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Implementation of the “Virtual Camber” Transformation into the Open Source Software QBlade: Validation and Assessment

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Abstract

Thanks to the renewed interest in vertical-axis wind turbines, research efforts are devoted at improving the accuracy of present simulation tools, many of which are underdeveloped if compared to those for horizontal-axis turbines. In particular, recent studies demonstrated that a correction for the “virtual camber” effect has a major impact on the simulation. In cycloidal motion indeed the blade aerodynamics are equivalent to those of a virtually-transformed airfoil with a camber line defined by its arc of rotation. In this study, the implementation of a specific module to account for the virtual camber effect in the Open-Source code QBlade is presented. The effectiveness of the model is then validated by four 1-blade and a full 3-blade H-Darrieus turbines, for which both experimental measurements and detailed CFD calculations were available. A sensitivity analysis on the impact of the virtual camber correction on the accuracy of a low-order simulation model has been carried out as a function of the chord-to-radius ratio and the airfoil thickness-to-chord ratio. Reference thresholds for the model applicability are presented for both variables.

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Keywords: Darrieus; wind turbine; virtual camber; lifting-line; CFD; simulation.

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Nomenclature

α	angle of attack, deg
β	pitch angle, deg
ϑ	azimuthal position of the blade, deg
c	blade chord, m
c_P	power coefficient
g,v	geometric, virtual (in superscripts and subscripts)
h	airfoil thickness, m
k	distance of the mounting point from the leading edge, m
p, q, x, y	coordinate axes in airfoil transformation
R	turbine radius, m
w	relative speed on the airfoil, m/s
HAWT	Horizontal Axis Wind Turbine
TSR	Tip-Speed Ratio
VAWT	Vertical Axis Wind Turbine
VC	Virtual Camber
*	non-dimensional

1. Introduction

After a long absence from research agendas, Darrieus Vertical Axis Wind Turbines (VAWTs) are being re-discovered presently [1], after the research stalled in the mid 90's in favor of Horizontal Axis Wind Turbines (HAWTs), which were adopted as the standard by the industry emerging at that time thanks to the higher power coefficients and the much better capability of self-starting even in low-speed winds. In particular, Darrieus VAWTs are presently identified as suitable for new installation contexts such as complex or built terrains [2] or offshore floating platforms [3], thanks to some inherent advantages (independence on wind direction, generator positioned on the ground, low noise emissions, good performance in misaligned flows [4]). Due to the lack of a systematic research in past years, however, there is a significantly lower number of design and certification tools available, many of which are underdeveloped if compared to the corresponding tools for HAWTs. If Computational Fluid Dynamics (CFD) techniques are rapidly diffusing in VAWT research, low- and medium-fidelity models (e.g. Blade Element Momentum theory [5] or the Lifting Line Free Vortex Wake method [6]) still represent an industry standard for the analysis of wind turbines. Whether used for a first rotor design or in coupled codes for the analysis of aero and other dynamics simultaneously, they are often used ahead of more advanced analyses due to their robustness and speed [7]. However, since these models do not physically model the blade-flow interaction, but they instead substitute it with lumped aerodynamic coefficients (i.e. lift, drag and moment coefficients), it is readily arguable that the accuracy of these latter are pivotal in order to ensure a good simulation accuracy [8].

Among the major aerodynamic effects that need to be modeled by selecting the proper aerodynamic polars, recent studies have demonstrated that the so-called ‘‘flow curvature effects” have a large impact on small Darrieus turbine performance [7]. These effects, caused by cycloidal motion of VAWT blades (i.e. a circular trajectory within a straight flow field), were first theorized by Migliore et al. [9], who showed that they can be modeled as a ‘‘virtual” blade camber and incidence, giving blade performance characteristics analogous to those of a cambered blade at incidence in a rectilinear flow [10]. In this study, the implementation of a specific module to account for the virtual camber effect in the Open-Source code QBlade is presented. The theoretical approach is described along with the main assumptions. The effectiveness of the model is then validated against two different study cases, i.e. a single NACA0018 in cycloidal motion and a full 3-blade H-Darrieus turbine, for which both experimental measurements and detailed CFD calculations were available from previous works. Moreover, the new code has been used to carry out a sensitivity analysis on the impact of the virtual camber correction on the accuracy of a low-order simulation model as a function of the chord-to-radius ration and the airfoil thickness-to-chord ratio. For both variables, reference thresholds for the model applicability are presented.

