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Virtual incidence effect on rotating airfoils in Darrieus wind turbines

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ABSTRACT

Small Darrieus wind turbines are one of the most interesting emerging technologies in the renewable energies scenario, even if they still are characterized by lower efficiencies than those of conventional horizontal-axis wind turbines due to the more complex aerodynamics involved in their functioning. In case of small rotors, in which the chord-to-radius ratios are generally high not to limit the blade Reynolds number, the performance of turbine blades has been suggested to be moreover influenced by the so-called "flow curvature effects". Recent works have indeed shown that the curved flowpath encountered by the blades makes them work like virtually cambered airfoils in a rectilinear flow.

In the present study, focus is instead given to a further effect that is generated in reason of the curved streamline incoming on the blades, i.e. an extra-incidence seen by the airfoil, generally referred to as "virtual incidence". In detail, a novel computational method to define the incidence angle has been applied to unsteady CFD simulations of three airfoils in a Darrieus-like motion and their effective angles of attack have been compared to theoretical expectations.

The analysis confirmed the presence of an additional virtual incidence on the airfoils and quantified it for different airfoils, chord-to-radius ratios and tip-speed ratios. A comparative discussion on BEM prediction capabilities is finally reported in the study.

1. Introduction

Increasing interest is presently being paid to understand where, beyond large wind farms, small and medium-size wind turbines can represent an alternative for delocalized power production [1], with particular focus on off-grid applications (e.g. [2,3]). *Inter alia*, the built and populated environment presently represent the research frontier [4], since the produced power could be immediately available for a large number of applications or simply used to reduce the energy demand of buildings [5]. Even in the flows in this environment are generally very complex, if properly positioned small turbines are thought to take advantage from augmented wind speeds [6] or specific interactions with the buildings [7].

Among other technologies, Vertical-Axis Wind Turbines (VAWTs), both drag (e.g. [8,9]) and lift-driven (e.g. [10,11]), are gaining popularity in view of similar applications, since they can work effectively even in presence of low-speed and unstructured flows with low noise emissions and high reliability [12]. In particular, Darrieus rotors are increasingly appreciated, as they are probably the only ones able to reach efficiencies somehow competitive with respect to Horizontal-Axis Wind Turbines (HAWTs) [13]. Moreover, differently from HAWTs, they are supposed to even improve their power coefficient in case of skewed flow [14,15].

At the present state-of-the-art, however, the global efficiencies of Darrieus turbines still lack from those of HAWTs, due to their intrinsically more complex aerodynamics coming from the revolution of blades around an axis orthogonal to flow direction. This generates a continuous variation of the angle of attack, which leads to additional phenomena, like for example dynamic stall [13].

Recently, a study by Bianchini et al. [16] demonstrated that the so-called "flow curvature effects" represent one of the main aspects to be assessed in order to achieve a deeper understanding of Darrieus turbines' aerodynamics. The first studies on these phenomena date back to the early '90s, when Migliore et al. [17], based on a one-dimensional analysis of the attended velocity vectors along the airfoil, theorized that the curved path VAWT blades follow imparts a *virtual camber* and a *virtual incidence* on them, i.e. that their performance would be analogous to that of a cambered blade at modified incidence in a rectilinear flow (see Fig. 1). Migliore and his colleagues anyhow theorized these effects only using non-dimensional theories and did not verified it on real turbines.

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Nomenclature

Acronyms

AoA	Angle of Attack
BEM	Blade Element Momentum
CFD	Computational Fluid Dynamics
HAWTs	Horizontal Axis Wind Turbines
SST	Shear Stress Transport
TSR	Tip-Speed Ratio
U-RANS	Unsteady Reynolds-Averaged Navier-Stokes
VAWTs	Vertical Axis Wind Turbines

Greek symbols

α	angle of attack (symbol) (deg)
β	angle between the wind speed and the relative speed (deg)
γ	skew angle of the wind velocity (deg)
δ	angle between the wind speed and the peripheral speed (deg)
ϑ	azimuthal angle (deg)
ω	specific turbulence dissipation rate (1/s)
Ω	revolution speed (m/s)

Latin symbols

A	turbine's swept area (m^2)
c	blade chord (m)
D	rotor diameter (m)
k	turbulence kinetic energy (m^2/s^2)
R	rotor radius (m)
Re_θ	momentum thickness Reynolds number (–)
U	undisturbed wind speed (m/s)
VI	virtual incidence (deg)
w	relative speed (m/s)
y^+	Dimensionless wall distance (–)

A recent work published by the authors have shown that the associated differences in performance between "geometrical" and "virtual" airfoils become a source of error in any analysis using the original blade profile's data [18]. Their attention was however fully focused on the virtual camber effect.

