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Optimal spanwise chord and thickness distribution for a Troposkien Darrieus wind turbine

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ABSTRACT

An innovative concept of Troposkien wind turbine blade, characterized by a variable chord and thickness distributions along the blade span, is here presented. The proposed optimal blade configuration is determined through the use of an in-house design code, the so-called WOMBAT algorithm, obtained by combining both an advanced optimization method and a Blade Element-Momentum (BE-M) performance prediction code. The resulting geometry, slightly corrected in order to be easily realizable, shows a consistent increase in the aerodynamic performance with respect to the considered baseline architecture.

1. Introduction

Vertical-axis wind turbine (VAWT) design methods are widely discussed in the literature: in fact, the complexity of the air flow around vertical blades as well as the resulting dynamic effects on the rotor have stimulated researchers to develop several approaches with the aim of estimating the behavior and the performance of this particular turbine. The design is mainly conducted by adopting Blade Element-Momentum (BE-M) based algorithms and successively validated by means of Computational Fluid Dynamics (CFD) codes.

BE-M based algorithms have been developed by several authors with the aim of predicting the aerodynamic performance of vertical-axis rotors without demanding a high computational effort (Glauert, 1935; Templin, 1974; Strickland, 1975; Read and Sharpe, 1980; Paraschivoiu, 1981, 1983). The best results derive from the Multiple-Streamtube Double Disk Theory, obtained by combining the Strickland's Multiple-Streamtube model (Strickland, 1975), which provides more accurate previsions than the original Single-Streamtube model developed by Templin (1974), with the Double Disk approach that considers the freestream velocity reduction passing from the upwind to the downwind portion of rotor blade revolution (Paraschivoiu, 1983; McCoy and Loth, 1981; Loth and McCoy, 1983; Paraschivoiu, 2002). In fact, the interaction between air and rotor is different for the downwind zone with respect to the upwind one: two separate computations are therefore to be performed. Limiting his research to a small Darrieus wind turbine (2 m high), Paraschivoiu (2002) proved the agreement of the Darrieus Turbine program (DART), based on the Strickland algorithm, with both experimental field data and wind tunnel measurements conducted by Sheldahl (1981).

The Multiple-Streamtube Double Disk numerical code requires some preliminary knowledge on the main functional parameters of the rotor, in particular:

- operating conditions: wind speed, angular velocity, wind shear, etc.;
- geometrical characteristics of the rotor: height, radius, etc.;
- lift and drag coefficients of the blade sections.

The last issue represents the most critical data to retrieve from the available literature. In fact, extended databases, from -180° to $+180^\circ$, are required for the numerical computations. Moreover, the usual operative conditions of a small-size VAWT determine a low airfoil Reynolds number. The most adopted database was provided by Sheldahl and Klimas (1981), who performed a series of wind tunnel investigations in order to evaluate the lift and drag coefficients over 180° angle of attack for the NACA-0009, -0012 and -0015 airfoils and for Reynolds numbers ranging from 350,000

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Nomenclature

a	Interference factor (dimensionless)
AEP	Annual energy production (kW h)
c	Airfoil chord (m)
C	Weibull scale factor (dimensionless)
C_D	Airfoil drag coefficient (dimensionless)
C_L	Airfoil lift coefficient (dimensionless)
C_m	Torque coefficient (dimensionless)
C_P	Rotor power coefficient (dimensionless)
$C_{P,y}$	Local power coefficient relative to a vertical blade element (dimensionless)
h	Height of a blade element (m)
H	Rotor total height (m)
k	Weibull shape factor (dimensionless)
n	Rotor angular velocity (rpm)
n_g	Number of genes (dimensionless)
N	Number of blades (dimensionless)
P	Power produced by the turbine (W)
r	Radius of a blade element (m)
R	Wind turbine maximum radius (m)
T	Total torque (N m)
t	Airfoil thickness (m)
S	Rotor swept area (m^2)
$\overline{u}$	Annual average wind speed (m/s)
U_∞	Wind speed (m/s)
$V_{blade,up}$	Flow velocity at the upwind actuator disk (m/s)
α	Blade relative angle of attack (between airfoil chord line and relative wind velocity) (rad)
λ	Tip speed ratio (dimensionless)
ρ	Air density [assumed 1.225 (kg/m^3)]
θ	Blade azimuthal coordinate (°)
ω	Rotational speed (rad/s)

to 700,000. The results were successively extended, through the adoption of numerical methods, to NACA-0018, -0021 and -0025, as well as to a wider range of Reynolds numbers.

