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How to extract the angle attack on airfoils in cycloidal motion from a flow field solved with Computational Fluid Dynamics? Development and verification of a robust computational procedure

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Abstract

One of the key problems faced by researchers dealing with Computational Fluid Dynamics simulations and rotating machines is represented by how to extract the angle attack from a numerically computed flow field. If this issue has been addressed successfully for some applications, in case of airfoils moving in cycloidal motion (i.e. having a rotational motion within a rectilinear flow field, like in Darrieus Vertical-Axis Wind Turbines) some proposals do exist, but always affected by some arbitrary choices on the velocity probing that are not supported by a proper verification. The aim of the present study is to try finding a robust computational procedure tailored for the scope. To this end, three different post-processing methods - detailed in the study - were considered and applied to the flow fields of 2-blade H-Darrieus rotor, coming from a high-fidelity unsteady model based on Computational Fluid Dynamics; the resulting blade angle of attack

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trends over one rotor revolution were then combined with available blade forces data to assess the corresponding lift and drag coefficients. In order to assess the actual accuracy of these approaches for a stable tip-speed ratio, the post-processed force coefficients were compared to the ones computed via a numerical pitching airfoil model, which received the sampled angle of attack trends as input; eventually, the pitched lift and drag values have been used to reconstruct the blade forces over one rotor revolution and compare them with the ones coming from full turbine simulations. Results show large scattering of obtained data, remarking the importance of the proper selection of the angle of attack sampling strategy for the analysis of turbine performance. Overall, the “LineAverage” approach, i.e. the use of multiple sampling points around the airfoil for velocity probing, has proved to be the most accurate method.

Keywords: Darrieus, Vertical Axis Wind Turbine, angle of attack, Particle Image Velocimetry, Computational Fluid Dynamics

1. Introduction

Applied research on Darrieus-type Vertical-Axis Wind Turbines (VAWTs) has been receiving a renewed attention for the last few years [1]. In particular, this technology is more often favorably associated to deep-sea, offshore floating installations due to the theoretical possibilities of shifting the generation system on the platform (so having a lower the center of mass), the absence of a yaw system, and the simple architecture [2]. Due to the lack of studies in the last thirty years of the 20th century, however, both the knowledge of involved physics and the state of development of existing simulation tools have fallen behind those for horizontal-axis machines, which still benefit from a higher energy conversion efficiency [3]. The greatest complexity in the analysis of Darrieus VAWTs relies in the fact that when an airfoil moves in cycloidal motion (i.e. it has a rotational motion within a rectilinear flow field), its aerodynamics are intrinsically more complex being characterized by a continuous variation of the angle of attack and the possible onset of many, related unsteady phenomena, like dynamic stall [4]. To study these phenomena and to explore more complex three-dimensional blade shapes [5], computational tools with a level of fidelity higher than that of the

ubiquitous Blade Element Momentum (BEM) theory are increasingly applied to VAWTs [6], like Lifting-Line methods [7], Actuator Line methods (using Reynolds Averaged Navier Stokes approaches [8] or Large Eddy Simulation [9]), or full Computational Fluid Dynamics (CFD) (e.g. [10]). This latter one proved to be very effective, even with a two-dimensional formulation [11], although very strict requirements in terms of simulation settings are needed [12].

However, the open question that always arises among researchers when using such methods is: how to extract the angle attack from a CFD-based flow field? This in fact represents the key element to exploit the information offered by high-order simulations so to develop proper correction and/or sub-models of use in the conventional lumped-parameter aerodynamics at the basis of engineering methods. Some proposals were made lately in the literature, which often were not supported by a proper verification due to the lack of suitable data. For example, a flow direction averaging in an area surrounding the airfoil has been proposed in [13], while in [14] a single sampling point of the airfoil leading edge is used for velocity probing. In addition, in [15] an empirical correction is used to correct the probed velocity in a rack of points in front of the airfoil. An important contribution was, however, that provided in [16], where the virtual camber effect taking place in the cycloidal motion was introduced in the correct evaluation of the attended pressure distribution along the airfoil at a given angle of attack. This method proved that accounting for this effect is pivotal to effectively transfer data to a lumped parameter model. However, it was affected by two major limitations. The first one is the fact that the velocity oncoming on the airfoil was probed in an arbitrary zone. Several methods have been proposed in the literature to this scope, often borrowed from horizontal-axis wind turbines, but up to now they were still affected by a certain degree of arbitrariness since no specific verification data was available. The second limitation of the method proposed in [16] was the fact that its applicability was limited only to a portion of the turbine revolution and it was not able to capture dynamic variations of the aerodynamics. As it will be shown in this work, the proposed method is thought to be able to effectively solve both issues and it is then considered sufficiently robust for use in any airfoil in cycloidal motion.

1.1 Outline of the study

Moving from this background, in the present study the unique experimental data collected using Particle Image Velocimetry (PIV) on a 2-blade H-Darrieus rotor in the TU Delft wind tunnel [17] were compared to high-fidelity, unsteady CFD simulations. Two operating conditions were tested, one in the unstable branch of the turbine characteristic curve (TSR=2) and one in the stable one (TSR=4.5). The main scopes of the comparison were to: a) compare the experimental and computed flow fields to assess the accuracy of the simulations and get an inner insight to the flow past rotating blades; b) reconstruct the AoA variation during the revolution and correlate it with the actual aerodynamic performance of the airfoils. For the latter purpose, three methods for the extrapolation of the AoA from the CFD flow field were selected: the *3-Points* [18], *Line Average* [19] and *Trajectory* [20] approaches. Originally developed for horizontal-axis machines, they were adapted to work with vertical-axis machines and then applied to the CFD data available for the TU Delft 2-blade rotor. The resulting AoA trends were then combined with available blade forces data to assess the corresponding lift and drag coefficients over one rotor revolution and correlate them with the most evident flow macro-structures and with the onset of dynamic stall. In order to assess the actual accuracy of these approaches, an ad hoc inverse verification procedure was ideated. The sampled force coefficients were compared to the ones computed via a pitching airfoil CFD model, which received the sampled AoA trends as input for the pitching motion law. As following step, the pitched lift and drag values were used, in combination with the sampled AoA and blade relative velocity V_r , to reconstruct the blade forces over one rotor revolution. Eventually, the method, whose reconstructed force profiles showed the best agreement with the ones coming from previous VAWT CFD simulations, was selected as the most accurate one. It must be noted how this analysis was limited to the stable branch of the turbine power curve (TSR=4.5), due to the inherent difficulties of developing a reliable CFD model for the rotor behavior during unstable operation (TSR=2).