2. The “virtual camber” effect modeling

The analytic description of the “Virtual Camber” (VC) effect can be found in the work of Migliore [9] and is not reported here. However, the physical phenomenology is briefly recalled to make the reader familiar with it.

In the kinematic analysis of Darrieus turbines, it is standard practice to refer to conventional 1D aerodynamic conventions, i.e. to define the instantaneous blade relative speed and angle of attack (please refer to Fig.1(a) for the reference system) as those values occurring at the point of attachment of the turbine blade to its support arm, which is typically located near the aerodynamic center of the airfoil in order to minimize the impact of the pitching moment [11]. Actually, since the radial distance of any point on the blade chord is unique with respect to the axis of rotation, the relative velocity (w) and the angle of attack (α) are also unique at every point on the chord (Fig.1(b)). Upon examination of the above and referring to the equations derived in [9], it is apparent that the chordwise variation of w and α is dependent upon the azimuthal position of the blade (ϑ), the tip-speed ratio (TSR), and the blade chord-to-radius ratio (c/R). As hypothesized by [9], the last is most important, as it can be shown that flow curvature effects become more pronounced as c/R increases. To understand the effect of the above on the actual performance of the airfoils in motion, conformal mapping techniques can be used. By this method, the geometric airfoil in the cycloidal motion can be transformed into an equivalent virtual airfoil in rectilinear flow (Fig.1(c)). In doing so, local velocities and angles of attack are preserved in the process so that the transformed airfoil in an assumed rectilinear flow should exhibit the aerodynamic behavior of the geometric airfoil in Darrieus-like motion [9]. This main hypothesis has been recently proven by [7] by means of detailed CFD analyses. The main consequence of practical use for low-fidelity methods is that, if sectional airfoil data are available or can be generated for the virtual airfoil shape, the aerodynamic characteristics of the orbiting blade will be likely known [8]. The model developed for the QBlade software then follows the conceptual steps presented in Fig.2(a).

The main equations needed for the airfoil transformation are reported below, with the conventions reported in Fig.2(b-c). Following the original notations from Migliore (g=geometric, v=virtual) [9], p_g^g and q_g^g represent the geometric coordinate system made non-dimensional by the geometric chord; the origin of the coordinate system is set at the blade mounting point.

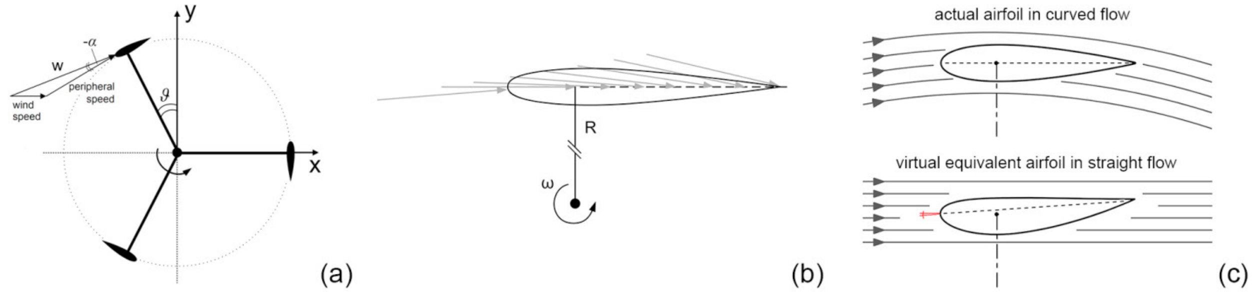

Fig. 1. (a) reference system; (b) local variation of w and α along the blade chord; (c) airfoil transformation due to flow curvature effects.

