5% for $\lambda$ increasing from 3.0 to 5.5. At optimal $\lambda$ ($\lambda = 4.0$), increasing TI from 0% to 5% improves $C_p$ by 7% while further increase of TI to 30% drops $C_p$ by 9%.

- Unlike the optimal $\lambda$ of 4.0, in dynamic stall ($\lambda = 2.5$) the contribution of different quartiles to the total power production is TI-dependent.

- Mean velocity in the wake is strongly influenced by TI. The sensitivity is less than that to $\lambda$ but more than that to Re.

- Increase of TI decreases the velocity deficit and the wake expansion while increases the wake recovery.

The main conclusions are:

- Two co-occurring sources of unsteadiness, $\alpha$ and $V_{rel}$, complicate the aerodynamics of VAWTs.

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- Maintaining the optimal $\lambda$ (at different freestream velocities) via a variable-speed VAWT substantially improves $C_p$ compared to a fixed-speed VAWT. The improvement is 168%, for example, at 4 m/s compared to a turbine operating at a fixed rotational speed of 65.1 rad/s.

- The upwind quartile is the major contributor to the total power production with more than 50% contribution in all $\lambda$ studied.

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- Within the range studied, $0.3 \times 10^5 \leq Re \leq 4.3 \times 10^5$ and $0 \leq TI \leq 30\%$, the turbine power coefficient $C_p$ and wake characteristics (i.e. mean velocity profile, velocity deficit and wake expansion) are strongly sensitive to Re and TI. Therefore, any experimental/numerical VAWT study performed for a scaled model (lower Re,) or at a different turbulence level needs to consider the strong sensitivity to Re and TI of any measured/calculated turbine power and wake data. The influence of these parameters on the power measurements would lead to unrealistic performance prediction for the full-scale turbine while their influence on the wake measurements would play a role when the effect of the turbine wake
Fig. 26. Time-averaged (over the last turbine revolution) normalized (with freestream velocity) streamwise velocity along the lateral line $-0.75 \leq y/d \leq 0.75$ at several downstream locations for different TI at $\lambda = 2.5$ and 4.0.
The findings of the current study highlight the importance of the impact of the operational parameters, i.e., \( \lambda, \text{ Re and } \text{ TI} \), on aerodynamic performance of VAWTs. In the present study, a Darrieus H-type VAWT has been investigated. Note that the difference between the Darrieus H-type VAWT and the other types of Darrieus VAWTs, such as the \( \phi \)-type, is limited to the blade shape in spanwise direction: the former has straight blades while the latter has curved ones. Therefore, neglecting the 3D tip effects and the variations of circulation along the blade span, the 2D cross-section of the Darrieus VAWTs have similar aerodynamic behavior at a given geometrical and operational condition and will also respond similarly to the variations of the operational parameters investigated in the present study. Therefore, as the focus of the present study is on the mid-plane of the turbine, the findings on the dynamic loads on the blades will be applicable to the other types of Darrieus VAWTs as well. Considering the impact of operational parameters on the turbine performance and wake, while the observed trends could be common between the H-type configuration and the other blade configurations, there could be differences in the absolute values mainly because the H-type and also the helical blade configurations benefit from a constant radius along the blade span, which therefore means that the tip speed ratio and Re remains constant along the span. This is while the case is different for the other blade configurations, such \( \phi \)-type, where due to the curved blade configurations each blade section has a different radius, thus a different tip speed ratio and Re. Therefore, extending the current findings for these configurations needs special attention to their spanwise variations of tip speed ratio and Re.

Note that the evaluation is based on comprehensive analyses of a low-solidity turbine with a symmetric airfoil. Dependency of the derived conclusions on the turbine geometrical parameters are worthwhile to be investigated. In addition, the optimal value of \( \lambda \), identified in this paper, is dependent on the turbine characteristics and will be different for a turbine of different solidity and/or airfoil shape. Therefore, such analysis will need to be repeated for that case to identify the optimal \( \lambda \).

The range of Re investigated in this study corresponds to the regime of interest for urban VAWTs. Extension of the conclusions for higher Re, applicable to large-scale offshore VAWTs, might demand further research.

Turbulence length scale, together with TI, is another important parameter which could influence the boundary layer events, VAWT performance and wake and such investigation is recommended for future research. In addition, the use of more advanced methods, i.e., hybrid RANS-LES and LES, together with detailed wind tunnel experiments to investigate the impact of turbulence characteristics for VAWT is also proposed.