2. Data and methods

In this section, the different methodologies adopted throughout the current study are presented.

First, the CFD model of the test rotor, required for the computation of the blade forces and the corresponding flow fields, is thoroughly described, together with the experimental data available for its validation. The different methods for the extraction of the angle of attack from the turbine CFD flow field are then introduced, followed by the inverse procedure proposed in the current work for the verification of the sampled AoA profile.

2.1 Reference experimental data

Experimental data used in the present study were taken from [17]. They are part of an extended experimental activity that has been performed in the Open Jet Facility (OJF) of the Delft University of Technology. The tested turbine model was a 2-blade (untwisted and untapered) H-Darrieus, whose main characteristics are reported in Table 1. Two functioning points were considered by [17] during the experimental campaign, corresponding to an *unstable* (TSR=2), i.e. characterized by dynamic stall over a major portion of one rotor revolution, and a *stable* (TSR=4.5) turbine operation, in which on the other hand the stall phenomenon is almost absent, respectively. The corresponding wind tunnel set-up is shown in Table 2.

The velocity fields in the near wake of the turbine have been obtained by particle image velocimetry (PIV), adopted in a planar 2D–2C configuration for the horizontal plane at the turbine mid span and in a stereoscopic 2D–3C configuration for the measurements on the vertical planes. Further details on the experimental setup and the data acquisition/processing can be found in [17].

2.2 Computational Fluid Dynamics simulations

The present work made use of different types of CFD simulations, always based on an Unsteady Reynolds-Averaged Navier-Stokes (U-RANS) approach and making use of the ANSYS® FLUENT® solver.

On one hand, the full test turbine was simulated in order to verify the agreement with experiments and to get both the computed flow field and the aerodynamic forces along the revolution. On the other hand, detailed simulations of the virtually transformed airfoil in an equivalent pitching motion were used as a benchmark to verify the correctness of the estimated angle of attack. The different simulation settings are summarized below.

Turbine model

The kind of analysis presented in this study required a robust and reliable numerical model of the test turbine, to be used for the evaluation of the flow field around the rotating blades and the corresponding aerodynamic forces. For the purpose, a dedicated U-RANS CFD model was employed, based on a consolidated numerical approach developed by the authors [21]. The latter exploits the coupled algorithm for pressure-velocity coupling, and the 2nd order upwind scheme for both RANS and turbulence equations. For turbulence closure, the $k-\omega$ SST model was adopted, in virtue of its suitability to VAWT simulation observed by the authors in previous works using both commercial [21] or research codes [22]. For detailed information about the settings for convergence definition, maximum inner iterations and residuals, please refer to [21].

Figure 1 shows the computational domain adopted in the present study. All boundaries were distanced from the turbine axis in such a way, that the standard far-field boundary conditions could be applied. Reference length unit for the analysis is the rotor diameter D . More in detail, a uniform flow velocity, corresponding to the freestream wind speed V_0 , was imposed at the inlet section, the ambient pressure condition at the outlet. For the lateral boundaries, a *symmetry* condition is defined. In order to allow the rotation of the machine, the computational domain was divided in two regions, coupled together via a *sliding mesh* technique: a) the external domain b) a circular region, which includes the turbine blades and shaft, rotating at a constant rotational speed Ω .

The selected mesh refinement level and timestep were selected based on the experience of the authors on similar test cases and were verified to be compliant with the results of the sensitivity studies presented in [21] and particularly with the thresholds for the dimensionless vorticity and the

Courant number proposed in [23]. An unstructured mesh, composed by triangular elements, was adopted for the whole domain, progressively refining towards the rotor region. In order to properly capture the development and mixing of the wake behind the rotor, an ad hoc drop-shaped refinement region was defined, as shown in Figure 2a. For the blade discretization on the other hand, an O-grid of quadrilateral elements was used, as visible in Figure 2b, so that the boundary layer around the airfoil could be adequately resolved. Complying with the requirements of the $k-\omega$ SST turbulence model, the size of the wall-adjacent cell was dimensioned to guarantee a dimensionless wall distance (y^+) lower than ~ 1 . In order to increase the accuracy of the analysis, two different spatial and temporal discretization strategies were selected for the turbine operating conditions under consideration, namely TSR=2 and TSR=4.5. An overview of the main settings is reported in Table 2. It is worth noting how, due to the inherently unstable nature of the blade flow at that operation point, characterized by large-scale vortex shedding on a considerable portion of the rotor revolution, a considerably higher resolution was adopted around the airfoil for TSR=2.