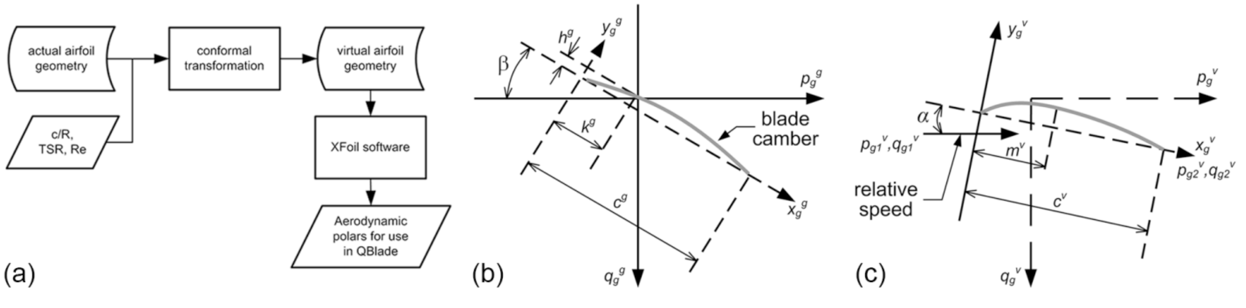

Fig. 2. (a) steps of the model; (b) parametrized original airfoil; (c) virtual airfoil after transformation.

In the simplified case of null pitch preset (β=0°), Eq. 1 reads (h^g is the original airfoil thickness, k^g is the distance of the mounting point from the leading edge):

$$\begin{cases} p_g^g = (x_g^g - k^g) \\ q_g^g = (y_g^g - h^g) \end{cases} \tag{1}$$

The virtual angle of attack (Eq.2) and the virtual over geometric chord ratio (c_v/c_g, Eq.2) can be then defined:

$$\alpha = \arctan\frac{(q_{g2}^v - q_{g1}^v)}{(p_{g2}^v - p_{g1}^v)} \tag{2}$$

$$\frac{c_v}{c_g} = \sqrt{(p_{g2}^v - p_{g1}^v)^2 + (q_{g2}^v - q_{g1}^v)^2} \tag{3}$$

The virtual airfoil coordinates can be then found by Eq.4:

$$\begin{cases} x_v^v = \dfrac{((p_g^v - p_{g1}^v)^2 \cdot \cos\alpha + (q_g^v - q_{g1}^v)^2 \cdot \sin\alpha))}{(c_v / c_g)} \\ y_v^v = \dfrac{((p_g^v - p_{g1}^v)^2 \cdot \sin\alpha + (q_g^v - q_{g1}^v)^2 \cdot \cos\alpha))}{(c_v / c_g)} \end{cases} \tag{4}$$

For additional details on the transformation equations, please refer to [9].

A relevant feature of the developed model is that the procedure depicted in Fig.1(c) is here repeated at each TSR investigated during the power curve calculation. This approach is the only one strictly correct, since the flow curvature effects are indeed not only dependent on the geometrical features of the rotor but also on the instantaneous revolution speed of the rotor itself. The repeated calculation of the polars - allowed by the inner integration between QBlade and the XFoil solver - of course increases the CPU cost of the calculation, but ensures much more accurate results that any other solver available up to now.

