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Energy Procedia 75 (2015) 677 – 682

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Aerodynamic Benchmarking of the Deepwind Design

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Abstract

The aerodynamic benchmarking for the DeepWind rotor is conducted comparing different rotor geometries and solutions and keeping the comparison as fair as possible. The objective for the benchmarking is to find the most suitable configuration in order to maximize the power production and minimize the blade solicitation and the cost of energy. Different parameters are considered for the benchmarking study. The DeepWind blade is characterized by a shape similar to the Troposkien geometry but asymmetric between the top and bottom parts: this shape is considered as a fixed parameter in the benchmarking process.
The number of blades in the analysis is varied from 1 to 4. In order to keep the comparison fair among the different configurations, the solidity is kept constant and, therefore, the chord length reduced. A second comparison is conducted considering different blade profiles belonging the symmetric NACA airfoil family.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: Vertical Axis Wind Turbine; DeepWind Project; BE-M algorithm; Aerodynamic benchmarking.

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1. Introduction

MW class horizontal-axis wind turbines (HAWTs) have experienced a considerable diffusion in the last decades, due to the increasing awareness for an upcoming necessity of renewable energy production. The rotor size experienced a constant increase in order to minimize the cost of energy, but recently an upper boundary is reached due to the difficulty to further model the material behaviour and guarantee a smooth operational life. In this context, vertical axis wind turbines (VAWTs) can play a crucial role: in fact, their inherent characteristics allow the creation of big size rotors affected by lower operational loads and simpler control policies. Among VAWTs, the Darrieus architecture provides the best performance and is therefore considered as the most promising rotor configuration. Nevertheless, the vertical-axis concept has not a well-consolidated design methodology and, differently from the horizontal-axis architecture, the optimal shape for the Darrieus wind turbine is still object of discussion [1]. The principal rotor configurations considered in literature are the straight blade (H) and the Troposkien shape, often transformed in the more practical

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.486

Straight-Circular-Straight (SCS) shape [2]. The Troposkien geometry has the structural advantage to be subject only to normal stresses, whereas the straight blade shape experiences also bending loads. On the other hand, considering the same rotor occupancy, the straight bladed turbine is characterized by a wider swept area to intercept wind than Troposkien shape.

FP7 DeepWind is the first project aiming to design a big-scale offshore floating vertical axis wind turbine with a nominal power generation of 5 MW [3]. Given the considerable rotor size needed to achieve this power production, the Troposkien shape is chosen in order to reduce the blade solicitation to normal stresses. The rotor shape was further analysed and optimized from the baseline to account for gravity effect, leading to a new blade geometry designed for the target operative conditions [4]. The purpose of this work is to conduct an aerodynamic benchmarking with different blade configurations, considering different numbers of blades, profiles and chord distributions.

Two types of simulation approaches have usually been adopted in order to predict wind turbine performance: Computational Fluid Dynamic (CFD) codes, based on the numerical resolution of the Navier-Stokes equations, and semi-empirical codes as Blade-Element Momentum (BE-M) and Vortex based algorithms, obtained by combining physical assumptions and experimental data. Whereas the first methods permit a deeper analysis of the air flow inside the turbine, the second ones require a much lower computational effort, giving a quick result that can be easily adopted for rotor design. Among the authors who supported the first approach, Carrigan et al. [5] applied a differential evolutionary algorithm combined with a CFD simulation tool, registering an improvement in the overall rotor performance of about 6% with respect to the baseline geometry, achieved with a consistent variation in both solidity and profile thickness. Also Bourguet et al. [6] adopted a multi-criteria optimization algorithm aiming at both reducing blade weight and increasing the power production by means of a full campaign of CFD simulations requiring 7 hours each, converging to a blade optimal shape very close to NACA 0025 airfoil.

The BE-M approach represents the most diffused semi-empirical algorithm for vertical axis wind turbine simulations. Several authors adopted algorithms based on the BE-M Theory, originally developed by Glauert for helicopter simulations [7] and by Templin et al for vertical axis wind turbine simulations [8], successively improved by Strickland [9, 10] and Paraschivoiu [11, 12], respectively introducing the multiple streamtube and double disk theories. This tool was successfully adopted for evaluating the optimal blade configuration for Darrieus wind turbines by Bedon et al. [13], showing that, depending on the target operative conditions considered, different blade designs should be adopted to maximize the power coefficient.

In the present work, a BE-M code based on the Paraschivoiu model [11, 12] is developed and validated against experimental results. The benchmark is conducted considering different numbers of blades and airfoil sections, aiming to maximize the energy production, minimize the blade solicitation and the cost of energy.

2. Simulation Algorthm

The BE-M algorithm considered in the present work is the Double Disk Multiple Streamtube developed by Paraschivoiu [11, 12] improving the Single Disk Multiple Streamtube model originally proposed by Strickland [9]. The method relies on an iterative procedure to obtain an air induction factor, defined as:

$$a = 1 - \frac{V_i}{V} \tag{1}$$

where V_i is the velocity at the upwind or downwind blade and V is the free-stream velocity, which allows to estimate the energy absorbed from the air by the rotor and therefore the aerodynamic energy produced. The iterative procedure is conducted by equating the streamwise force provided by moment considerations with the blade element force: the procedure is largely described in literature and for more details the reader is addressed to references.

The main input for this method are the operative conditions, blade geometry and airfoil lift and drag coefficients. In fact, VAWT blades experience wind coming from a direction varying among 360°: aerodynamic drag and lift coefficients have therefore to include data over the stall [14, 15]. A suitable aerodynamic database should be therefore selected in order to obtain reliable simulations.