Pitching airfoil model

At the core of the inverse procedure, used in this study for the selection of the proper AoA sampling method (see Section 2.4), stands a dedicated pitching airfoil CFD model. As shown in Figure 3, the corresponding computational domain is separated into two parts: an external bullet-shaped region and an internal circular one, containing the airfoil under testing. The adoption of a *sliding interface* allows the rotation of the latter, whose angular position can be varied during the simulation according to a specific user-defined profile. Considering a uniform freestream velocity V_0 at the inlet, such feature can be exploited to impose a generic angle of attack history to the airfoil under consideration. If the latter is sampled from the CFD flow fields coming from a full rotor simulation via a dedicated method, this strategy can be extended to VAWT analysis, allowing to evaluate the turbine blade azimuthal lift and drag profiles, which will be eventually used to reconstruct the corresponding rotor forces. As it will be further discussed in Section 3.4, the main limitation of the proposed model is that, since the flow velocity imposed at the inlet is constant over

time, it is not able to account for the blade Reynolds number fluctuations occurring in the real machine. This loss of accuracy is particularly relevant when simulating the *downwind* rotor region at the high TSRs, where the incoming flow is slowed down by its interaction by the *upwind* one [13].

The CFD model used for the present study is based on the solution of the two-dimensional unsteady Reynolds Averaged Navier Stokes equations (*U-RANS*), exploiting for the closure of the turbulent problem the *Transitional $\kappa\text{-}\omega$ SST (Shear Stress Transport)* model. Originally developed for a NACA0021 profile, it has been thoroughly validated in both static and dynamic conditions, i.e. sinusoidal pitching movement at a reduced frequency $f=0.05$ [24]. Benchmark for the comparison were the experimental data collected in the wind tunnel of the Hermann-Föttinger-Institute (HFI) of the TU Berlin. For both analyses, a chord-based Reynolds number of 180k and a range of AoA between -30 and +30 degrees were considered.

The computational domain has an *open field* configuration, with an overall extent of $L=60c$ and a width of $W=40c$ to avoid blockage effects (see Figure 3). At its boundaries, the standard far field boundary conditions for external flows are applied: uniform velocity at the inlet boundary, ambient pressure at the outlet one. The blade surface is modeled instead as smooth no-slip wall.

For its discretization, an unstructured, triangular mesh was employed. In order to optimize the overall number of mesh elements and their distribution, local refinements were applied in proximity of the airfoil and its wake (see Figure 4a). As clearly visible in Figure 4c, an O-grid of quadrilateral elements was used around the blade boundary layer: the size of the wall-adjacent cell is able to guarantee a value of the dimensionless wall distance (y^+) lower than ~ 1 , while the total number of layers is 40. The resulting mesh presents a fairly high quality, with an average skewness of 0.14 and orthogonality of 0.95. For further details about mesh definition and sensitivity analysis, please refer to [24]. The simulation timestep on the other hand was selected to be consistent with the turbine operating point under consideration (please refer to Table 3).

2.3 Extraction methods for angle of attack

Different methods have been developed over the years for the extraction of the angle of attack on wind turbine blades, either from numerical (CFD) or experimental flow field data [25]. As discussed, the critical issue in doing so is the correct probing of the relative speed, which one has to use as a reference. The majority of available approaches, originally developed for horizontal-axis wind turbines (HAWTs), and only in some cases adapted to VAWTs [20], are based on the use of one or several sampling points to gather information about the velocity field around the airfoil. Both the original proposal from Shen et al. [26] and their following improvement [27] for instance use one point in front of the airfoil, for then correcting the sampled velocity to account for lift-related induction effects. Same strategy is followed in Herráez et al. [28], where the induced velocity contribution is filtered instead by locating the reference point on the bisectrix between two adjacent blades. More complex strategies use either multiple points along the turbine blade, such as the 3-Points [18] and the *LineAverage* methods [19], or along the turbine swept area, i.e. the AAT [29]. Recently, an ad hoc sampling procedure has been developed for VAWTs [30] and applied to the variable pitch optimization of a test turbine.

From sampled field data, the so-called undisturbed velocity $\vec{V}$ is obtained, which is then combined with the turbine peripheral speed ΩR to compute the angle of attack α on the blades:

$$\alpha = \text{atan}\left(\frac{-V_n}{V_t}\right) = \text{atan}\left(\frac{-V_x \sin \theta + y \cos \theta}{-V_x \cos \theta - y \sin \theta - \Omega R}\right) \quad (1)$$

where Ω is the turbine rotational speed, R is the turbine radius and θ the blade instantaneous azimuthal position. Conventions and notations adopted for the current study are presented in Figure 5. Although the arrangement of these points varies from one method to the other, it is always based on a two-dimensional modelling of the flow on the airfoil. Consequently, they tend to lose coherence when the flow becomes inherently three-dimensional, i.e. near the blade tip or under massive flow separation [31]. If this represents a minor problem in HAWTs, where these issues are limited to the root and tip sections of the blade [25], it becomes of paramount importance when the focus is shifted

on VAWTs. As anticipated in section 1, in fact the blades of these machines are usually subject to large AoA oscillations, which in some parts of the rotor revolution largely exceed the static stall limit. On top of that, the majority of small VAWTs are characterized by blades with low aspect ratio, so that the influence of the tip three-dimensional flow is extended to a major part of their span.

Starting from these considerations, the following approaches were selected from the literature and adapted for this study to work with VAWTs: the *3-Points*, *Line Average* and *Trajectory* methods.

3-Points method

Originally developed by Rahimi et al. [18], and then further fine-tuned by the same authors in [25] to study the behavior of horizontal-axis turbines in yawed flow conditions, the 3-Points method exploits six points in total, three on the suction side and three on the pressure side of the blade, to extract the AoA information from the flow field. As shown in Figure 6a, for each side of the airfoil, the three points are located at a distance of $0.25c$, $0.5c$ and $0.75c$ in the chord-wise direction starting from the leading edge, approximately $1c$ away from the blade aerodynamic center in the normal direction.