3. QBlade

QBlade [6] uses the Lifting Line Free Vortex Wake (LLFVW) method to calculate the rotor aerodynamics. A large benefit of using a free vortex wake simulation code over momentum balance based BEM codes that are common in engineering level wind turbine simulation tools, is that the wake is modeled in 3D, using the true rotor geometry, and no reduction of the problem into streamtubes is necessary. This simplifies the setup of the problem greatly, and increases the accuracy if large deflections of structural components, such as the rotor blades, occur during the simulation. Furthermore, as the "flow history" is contained in the 3D vortex representation of the wake, the LLFVW method is not limited to steady state solutions of the flow field but is also able to capture the aerodynamics forces and flow features under highly transient conditions with great precision [12]. Overall, vortex methods offer a physical sound representation of rotor aerodynamics with far less assumptions than the momentum balance based methods. These benefits come at a significantly higher computational cost, but in recent publications [6] it could be shown that, due to the ever growing processing power of modern PC's and by using massive GPU parallelization and adaptive wake element reduction techniques, running even full load calculations on a single workstation in a reasonable timeframe is feasible. In QBlade, the turbine blade is discretized into panels, to which the circulation is assigned from tabulated lift and drag airfoil data (that can be automatically calculated by the integration with the XFoil software [13]). The spanwise oriented Lifting Line at the blades is connecting the quarter chord positions of the panels. Chordwise oriented bound vorticity at the blades accounts for the circulation gradient in the spanwise direction. Blade struts are included in the model through aerodynamic panels for which only the drag influence is calculated. The wake is modeled through free vortex line elements that are convected with the local point velocities during every timestep. All point velocities in the model are calculated using a Biot-Savart kernel for the combined influences of all the vortex elements in the simulation setup. The employed Biot-Savart kernel is regularized using a vortex core model that also accounts for vortex viscosity and stretching. To reduce the calculation time per timestep, which scales proportionally to the square of the total number of vortex elements, the calculations are carried out in parallel on the GPU using the OpenCL framework. The Lifting Line Free Vortex Wake method in QBlade contains several techniques to model unsteady airfoil aerodynamics, including dynamic stall, and model to simulate flaps or other active flow control techniques [14].

4. Model validation and capabilities assessment

The new model for virtual camber corrections has been assessed by means of two test cases. The first one refers to the four different 1-blade rotors (Tab.1) that have been simulated via CFD in [7] and [15]. More precisely, assuming a ratio of the airfoil chord to the circle's radius of 0.114 and 0.25 (same chord, different radius), a standard NACA0018 airfoil was analyzed, along with the two corresponding conformally-transformed profiles. The second test case instead refers to famous the 3-blade rotor tested in the large wind tunnel of the Politecnico di Milano by [16], and recently simulated by CFD in [17]. For brevity reasons, no details on the CFD simulation strategy and settings can be reported here. The reader can refer to [7], [15] and [18] for more information.

Table 1. Case study 1: main features of the four tested rotors.

Turbine feature	Value	
Blade number	1	
Airfoil (geometric)	NACA0018/transformed	NACA0018/transformed
c/R	0.250	0.114
Wind speed	8 m/s	

Table 2. Case study 2.

Turbine feature	Value
Blade number	3
Airfoil (geometric)	NACA0021
c/R	0.167
Wind speed	9 m/s

Figure 3 first reports the comparison between the CFD simulations of the four rotors of Case Study 1 and the QBlade simulations of the same using the correction for virtual camber. To improve the readability of the results, homologous colors were given to the series which were supposed to match one to each other based on the virtual camber effect. In detail, a blade simulated using the coefficients of the NACA0018 is expected to behave like the virtual airfoil with outward camber (labelled as "transformed airfoil"), while using the coefficient of the transformed airfoil, the performance of a physically-built NACA0018 is expected.