The conclusions can significantly support more accurate performance prediction of VAWTs for various operating conditions. Additionally, the results recommend that the design of VAWTs needs to steer towards optimal variable-speed operation, similar to HAWTs, while the cost effectiveness of variable-VAWTs is proposed for future research.

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Appendix A. Method for calculation of the experienced angle of attack and relative velocity

For VAWTs, for simplicity it is customary to neglect the turbine induction in the performance analysis. This assumption provides the geometrical values of the relative velocity \( V_{rel,geo} \) and the angle of attack \( \alpha_{geo} \), which are defined based on ignoring the induced velocity component of the incoming flow. Based on \( V_{rel,geo} \) and \( \alpha_{geo} \), lift and drag coefficients are calculated which are different from the values actually experienced by the blades. The geometrical relative velocity is defined as a vector sum of the freestream velocity, \( \vec{U}_w \), and the blade tip speed, \( \Omega \times \vec{R} \) using Eq. (1). Based on this assumption, the geometrical values of the tangential and normal velocity components (Vt and Vn) are calculated using Eqs. (2) and (3).

\[
\vec{V}_{rel,geo} = (\vec{U}_w \times \vec{R}) + \vec{U}_w
\]

\[
V_t = R\Omega + U_w \cos(\theta)
\]  

\[
V_n = U_w \sin(\theta)
\]

Finally, the magnitude of the geometrical relative velocity and angle of attack are calculated using Eqs. (4) and (5):

\[
\left| \vec{V}_{rel,geo} \right| = \sqrt{V_t^2 + V_n^2}
\]

\[
\alpha_{geo} = \arctan \left( \frac{V_n}{V_t} \right)
\]

**Fig. A1.** Monitor points for sampling velocity components to calculate the induced velocity.
The overall variations of $\alpha$ are significantly different from a fully sinusoidal function which is the case for $\alpha_{geo}$. 

At $\theta = 0^\circ$ and $180^\circ$, due to the lateral deviation of the flow at the turbine incidence (streamtube expansion), $\alpha$ has a negative non-zero value. This is while $\alpha_{geo}$ always predicts zero value at such $\theta$. 

The impact of the shaft wake on $\alpha$, which is seen as a sudden reduction in magnitude, is neglected by $\alpha_{geo}$. 

For all cases, $\alpha_{geo}$ overestimates the amplitude of variations compared to $\alpha$. This is due to ignoring the induced velocity by the turbine. In the turbine fore half, the overestimation is approximately $2.0^\circ$, while this value goes up to $8.3^\circ$ in the turbine aft half. In the turbine fore half, the trend of $\alpha_{geo}$ is similar to that of $\alpha$. However, significant differences are present in the turbine aft half. 

The geometrical and experienced values of relative velocity are also noticeably different, esp. in the turbine aft half. 

During the fore turbine half, the experienced $C_l$ is slightly higher that the geometrical values at the same azimuthal position while the experienced $C_l$ - $\alpha$ curve is considerably shifted upward compared to the geometrical one. 

The experienced $C_d$ is significantly lower than the geometrical one almost during the whole revolution. 

The slope of $C_d$ curve is lower for the experienced values (Fig. A2f), while no significant difference in slope is observed for $C_l$ (Fig. A2e). 

$C_{d,\text{max}}$ is significantly overestimated by geometrical values while $C_{l,\text{max}}$ is slightly underestimated. Both values occur at higher $\alpha$ compared to the experienced values. 

The magnitude of asymmetry (hysteresis) in dynamic load variations (the absolute difference between the higher and lower values of $C_l$ and $C_d$ at selfsame $\alpha$) is almost the same for geometrical and experienced polars.
Therefore, although $\alpha_{\text{geo}}$ can be employed to provide a first approximation of $\Delta \alpha$ with respect to the tip speed ratio for VAWTs, special attention should be paid to the non-negligible differences between the geometrical and experienced angle of attack, relative velocity, lift and drag coefficients.

![Fig. A2. Experienced (exp.) and geometrical (geo.) values of angle of attack, relative velocity, lift and drag coefficients during the last turbine revolution for different tip speed ratios. $\alpha_{ss}$ denotes the inviscid static stall angle from Xfoil [106]. (Re $= 2.0 \times 10^5$).](image)

Therefore, although $\alpha_{\text{geo}}$ can be employed to provide a first approximation of $\Delta \alpha$ with respect to the tip speed ratio for VAWTs, special attention should be paid to the non-negligible differences between the geometrical and experienced angle of attack, relative velocity, lift and drag coefficients.

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