The extraction of the AoA occurs in two main steps: 1) at each station along the chord, the average velocity vector is computed from the values sampled in the corresponding couple of points, via an ad hoc interpolation function; 2) the undisturbed velocity vector $\vec{V}$ is computed as the arithmetic average of the velocities coming from each station, as shown in equation (2):

$$\vec{V} = \frac{\vec{V}_I + \vec{V}_{II} + \vec{V}_{III}}{3} \quad (2)$$

According to [25], such strategy should be able to reduce the influence of bound circulation, together with the effects of upwash and downwash, over the measured incoming velocity. Furthermore, unlike other methods that have been developed for HAWTs, the 3-Point approach

should be able to account for instantaneous velocity oscillations on the turbine blades, thus allowing one capturing also dynamic effects.

Line-Average method

The Line Average method (LineAve) has been introduced by Jost et al. [19], in the attempt of increasing the accuracy of previously available methods in capturing the effects of shed and trailing vorticity on the measured angle of attack on turbine blades. To this end, the undisturbed velocity $\vec{V}$ is computed as the integral average of the flow velocity field along a closed line around the airfoil (see Figure 6b). According to the creators of the method, this sampling strategy should be able to completely remove the effect of bound circulation on the local inflow velocity, since in the averaging process the induced velocity components on any pair of opposite points on the closed path are levelled out, still accounting for the net distortion associated to trailing vorticity. This feature is particularly useful when modelling the flow around the blade tip. Nevertheless, since the method always includes the wake behind the profile, it might yield an unstable AoA trend when working in stalled conditions.

In the present study, in particular, it has been chosen to use a circular sampling line, centered in the aerodynamic center of the airfoil (assumed as the quarter-chord) and with a radius $r=1c$. According to [19], this configuration yields the best performance in terms of AoA sampling accuracy. Regarding the sampling resolution, two different configurations were tested, as shown in Figure 6b: a low-resolution (points #, $N=6$) and high-resolution (points #, $N=80$) ones.

Trajectory method

The Trajectory method is an adaptation by Bianchini et al. [20] to VAWTs of the approach proposed by Shen et al. [26], originally conceived for HAWTs. As shown in Figure 6c, the local inflow velocity is sampled in a single monitor point on the trajectory outlined by the rotating blade, at a specified distance upstream its aerodynamic center. In virtue of this strategy, the trajectory method is extremely easy to implement but, due to the lack of additional sampling points around the airfoil, it cannot provide any information about bound circulation and trailing vorticity. As a

consequence, a theoretical model must be embedded into the method to account for the local flow deformation induced by these phenomena. More in detail, the vorticity distribution around the blade is modelled as a concentrated point vortex located in its aerodynamic center and with a magnitude equal to the bound circulation Γ , that, according to the Kutta-Joukowski theorem, can be computed as in equation 3:

$$\Gamma = \frac{L}{\rho V_r} \quad (3)$$

where L is the lift force on the blade, ρ is the freestream flow density and V_r is the relative air speed with respect to the airfoil. The induction exerted by the blade circulation on the flow at the sampling point is then computed via the Biot-Savart law (equation 4):

$$V_{in} = \frac{\Gamma}{2\pi d} \quad (4)$$

being d the distance between the sampling point and the blade aerodynamic center. The undisturbed velocity $\vec{V}$ is obtained by subtracting the induced velocity vector $\vec{V}_{in}$ from the one sampled in the monitoring point $\vec{V}_s$:

$$\vec{V} = \vec{V}_s - \vec{V}_{in} \quad (5)$$

Once $\vec{V}$ is known, the angle of attack α is computed from Eq. 1. It must be noted that, since the lift force L is dependent on α , the procedure described so far must be applied in an iterative way. As demonstrated by Bianchini et al. [20], such correction strongly increases the robustness of the method, making the computed AoA almost independent from the sampling point position. Following the guidelines proposed in the same study, a distance of $1c$ between the sampling point and the blade quarter-chord is adopted for the current work.

2.4 Turbine forces reconstruction procedure

As anticipated in Section 1, an ad hoc inverse procedure was developed to assess the accuracy of the tested AoA sampling methods. The proposed strategy exploits the pitching CFD airfoil tool

described in Section 2.2 as an equivalent model of the original VAWT rotor, which is able to evaluate the blade loads profile as a function of the input AoA history. If the pitching motion law is imposed to be equivalent to the trend of the relative incidence “seen” by the VAWT blade during one revolution, then it becomes possible to have an estimate of the turbine blade lift and drag coefficients azimuthal profiles. Since the input AoA history is directly extracted from the full rotor CFD flow fields via the selected sampling methods (see Section 2.3), the resulting force coefficients can be used either as a direct benchmark for comparison, or to reconstruct the corresponding aerodynamic forces trend over one rotor revolution. Once each tested AoA sampling method has been assigned its respective blade forces dataset, it is straightforward to compare it to the one computed with the original CFD model of the turbine, obtaining as a result the relative accuracy of the different sampling approaches under study. A detailed view of the corresponding workflow is shown in Figure 7.

More specifically, the following steps can be identified:

a₁) the AoA azimuthal profile coming from the selected sampling method is given as rotation profile in input to the pitching CFD model;

a₂) the V_r azimuthal profile coming from the selected sampling method is averaged and then applied as uniform value at the computational domain inlet;

b) the “Darrieus-like” pitching airfoil CFD simulation is run until periodic convergence is reached;

c) the resulting lift and drag curves as a function of AoA are combined with the available AoA and V_r profiles as a function of the azimuthal position to evaluate the corresponding normal and tangential forces acting on the blade, as if it was mounted on a Darrieus rotor.