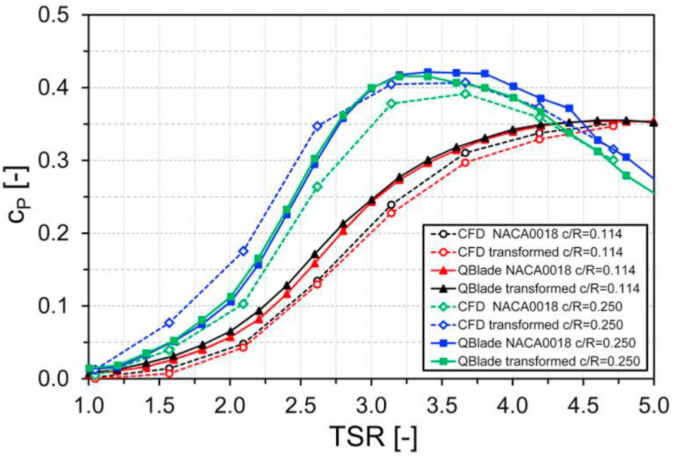

Fig. 3. Results of the four rotors of Case Study 1: CFD vs. QBlade with VC model.

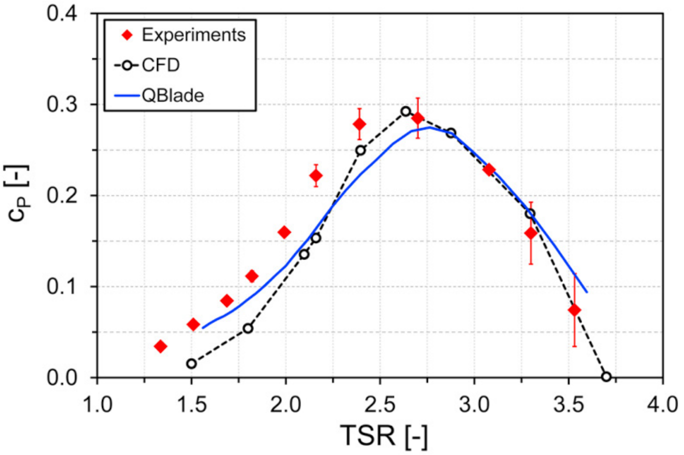

Fig. 4. Power curve of the 3-blade turbine of Case Study 2: experiments vs. CFD vs. QBlade with VC model.

Upon examination of Fig.3, it is apparent that, even if coming from a medium-fidelity modeling technique, QBlade predictions (run with no tip-loss model to fit the two-dimensional CFD) using the polar of the virtually transformed airfoil quite nicely fit the trend coming from the 2D CFD simulation, with agreement on both the peak values and the location of the maximum torque output. On the other hand, if the turbine is simulated with the polars of the "geometrical" airfoil, the agreement becomes poorer, confirming the need for the proposed model. It should be noticed that, as expected, the influence of the virtual camber effect is more evident for the higher *c/R* ratio. The second validation (Fig. 4) was instead carried out simulating the full 3-blade rotor of [16]. According to [17], in order to make the results directly comparable with experimental data, both CFD simulations and QBlade were corrected by purging them from the parasitic torque of the supporting struts that were present during the tests. Again, nice agreement was found between the QBlade simulations and both experiments and CFD data, corroborating the effectiveness of the software, completed by the virtual camber model, in predicting the aerodynamic performance of Darrieus wind turbines.

5. Sensitivity analyses

The validated model was then used to carry out a sensitivity analysis on the relative effect of VC on the accuracy of aerodynamic performance estimation. The three main parameters that have been investigated are the *c/R* ratio, the TSR and the airfoil thickness-to-chord ratio; this latter represents one of the main design choices in selecting a Darrieus symmetric VAWT blade. Three airfoils were considered, i.e. the NACA0012 (often used in the past for slender Darrieus blades), the NACA0018 (used in the 1-blade study cases) and the NACA0021 (used in the 3-blade study case). Using these three airfoils means that the following results should be interpreted as the relative error made by low- and medium-fidelity models (like QBlade) in predicting the aerodynamic performance of a rotor physically built with a symmetric airfoil, whenever the VC effect is neglected in the simulation. To more clearly stress this aspect, results have been reported in a non-dimensional form, i.e.: a) the TSR was reported as TSR*, i.e. it was divided by the TSR of peak performance. The two values at TSR*=0.5 and TSR*=1.5 then represent a working point in the unstable (left) part or in the stable (right) part of the operating curve, respectively; b) the power coefficient was reported as c_P*, i.e. it was divided by the power coefficient of the original (uncambered) airfoil at the same *c/R* ratio. By doing so, c_P* represents the relative difference in terms of power obtained either accounting or discarding the VC effect. It has to be further noticed that all the analyses were carried out using a hypothetical 1-blade turbine with infinite aspect ratio, in order to purely focusing on the aerodynamic phenomena, with no additional effect given by the blade-to-blade interaction or the polar correction due to tip-effects [7].