This study sets out instead to both assess the presence of the virtual incidence and to estimate its impact on airfoil's performance in order to judge how best account for it in low-order simulation methods, like Blade Element Momentum (BEM) codes.

To do so, the same three airfoils analyzed in Ref. [18] were considered, i.e. a conventional symmetric NACA 0018 and two modified profiles based on it. In details, the two modified profiles have been conformally transformed to fit their camber lines to the arc of a circle, such that the ratio between the airfoil chord and the circle's radius, c/R, is 0.114 or 0.25 (Fig. 2).

The two c/R values were selected as compatible with the ones originally used by Migliore [17], whose theory was used as a comparison in the present study. Based on the applied transformations, the $c/R = 0.114$ airfoil has a maximum camber of 1.42% at 50% of chord, while the $c/R = 0.25$ has 3.11% maximum camber, again at 50% of chord. Following the indications of Ref. [18], it has to be attended that "in tunnel-like flow condition the transformed airfoils should perform as the unmodified NACA 0018 would in VAWTs with similar c/R ratios and conversely the NACA 0018s results in rectilinear flow should correspond to those of the transformed airfoils when used in the VAWTs" [18].

To analyze the airfoil's behavior and then estimate the actual incidence they are experiencing, CFD simulations have been carried out at different tip-speed ratios and analyzed in terms of incidence angles experienced by the profiles using a novel method developed by the authors [19].

2. Case study and CFD simulations

CFD simulations were used to investigate the aerodynamic behavior of the selected airfoils when rotating onboard a Darrieus turbine. The use of CFD to go into the aerodynamics details of the phenomena and then define proper corrections to be transferred to low-order simulation methods is indeed a recent trend in the research, which is disclosing very interesting horizons for a further comprehension of many details of airfoils' functioning (e.g. [20,21]).

Four "single-bladed" rotors were considered, obtained by combining the two c/R ratios with both the NACA 0018 and the relevant transformed airfoils in each case.

Table 1 reports the main geometrical features of the four simulated models. The airfoil chord was kept constant in all the simulations, while the revolution radius was changed to achieve the two desired chord-to-radius ratios.

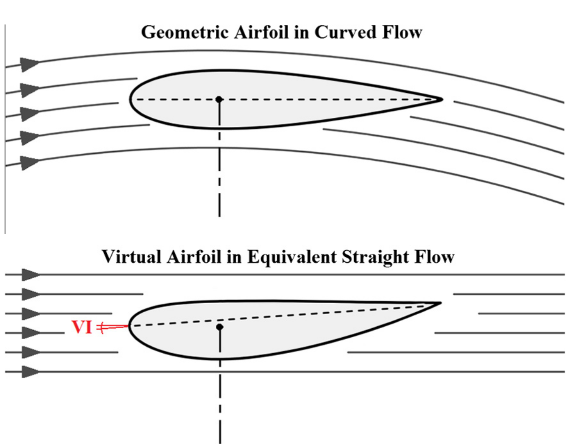

Fig. 1. Flow curvature effects on an airfoil in Darrieus-like motion.

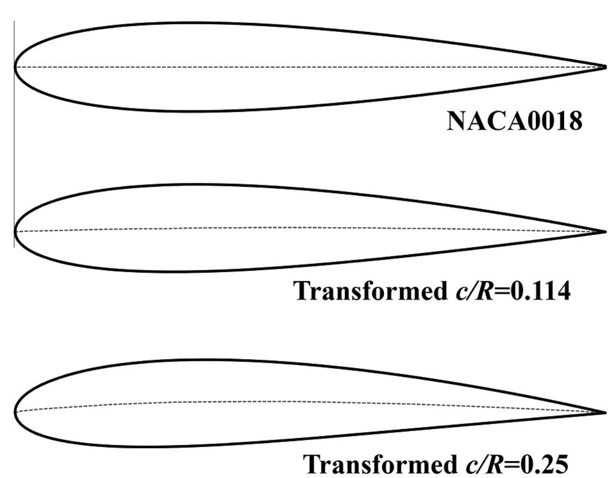

Fig. 2. The three profiles used in this study.