It must be noted how, before being used in the pitching CFD model, the turbine blade had been conformally mapped in an equivalent cambered airfoil. This procedure is necessary to take into account the flow curvature effects characterizing the profile when rotating in VAWT motion, as demonstrated by [16].

3. Results

In this section, the main outcomes of the current study are presented. After a brief section about the turbine CFD model validation against experimental data, the AoA azimuthal trends deriving from the different sampling methods under consideration are compared and commented. In order to better support the discussion, the lift and drag coefficients hysteresis loops, obtained by combining the extracted AoA trends with the computed CFD rotor forces, are also presented. Eventually, the selection process of the optimal AoA sampling method, based on the proposed inverse verification procedure, is described.

3.1 Turbine model validation

As one may argue, the essential first step of the work was to assess the reliability of the developed CFD model of the turbine, since the relative data will be used as a surrogate of experiments to feed the developed procedure. This was done by comparing the computed blade forces and flow fields surrounding the rotor with the ones available from experimental data (see Section 2.1).

Figure 8 reports the comparison in terms of normal force F_N , in this case normalized over the freestream momentum $q_\infty = 0.5\rho V_0^2$ and the turbine radius R , between numerical and experimental data over one rotor revolution. Fairly good agreement is apparent at both TSRs, especially in the upwind region ($0^\circ \leq \theta \leq 180^\circ$), while in the downwind region ($0^\circ \leq \theta \leq 360^\circ$), probably due to the disturbances associated to the blade shed vorticity and the presence of the shaft (see Figure 9), the CFD curve tends to slightly deviate from experimental points. The same degree of matching, at least from a qualitative point of view, can be observed between the experimental and numerical flow fields shown in Figure 9. Both the experimental axial velocity and vorticity fields are well reproduced by CFD, although the predicted wake appears to be narrower and less deflected than the measured one. Overall, the fair agreement between the two approaches justified the adoption of the developed tool for the analysis of the angle of attack on the rotor blades, which is presented in Section 3.2.

3.2 Trends for the angle of attack

The different methods outlined in Section 2.3 were then applied to the CFD data, in order to reconstruct the corresponding AoA trend along one rotor revolution. The analysis was repeated for the same two turbine operating conditions, i.e. TSR=2 and TSR=4.5. The comparison is reported in Figure 10 and Figure 11, respectively.

Upon examination of Figure 10, fairly good agreement in terms of AoA between the tested methods is observed for low blade load conditions, i.e. for $\text{AoA} \leq 5^\circ$. When the angle of attack further increases up to the static stall limit ($\text{AoA} \approx 10^\circ$), the different curves start diverging one from the other. The overall deviation, however, remains limited to a few degrees. Conversely, as the static stall limit is largely exceeded, the scattering between the various curves grows exponentially, leading to deviations larger than 10° in the most critical conditions (e.g. $\theta=100^\circ$, TSR=2). In particular, the *Trajectory* method is the one predicting the highest AoA values, followed by the *LineAverage* and *3-Points* ones. Such phenomenon, which has already been identified by Rahimi et al. [25], can be understood by recalling the theory underlying the formulation of the adopted methods.

All of them are in fact based on the two-dimensional inviscid airfoil circulation theory [32], which assumes that the local flow around the blade can be interpreted as the superposition of the freestream and a free-vortex flow, which in turn depends on the intensity of the circulation Γ on the profile (see Equations (3) and (4)). As long as this condition holds, i.e. viscous phenomena are confined to the narrow region in the airfoil boundary layer and wake (*attached flow*), the different methods maintain a fair coherence one with the other. This occurs in a certain measure for TSR=4.5. On the contrary, when the static stall angle is exceeded, massive separation occurs on the airfoil surface. The circulation around the blade, as well as the overall vorticity distribution, are disrupted by the growth of the suction side boundary layer or, in case of dynamic stall, by the shedding of vortexes. For this reason, when applied to a critical rotor operation such as that at TSR=2, these methods become extremely sensitive to the arrangement of the monitoring points. The stall phenomenon has notable implications for the *3-Points* and *LineAverage* methods, in virtue of their characteristic sampling

scheme. For a specific angular position of the blade, some sampling points in fact might fall in the separated region on the airfoil suction side, introducing a relevant bias in the extracted AoA value. The main consequence is the onset of the severe oscillations observed in the corresponding AoA trends, as shown in Figure 10a. If the extent of such irregularities is limited for the *3-Points* approach, although not negligible, it becomes extremely relevant for the *LineAverage* method, due to the higher number of sampling points falling in the airfoil wake. As apparent from Figure 10, this holds for both N=6 and N=80 configurations, which differ one from the other only for a limited number of singularities. For further details, please refer to [33].

3.3 Sampled trends for the lift and drag coefficients

Before the inverse verification procedure, based on the pitching airfoil CFD model, could be performed, the available normal and tangential blade forces data were decomposed along the lift and drag directions, thanks to the availability of the AoA trends reported in Figure 10, to assess the corresponding lift (C_L) and drag (C_D) coefficients over one rotor revolution. It must be noted that the *LineAverage* method with N=6 has not been included in this analysis, since the scarce definition of the sampled trends does not allow its adoption in technical applications.

In Figures 12 and 13, the computed aerodynamic coefficients are plotted against the corresponding angle of attack for TSR=2 and TSR=4.5, respectively. For both operating conditions, the attended experimental static polar data for the airfoil at Re=150k [34], which is the average Reynolds number of the test turbine blade for TSR=4.5, are also reported as reference. It has to be noted that these data do not correspond to those of the “geometrical” NACA0018 airfoil, but to a virtual one cambered by the same revolution radius of the trajectory followed onboard the Darrieus turbine. As discussed, this procedure was made to account for the virtual camber effect characterizing airfoils in cycloidal motion [34]. In order to improve the readability of the graphs, the points that were considered to be unphysical, i.e. deriving from bias errors of the AoA extraction method, or associated to dynamic effects, were represented as point clouds or discontinuous lines. This is the case for instance of the

AoA values sampled in the deep stall region (see Figure 12). Furthermore, the curve branch corresponding to the turbine shaft wake region was removed.