Figure 5 reports the results of the sensitivity analysis. Logically, at *c/R*= 0 the virtually cambered airfoils coincide with the NACA airfoil; for this reason, the three curves corresponding to all TSR* values start at c_P* =1. At first sight, consistent trends where found, with the relative performance differences increasing with the airfoil thickness.

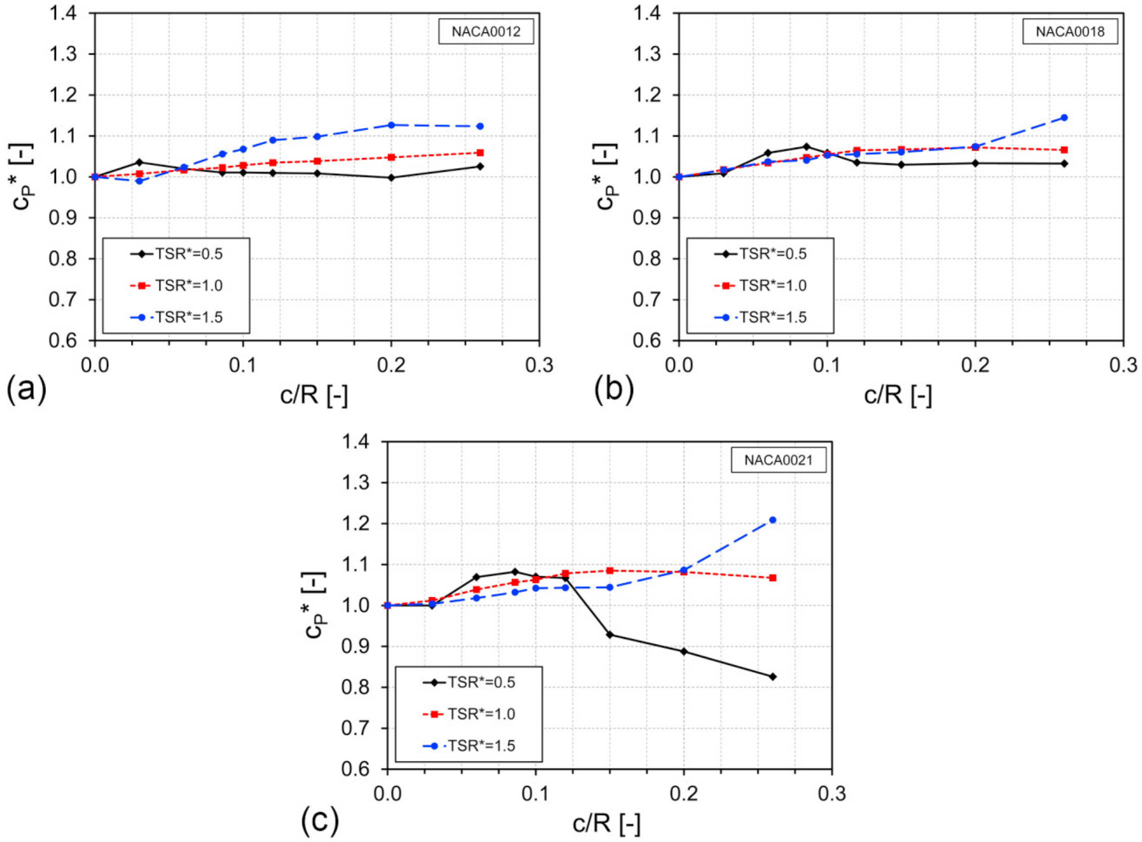

Fig. 5. Results of the sensitivity analysis on the VC effect as a function of the airfoil type, the *c/R* ratio and the TSR.

