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Three-Dimensional Modeling of a Twisted-Blade Darrieus Vertical-Axis Wind Turbine

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Abstract—A complete CAD procedure to model a twisted-bladed vertical-axis wind turbine (VAWT) is presented with the aim of determining some practical guidelines to be used for the generation of an easily-meshable CAD geometry to be adopted as the basis of both CFD and FEM numerical simulations.

Keywords—Vertical-axis wind turbine (VAWT), twisted blade, CAD, 3D modeling.

I. INTRODUCTION AND BACKGROUND

DUE to both the growth of concerns on environmental issues and the limited sources of fossil fuels, the penetration of wind energy in future power systems is going to rapidly increase. The majority of wind turbines that are currently operating in wind farms present a classical three-bladed rotor configuration with a horizontal axis (HAWT, horizontal-axis wind turbine). Nevertheless, in recent years, a renewed interest in vertical-axis wind turbine (VAWT) architectures is being registered, especially for small scale rotors, motivated by a perceived future demand for decentralized electricity generation within cities and rural communities [1].

The most adopted VAWT is the Darrieus rotor, patented in the USA in 1931 by G. J. M. Darrieus [2], whose aim was to extract wind energy for electrical power generation [3]. The original Darrieus architecture was made by a set of curved blades approximating the shape of a perfectly flexible cable, namely the Troposkien shape. Later, vertical-axis architectures based on straight blades appeared under the names of H-Darrieus or Squirrek Cage Darrieus turbines [4]. The Darrieus architecture presents several advantages over the more common HAWTs [5] [6], namely:

- better aesthetics due to its three-dimensionality. This aspect is of the utmost importance, being the rotor conceived to operate inside the urban environment;
- no need to constantly yaw into the local wind direction. This brings to a better performance in turbulent flows;
- lower sound emission, due to the relatively low translational speed of the blade sections, making these rotors more suitable for installations in residential areas;
- lower manufacturing cost with respect to a horizontal-axis turbine, due to a simpler blade geometry;
- possible ground installation of both generator and gearbox, allowing easier inspections and maintenance.

On the other hand, VAWTs generally present a reduced power efficiency with respect to HAWTs [7].

A large number of recent industrial design works have been supported by computer aided engineering (CAE), which includes a wide variety of numerical tools such as computer aided design (CAD), computational fluid dynamics (CFD) and finite element analysis (FEA). Commercial CFD codes, as well as CAD and FEA softwares, have been rapidly advancing due to market demands [8], allowing a quicker and better analysis of different geometries and operational cases.

One of the major problems that typically arise when the designers deal with CAE, is the need to match the geometry obtained using CAD with the mesh generator for the CFD analysis. Dawes et al. [9] analyzed the whole numerical process from CAD to CFD with the aim of reducing bottlenecks in the CAD-to-mesh-to-solution cycle, in order to allow CFD to participate directly to the design process: it was observed that one of the key bottleneck is getting access to the complex geometry held in a CAD system and converting it into a suitable mesh system for the numerical analysis. The concept of badly meshable geometry was formally recognized by Samareh [10], who described several CAD features unsuitable for CFD mesh generation: generally speaking, a CFD engineer could expect to receive a highly complex CAD for the aerodynamic analysis, which would often contain many features of very little aerodynamic interest that might nonetheless give problems in grid generation and flow solving procedure [9]. From here the need for the CAD designer to generate a three-dimensional geometry as simple as possible, avoiding unnecessary passages and features.

The aim of this work is to describe the main passages of the creation of a complex VAWT architecture, from the selected airfoil to a finite 3D twisted blade, in order to generate an easily meshable geometry to be adopted for CFD and FEM computations.

II. MAIN GEOMETRICAL FEATURES OF THE MODEL

Table I summarizes the main geometrical features of the considered rotor, composed by three helical-shaped blades of NACA 0021 section and based on the work of Raciti Castelli and Benini [11].

TABLE I
MAIN GEOMETRICAL FEATURES OF THE TESTED MODEL

c [mm]	85.8
H [mm]	1545
D [mm]	1030

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Fig. 1 represents a schema of the twisted rotor blade, showing the phase angle φ between upper and lower blade sections, as well as blade inclination γ with respect to the horizontal.

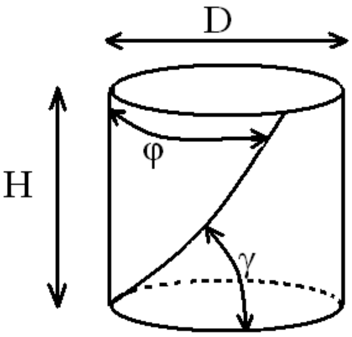

Fig. 1. Geometrical schema of the proposed rotor architecture

Blade inclination angle γ with respect to the horizontal can be related to the phase shift angle between upper and lower blade sections by the formula:

$$\gamma = tan^{-1}[H/(\phi(rad) \cdot R)] \qquad (1)$$

For the proposed geometry, the phase shift angle between upper and lower blade sections was $120°$, determining a blade inclination of $54.4°$ with respect to the horizontal.

III. CAD 3D MODELING

The complete twisted blade geometry was created on the basis of 21 airfoil sections (determined on the basis of $N_z = 20$ vertical subdivisions of the whole rotor blade): as a first step, NACA 0021 airfoil coordinates were determined through the NACA 4 digit generator [12] available for Matlab. The shape of the obtained unitary chord airfoil was then scaled to the desired blade section dimensions and finally translated of one radius length to its relative position with respect to rotor axis.