For $TSR=2$, a heavily hysteretic behavior of the lift and drag coefficients can be observed over the whole rotor revolution. Although at this operating condition the influence of the blade Reynolds number variation during rotation cannot be neglected, this phenomenon can be mainly related to the onset of dynamic stall. As the AoA is raised beyond the static stall limit ($AoA \approx 15^\circ$), the lift coefficient keeps increasing until it reaches a maximum value, which is way higher than that allowed in static conditions. From a physical point of view, this corresponds to the formation of the leading-edge vortex on the airfoil suction surface (see Figure 14a) [35]. When such vortex is shed away from the profile, the lift coefficient drops down to values much lower than the static ones, while an opposite trend is observed for the drag coefficient, which reaches its maximum value. This condition holds for the whole lower branch of the hysteresis loop, i.e. when the AoA is lowered until returning to the starting point.

Upon examination of Figure 12, it can be observed how the phenomena described so far are well captured by all tested methodologies, which nonetheless deviate one from the other due to the scattering already encountered in the corresponding AoA trends (see Section 3.2). Once again, such dispersion is quite limited in the pre-stall region, while it becomes extremely relevant in the deep stall one; both the extension and the shape of the post-stall hysteresis loop change dramatically from one method to the other, making the selection of the proper approach crucial when analyzing highly unstable turbine operating conditions such as $TSR=2$. Nonetheless, the data gathered so far are not sufficient to derive a rigorous selection criterion, at least for this operating point.

A clearly hysteretic behaviour of the lift and drag coefficients is also observed for $TSR=4.5$ (see Figure 13), although with a much lower extent than for $TSR=2$. In this case however, since the AoA oscillation is contained in the static stall limit, such trend cannot be attributed to dynamic stall, but rather to an inherently inviscid phenomenon. In strongly unsteady conditions, i.e. elevated reduced frequencies, as those experienced by VAWT blades in fact, inertial effects introduce a *delay* of the

flow incidence on the blades with respect to their angular position, leading to an effective AoA which is different from the expected one [24]. This distortion can be clearly observed in Figure 15, where the blade surface stress field is reported for the same sampled angle of attack ($\text{AoA}=3.1^\circ$), but two different motion conditions, i.e. upwind pitch-up ($0^\circ \leq \theta \leq 100^\circ$), and pitch-down ($100^\circ \leq \theta \leq 180^\circ$). In pitch-down conditions in particular, the blade experiences a higher effective AoA, i.e. aerodynamic loading, than in the pitch-up one: the corresponding pressure difference between the airfoil suction and pressure sides is larger, as well as the separated region at the trailing edge. The extension of the latter is easily identified in Figure 15b from the position of the separation point, i.e. where the flow skin friction coefficient drops to zero [32].

In contrast with $\text{TSR}=2$, for $\text{TSR}=4.5$ relevant information regarding the proper method selection can be already inferred from the data derived from the previous AoA analysis. It must be noted that the following considerations refer to the *upwind* rotor region, i.e. for positive values of AoA, since the blade behavior in the *downwind* one is biased by its interaction with the vorticity shed by the upwind blades and shaft [36]. Therefore, no rigorous comparison with the available experimental polar database can be performed.

As clearly visible from the lift and drag curves in Figure 13, the *LineAverage* approach is the one showing the highest agreement with the reported experimental static data. Such matching occurs in terms of both average trends, i.e. considering the average curve between the upper and lower branches of the sampled hysteresis loops, and maximum value. This is particularly evident for the drag curve in Figure 13b, apart from small deviations related to experimental and numerical uncertainties. The *Trajectory* method instead presents two main issues: on the one hand, it suffers from the same discontinuities encountered in AoA trends (see Section 3.2), while on the other hand it tends to largely overestimate both lift and drag values over the whole range of AoAs under consideration. If this deviation is still contained for the C_L loop, at least for lower values of angle of attack ($\text{AoA} \leq 7^\circ$), it becomes extremely relevant for the sampled C_D curve, which starts diverging, always in average terms, from the experimental one already at $\text{AoA} \approx 5^\circ$ (see Figure 13b). The observed deviation is

maximum for $AoA \approx 10^\circ$, with a C_D value approximately double of the static one. Finally, the *3-Points* is the one yielding the least accurate results among the tested methods. Upon examination of Figure 13b, it can be seen how the sampled drag loop not only deviates significantly from the experimental airfoil data, but, as the AoA is raised beyond 4° , shows an inherently unphysical behavior. In contrast with what is commonly observed, sampled C_D decreases with increasing AoA , reaching for a small section of the lower branch ($4^\circ \leq AoA \leq 7^\circ$) even negative values. Such phenomenon might be understood based on the procedure adopted for the calculation of C_L , C_D from sampled AoA values. At given normal and tangential blade forces, an underestimation of the AoA in the pre-stall region results in an underrated lift component in the tangential direction and, correspondingly, in an excessive lift component in the normal one. In order to maintain the coherence of input blade loads, the calculated drag force results in a reduced magnitude, reaching even negative values when the defect is too high.

3.4 Trends for reconstructed blade forces

In order to verify in a rigorous way the relative accuracy of the tested AoA sampling methods, the blade normal and tangential forces azimuthal profiles were reconstructed from the collected AoA trends (see Section 3.2) via the inverse procedure detailed in Section 2.4. The latter was applied to the *LineAverage* and *3-Points* approaches only, whilst the *Trajectory* one, due to the discontinuity issues already encountered in Sections 3.2 and 3.3, could not be tested.