Some authors implemented numerical algorithms to extend the aeronautical databases currently available in the literature to the range of operational values that wind turbines usually require. Raciti Castelli et al. (submitted for publication) proposed several hybrid databases, generated through the numerical prediction of the aerodynamic coefficients of symmetrical NACA airfoils, characterized by a thickness-to-chord ratio comprised between 0.09 and 0.25: the construction of the hybrid polars was based on the combination of the predictions of the well-known Xfoil numerical code with the averaged aerodynamic coefficients provided by Sheldahl and Klimas (1981). Bedon et al. (2013) also proposed an extended polar prediction tool for symmetrical airfoils, based on the interpolation of Sandia coefficients (from Sheldahl and Klimas, 1981) with respect to the thickness-to-chord ratio: the validation of the proposed algorithm was performed through the comparison with experimental data from the Sandia 2 m vertical axis wind turbine (Sheldahl, 1981). This algorithm was eventually combined with both the BE-M code developed by Raciti Castelli et al. (2012) and the genetic algorithm included in the Matlab commercial suite (Matlab, 2012), based on the work of Deb (Deb, 2001). The so-created algorithm was defined as WOMBAT (Weatherly Optimization Method for Blade of Air Turbine) and can be included in the final (advanced) design process of a VAWT. Several test cases were performed, considering different objectives as a proof of concept: the increase in the power coefficient with respect to the considered baseline configuration resulted up to 14%.

Genetic algorithms have already been proposed as optimization tools for the design of a wind turbine geometry. Bourguet et al. (2007) suggested a design procedure for blade sections, adopting both a CFD code and a multi-criteria optimization algorithm: the selected design criteria were both the increase of nominal power production and the reduction of blade weight, obtaining an optimal airfoil shape very similar to the NACA-0025. Carrigan et al. (2012) applied a differential evolutionary algorithm, combined with a two-dimensional CFD simulation tool, in the design process of a H-Darrieus wind turbine: the efficiency increases from the baseline NACA-0015 geometry resulted around 6% and was achieved with a reduction of 40% in rotor solidity and an increase of 58% in rotor blade thickness.

The aim of the present work is the advanced design of a small-size Troposkien shaped Darrieus VAWT characterized by a non-uniform distribution of both blade section and thickness-to-chord ratio along the spanwise direction. A non-optimized 42 m high Troposkien rotor, characterized by a discretely variable chord and thickness distributions, was already realized and tested by Ashwill (1992). Nevertheless, the intent of the authors is hereby to provide a general optimization procedure, as well as the chord and thickness optimal distributions, for a compact rotor architecture (2 m high) based on the work of Sheldahl (1981), using the WOMBAT algorithm.

2. Case study

The blades of vertical-axis Darrieus turbines have traditionally been designed as an extruded profile, eventually bent to form a Troposkien shape. This geometrical configuration has been experimentally tested several times, thus generating a copious literature. In the present work, the 2 m wind turbine tested by Sheldahl (1981) is considered as the baseline configuration for the optimization procedure. The rotor is 2 m high, with a maximum radius of 0.98 m. The blade shape is straight-circular-straight (SCS): this is considered as a good approximation of the Troposkien architecture (Reis and Blackwell, 1975) but cheaper to manufacture. The main geometrical specifications of the turbine are summarized in Table 1. A picture of the described rotor installation in the Sandia site test is shown in Fig. 1.

The main performance parameters considered in the present work are the power production P and the power coefficient C_P, defined as

$$C_P = \frac{P}{0.5 \cdot \rho \cdot U_\infty^3 \cdot S} \tag{1}$$

being P the power production, ρ the air density, U_∞ the free-stream wind speed and S the swept area of the rotor.

Table 1
Main geometrical features of the baseline rotor configuration (from Sheldahl, 1981).

H (m)	2
R (m)	0.98
N (dimensionless)	3
c (mm)	58.77
Blade profile	NACA-0012
Blade shape	Straight-circular-straight (SCS)