As can be seen from Fig. 2, the airfoil section was eventually rotated of $(\pi/2 - \gamma)$ around the radial direction (passing through its centre of pressure, located at c/4 for a NACA series profile) using the rotation matrix R_y, defined as:

$$R_y = \begin{bmatrix} cos(\pi/2-\gamma) & 0 & -sin(\pi/2-\gamma) \\ 0 & 1 & 0 \\ sin(\pi/2-\gamma) & 0 & cos(\pi/2-\gamma) \end{bmatrix} \qquad (2)$$

As can be seen from Fig. 3, each successive section is obtained by translating the previous one of H/N_z in the z direction and rotating it along the z axis of the angle θ, defined as:

$$\theta = \phi/N_z \qquad (3)$$

determining the following rotation matrix:

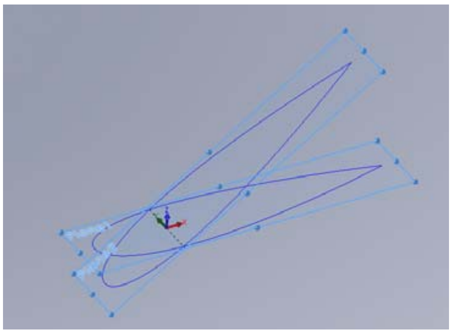

Fig. 2. Rotation of the airfoil section around the radial direction

$$R_z = \begin{bmatrix} cos(\theta) & -sin(\theta) & 0 \\ sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (4)$$

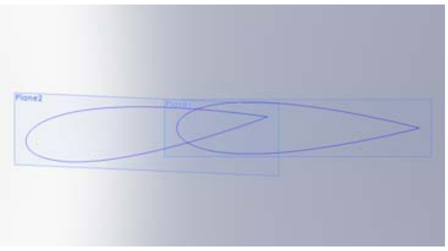

Fig. 3. Rotation along the z-axis

The 21 airfoil sections determining the 3D architecture of the proposed rotor blade are shown in Fig. 4. The commercial softwer *SolidWorks* was adopted for the modeling of the rotor blade.

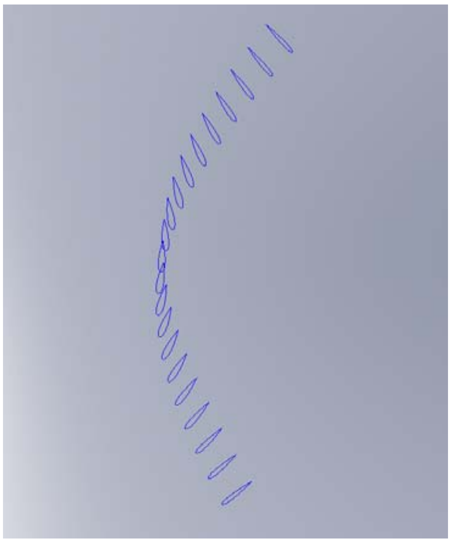

Fig. 4. Airfoil sections determining the 3D architecture of the proposed rotor blade

The *loft* function was eventually adopted to interpolate all the blade sections, in order to create a solid part. As can be seen from Fig. 5, with the aim of determining a better interpolation, two guide lines, passing through both the leading edge and the trailing edge of the blade, were defined.

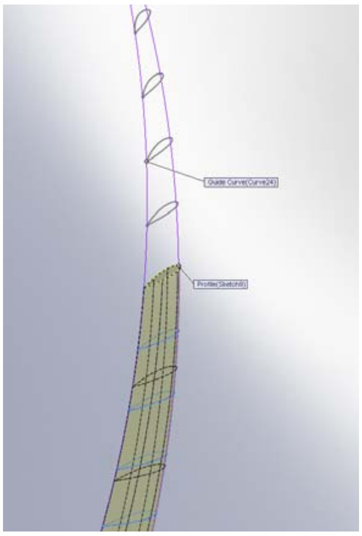

Fig. 5. Interpolation of the blade sections

Fig. 6 represents the resulting three-bladed rotor, determined by revolving of 120° around the z axis the solid part of the 3D blade geometry twice. As can be clearly seen, the end tip of the blades are inclined of $(\pi/2-\gamma)$ with respect to the horizontal, in order to result perpendicular to blade leading edge, thus achieving higher performance due to the upwards deviation of stream lines close to the twisted blade, as suggested by Raciti Castelli and Benini [11].

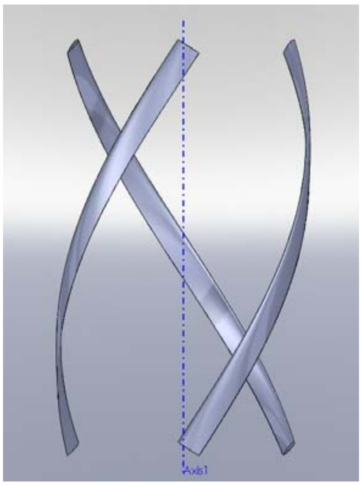

Fig. 6. Frontal view of the complete three-bladed rotor

IV. CONCLUSIONS

A complete CAD procedure to model a twisted-blade vertical-axis wind turbine was presented, in order to generate an easily meshable geometry to be adopted for CFD and FEM simulations. Starting from the computation of the local airfoil coordinates for each blade section, a 3D model of the blade geometry is created using both basic geometrical transformations (airfoil section rotation and translation) and the loft function of the SolidWorks code.

NOMENCLATURE

c [mm]	blade section chord
D [mm]	rotor diameter
H [mm]	rotor height
N_z [-]	vertical subdivisions of the whole rotor blade
R_y [3x3]	rotation matrix for blade section inclination with respect to the horizontal
R_z [3x3]	blade section rotation matrix with respect to the vertical rotor axis
ϕ [rad]	phase shift angle between upper and lower blade sections
θ [rad]	blade section rotation along the vertical rotor axis
γ [rad]	blade inclination angle with respect to the horizontal

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