Figure 16 shows the lift and drag coefficients profiles deriving from the performed pitching airfoil simulations. In contrast with their sampled counterparts (see Figure 13a), the reported C_L trends are fairly coherent one with the other and aligned, in average terms, with the experimental static data. The only deviation between the two curves is the considered AoA range, which is wider for the pitching law derived from the *LineAverage* method. As for the data sampled from the VAWT CFD flow field, both lift loops are characterized by a notable hysteresis. Considering that the adopted pitching model does not include in its formulation the influence of blade Reynolds variation (all

simulations were in fact carried out at constant inlet flow velocity), this confirms the influence of dynamic effects on the blade behavior (see Section 3.3). Such assumption is further supported by the fair agreement shown by the sampled and pitched blade pressure fields, reported in Figure 17 for the *LineAverage* method at $AoA=3.1^\circ$. It is apparent in fact how the deviation in terms of blade loading experienced by the turbine blades between the pitch-up and pitch-down phases presents the same characteristics in both datasets.

The same consideration made for the lift coefficient can be made for the drag one. In this case, nonetheless, the pitched hysteresis loops tend to be overestimated, in terms of cycle amplitude and average value, with respect to sampled and static data (see Figure 18b). This could be related to the intrinsic limitations of the adopted CFD model in reproducing the behavior of airfoils in VAWT-like motion, in particular the aforementioned Reynolds number oscillation experienced by the blades over one rotor revolution. Apart from these minor uncertainties though, the aerodynamic coefficients trends predicted the pitching CFD model were considered sufficiently accurate to be used as the benchmark for the selection of the proper AoA sampling method.

Upon examination of Figure 18, where the sampled lift and drag coefficients resulting from the post-processing of the Darrieus turbine results are compared with the pitched ones, the preliminary considerations made in Section 3.3 can be confirmed. The lift curve obtained by the *3-Point* sampling starts losing coherence with respect to its pitched counterpart already for $AoA \geq 4^\circ$, overestimating the corresponding blade loading values. Once again, the sampled drag profile tends to deviate from the pitched one in an inherently unphysical way, reaching its minimum at the maximum angle of attack ($AoA \approx 8^\circ$). These discrepancies are reflected on the reconstructed normal and tangential forces profiles, which, as apparent in Figure 19, present a significant deviation from the ones coming from the validated VAWT CFD model. Such discrepancy is particularly pronounced for the tangential component (see Figure 19b), with an observed underestimation of the peak value of approximately 34% with respect to the VAWT CFD results ($\theta=100^\circ$). Shifting the focus to the *LineAverage* approach instead, it is possible to recognize from Figure 18 a fair agreement between the pitched and sampled

data. The lift curves are fully coherent one with the other, except for a small deviation in the ascending branch of the loop at high angle of attack ($7^\circ \leq \text{AoA} \leq 10^\circ$). The adopted pitching CFD model tends nonetheless to overestimate the blade drag coefficient, especially in the ascending branch of the hysteresis loop, leading to an underestimation of the reconstructed tangential force with respect to the actual VAWT's one over the whole rotor revolution. From a perusal of Figure 19b, it can be noted that this difference is particularly marked in the first half of rotor upwind revolution ($0^\circ \leq \theta \leq 100^\circ$), reaching its maximum at the peak torque point. The VAWT normal force conversely is almost perfectly matched by the reconstructed one (see Figure 19a).

Finally, the *Trajectory* method is once again the one predicting the highest C_L and C_D values, especially for high angles of attack. Such phenomenon is particularly evident from Figure 18a, where, apart from differences in the predicted AoA range, the sampled lift curve tends to deviate from the pitched *LineAverage* one already for $\text{AoA} \geq 4^\circ$ in the ascending branch of the curve, for then largely overestimating it in the descending one. At a first glance, this seems not to be the case for the drag curve (see Figure 18b), since the sampled and pitched loops present a fair agreement, at least in average terms. Nonetheless, since it has been seen that the pitching CFD model tends to overpredict the drag force with respect to experimental data, this is a further confirmation of the tendency of the *Trajectory* approach to overestimate both aerodynamic coefficients.

4. Prospects and discussion

Based on the presented results, the *LineAverage* has proved to be a reliable and robust approach for the computation of the angle of attack on airfoils in cycloidal motion from a resolved velocity field, whether experimental or numerical. Before being recommended as a general methodology though, its range of applicability has to be discussed and, if needed, verified, by extending the verification procedure proposed in this study to other rotor configurations and operating points. The

reader should also remember that, beyond the selection of the *LineAverage* method for velocity sampling, the accuracy of the overall procedure for the determination of the AoA relies on the two key elements of flow curvature correction [34] and overall airfoil polar data quality [37].

According to the original study by Jost et al. [19] and the later comparative work of Rahimi et al. [25], the *LineAverage* provides sufficiently accurate results for a wide variety of airfoils shapes and dimensions, as those encountered in large HAWTs blade design. In both studies, in particular, the DTU 10 MW reference turbine [38] was considered, characterized by a blade thickness t/c ranging from ca. 0.6 at root to 0.24 at tip. Its application is nonetheless limited to operating conditions, in which the predicted AoA range is contained within the static stall threshold. The reliability of the method in fact has not been verified for massively separated flows yet. Furthermore, as described in Section 3.2, its stability is undermined when working in stalled conditions, due to the sampling of the velocity distortion in the airfoil separated wake.