In further detail, the general trends indicate that:

- the TSR*=1 curve (peak turbine power) shows that, if the *c/R* increases, the difference compared to the NACA airfoil becomes larger. For *c/R* smaller or equal to 0.15, the relative difference stays within 5% for the two thinner airfoils (NACA0012 and NACA0018) but rises up to 10% for the NACA0021. For higher *c/R* the NACA0012 and NACA0018 airfoils can reach up to a 12%-15% difference in comparison to expected performance, while the NACA0021 can reach even a 20% difference. Overall, the thicker airfoil clearly shows that neglecting the VC effect almost always results in a significant error in the turbine peak performance. Conversely, when the thickness-to-chord ratio in lower than 0.18, at *c/R*<0.1 the airfoil behaves basically like the original uncambered NACA, inducing a small VC effects;
- the TSR*=0.5 curve shows two different trends: one for *c/R* smaller than 0.12 and one for higher values. For *c/R*<0.12 the c_P is slightly higher than that of the geometric NACA airfoil (the virtually cambered airfoil has superior performance at low Reynolds number and larger angles of attack [7]): the relative difference can be even significant: up to 9% for the NACA0021. For *c/R*>0.12, the c_P* trend of the thinner airfoils is flat and almost equal to 1, meaning that in these cases the virtually cambered airfoil basically performs similarly to the geometric NACA. This is probably due to the fact that the resulting very solid rotors have very poor performance at this lower TSR, mainly dominated by flow blockage within the rotor. The NACA0021 instead highlights a remarkable performance drop, probably connected to the well-known aerodynamic issues connected to too-solid rotors (high *c/R* ratios and high thickness-to-chord of the airfoil) [19]. Overall, it has to be noticed that the present analysis must be mainly intended in terms of relative difference between the data of symmetric and transformed airfoils, since the change of airfoil could change the optimal TSR;
- The TSR*=1.5 curve mainly shows the same trend of the TSR*=1 curve, but the relative difference is always larger, with maximum differences at the highest *c/R* of 12%, 15% and 21% for the three airfoils. This can be

related to the fact that the angle of attack variation at a high TSR has a limited range (the flow is attached to the airfoil for the majority of the revolution): in this situation, the variation of the aerodynamic coefficients in the linear region between the uncambered geometric NACA and the virtually transformed airfoils may result in massive aerodynamic performance differences.

4. Conclusions

In the present study, the implementation of a module to account for the Virtual Camber correction in the open source simulation code QBlade has been presented. The effectiveness of the correction has been first assessed on two study cases (four 1-blade and a full 3-blade H-Darrieus turbines), for both experimental measurements and detailed CFD calculations were available.

Then, a sensitivity analysis on the impact of the virtual camber correction on the accuracy of a medium-fidelity simulation model has been carried out as a function of the chord-to-radius ratio, the airfoil thickness-to-chord ratio and the operational TSR. The analysis showed that the VC correction can have a massive impact on the accuracy of the simulation reaching up to 20% at the peak power and 60% in a high-TSR condition for the NACA0021. Overall, a thicker original airfoil is much more sensible to the VC. Whenever the thickness-to-chord ratio of the airfoil in lower than 0.18, at $c/R<0.1$ the airfoil behaves basically like the original uncambered NACA, inducing a small VC effects. For higher c/R ratios, it is shown that the VC correction becomes necessary to ensure accurate results.

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