The extension to vertical-axis machines performed in the present study confirmed the validity of the method under the aforementioned assumptions. The selected test case has proved to be the ideal starting point for the verification of the approach. Thanks to the machine low solidity in fact, together with the availability of high-fidelity experimental data for a stable operating point such as TSR=4.5, it has been possible to understand how the proposed sampling strategy performs in the case of "isolated" rotating airfoil, i.e. in absence of significant second-order aerodynamic effects such as blade-to-blade or blade-to-wake interaction. Also, the unique possibility of having an experimental validation of CFD by dedicated experiments was considered key to assess the method, since it represents the evidence that the physical phenomena under analysis are the ones really taking place past the considered rotating blades. Obtained results also justify the adoption of the *LineAverage* for the analysis of Darrieus rotors larger than the considered test case but characterized by the same solidity. For medium-to-high solidity machines on the other hand, i.e. designed with a number of blades higher than two and/or higher blade chord-to-radius ratio, the approach applicability must be verified in dedicated studies, by applying the procedure described in the present work. In this case in

fact, the flow field around one blade might be distorted by its interaction with the other ones, thus undermining the assumptions that lie beneath the sampling method construction.

5. Conclusions

The scope of the present study was to define a robust procedure to extrapolate the angle of attack of the flow oncoming an airfoil in cycloidal motion from a CFD-computed flow field. More specifically, a combined experimental and numerical approach was used to finally solve the issue related to the probing of the relative speed, which was up to now affected by a certain degree of arbitrariness in existing methods.

To this end, an *ad hoc* unsteady CFD model of a test turbine has been developed and validated with PIV experimental data collected by estimated colleagues. The corresponding numerical flow fields have been then post-processed with three different methods, so that the angle of attack could be reconstructed along one rotor revolution.

The resulting AoA trends showed a non-negligible sensitivity with respect to the selected method, especially for AoA values approaching and exceeding the static stall limit. The maximum scattering has been observed for deep stall conditions, as the ones encountered for a large part of the rotor revolution at TSR=2. Such phenomenon is particularly pronounced for the methods that sample the local velocity in the wake, such as the *3-Points* and the *LineAverage* ones, due to their interaction with the vorticity shed by the airfoil.

Eventually, the obtained AoA trends were combined with the available CFD blade forces data to evaluate the corresponding lift and drag coefficients over one rotor revolution. The resulting curves were compared to the ones coming from an *ad hoc* inverse procedure, based on the calculation of aerodynamic coefficients via an equivalent pitching airfoil CFD model. In this way, the relative accuracy of the selected approaches in computing the blade angle of attack could be assessed.

For the unstable turbine operation ($TSR=2$), the *Trajectory* method is the only one presenting a stable behavior, since, unlike the *3-Points* and *LineAverage* ones, none of its sampling points fall in the vorticity shed by the airfoil. Nonetheless, since the verification procedure has not included this operating condition, nothing can be concluded on the accuracy of the sampled AoA.

Focusing on the stable turbine operation ($TSR=4.5$), for which reliable comparative data were available only, the *Trajectory* approach presented severe discontinuities for AoA values near zero. This is probably related to lack of convergence in those conditions. From an accuracy point of view, it has been shown how this method tends to overestimate the angle of attack over the whole rotor revolution, leading to lift and drag values higher than those predicted by other schemes and static experimental tests. Nonetheless, the verification procedure with experiments could not be applied, due to discontinuity issues, no further consideration can be made. The *3-Points* method, on the other hand, has shown the lowest accuracy among the tested ones, strongly underestimating the blade AoA. This has reflected on completely unphysical trends of the sampled aerodynamic coefficients, with the drag one reaching negative values at the maximum blade loading.

Finally, the *LineAverage* approach has proved to be the most accurate method when dealing with stable turbine operation ($TSR=4.5$), with the highest degree of agreement not only between sampled and pitched aerodynamic coefficients, but also between reconstructed and simulated blade forces. For the reasons above, its application to VAWT analysis is strongly recommended by the authors in combination with the consolidate procedure for AoA reconstruction based on the virtual cambering correction.

6. Nomenclature

Acronyms

590	AoA	Angle of Attack	
591	BEM	Blade Element Momentum	
592	CFD	Computational Fluid Dynamics	
593	PIV	Particle Image Velocimetry	
594	SST	Shear Stress Transport	
595	TSR	Tip-Speed Ratio	
596	U-RANS	Unsteady Reynolds-Averaged Navier-Stokes	
597	HAWTs	Vertical Axis Wind Turbines	
598	VAWTs	Vertical Axis Wind Turbines	
599			
600	<u>Greek symbols</u>		
601	α	Angle of Attack (symbol)	[deg]
602	ϑ	Azimuthal Angle	[deg]
603	Γ	Blade Bound Circulation	[m ² /s]
604	ρ	Flow Density	[Kg/m ³]
605	σ	Turbine Solidity	[-]
606	ω	Specific Turbulence Dissipation Rate	[1/s]
607	Ω	Revolution Speed	[rad/s]
608			
609	<u>Latin symbols</u>		
610	c	Blade Chord	[m]
611	C_D	Drag Coefficient	[-]
612	C_L	Lift Coefficient	[-]
613	D	Rotor Diameter	[m]
614	F_N	Blade Normal Force	[N]
615	F_T	Blade Tangential Force	[N]

616	k	Turbulent Kinetic Energy	$[m^2/s^2]$
617	R	Rotor Radius	$[m]$
618	Re	Reynolds Number	$[-]$
619	V	Undisturbed Wind Speed	$[m/s]$
620	V_0	Freestream Wind Speed	$[m/s]$
621	V_r	Blade Relative Wind Speed	$[m/s]$
622	y^+	Dimensionless Wall Distance	$[-]$

623 **7. References**

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