In the present work, the database provided by Jacobs [16, 17] for NACA 0015, NACA 0018 and NACA 0021 and by Bullivant [18] for NACA 0025 are considered. These database are provided for different Reynolds number ranging from 10^5 to $3 \cdot 10^6$ and angles of attack lower than 30°: in order to overcome this limitation, the aerodynamic coefficients for higher angles of attack are derived from Sheldahl [19], whose reliability for lower angles of attack is questionable.

3. Case Study

In the present work, the rotor architecture from the DeepWind project is considered. The rotor shape was optimized considering inertial and gravity forces and is kept constant in the aerodynamic benchmarking. The blade shape is shown in Figure 1. The baseline rotor configuration is characterized by the parameters reported in Table 1.

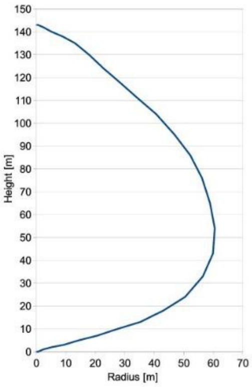


Figure 1: DeepWind optimized blade rotor.

Height	143 m
Radius	60.5 m
Airfoil	NACA 0018
Chord	5 m
Blade number	2
Solidity	0.165
Max. rotation speed	6 rpm

Table 1: Baseline parameters for the DeepWind project rotor.

4. Benchmarking

This section presents the results obtained from the benchmarking of different blade configurations in order to maximize the power production and minimize the blade loads and costs. Two different benchmarking campaigns are conducted, respectively varying the number of blades keeping the solidity constant and varying the profile thickness.

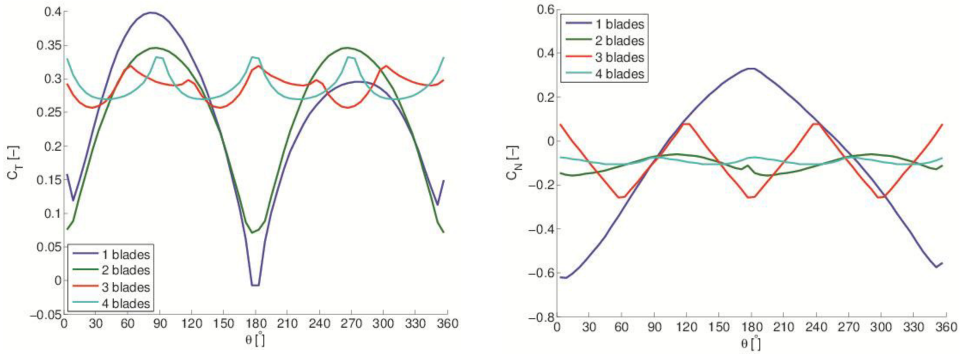
4.1. Number of blades

The number of blades is object of the present investigation. In order to keep the comparison fair, the same solidity among the different configurations is considered by decreasing the chord size. The performance is expected not to be influenced by the blade number: in BE-M computations, solidity is the key factor for the performance variation. The blade tangential and normal force coefficient [9] are defined as:

$$C_T = C_L \sin(\alpha) - C_D \cos(\alpha) \tag{2}$$

$$C_N = C_L \cos(\alpha) - C_D \sin(\alpha) \tag{3}$$

being C_L and C_D respectively the airfoil lift and drag coefficient at the angle of attack α.
The rotor loads are obtained by scaling, projecting and combining these coefficients in the parallel and orthogonal to the wind speed directions. The loads are represented by the thrust C_T and lateral force C_N coefficients and represent a measure of the stress in the tangential and the normal direction (see reference for details). A big difference is registered among the different configurations, given by the combination of forces acting on diferent blades at the same time. The coefficient values are shown in Figure 2.



a) Thrust force coefficient b) Normal force coefficient

Figure 2: Rotor thrust and lateral force coefficients computed by BE-M algorithm with respect to the different number of blade

The worst rotor configuration in terms of loads is characterized by the single blade: both the thrust and lateral coefficients experience a large variation along the azimuthal positions. The two- and three-bladed configurations present both peculiarities: the first is characterized by a higher thrust coefficient variation and a very limited lateral force coefficient variation with respect to the second. This is justified considering the axial-symmetry of the two bladed configuration, whose lateral loads are more balanced than in the three bladed configuration. Finally, the four-bladed configuration present the smallest excursion in both factors.

4.2. Blade airfoil

Different blade airfoils are tested with respect to the baseline configuration in order to find the most suitable. The airfoils considered belong to the symmetric NACA family and their choice is limited by the availability of aerodynamic coefficients extended to 180°. As previously stated, the database from Jacobs [16, 17] and Bullivant [18] are considered, being the first one validated against experimental data and the second one the only one available for high Reynolds number. The databases are eventually extended considering Sheldahl database [19] for angles of attack higher than 30°: these data are not experimentally measured but numerically estimated considering the PROFILE algorithm by Eppler [20]. The simulations are conducted considering a wind speed ranging from 4 m/s and 25 m/s and rotational speed from 0 rpm to 6 rpm. The power curves for the different blade configurations are shown in Figure 3. The highest power productions are achieved with NACA 0015 and NACA 0018 profiles, whereas for higher thicknesses the performance is strongly reduced. This can be related to the lower lift values those profile can provide, penalizing the production in the non-stalled profile region.

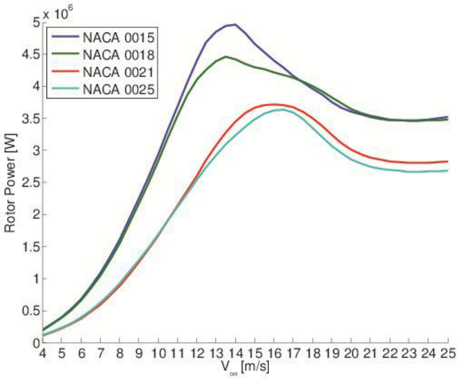
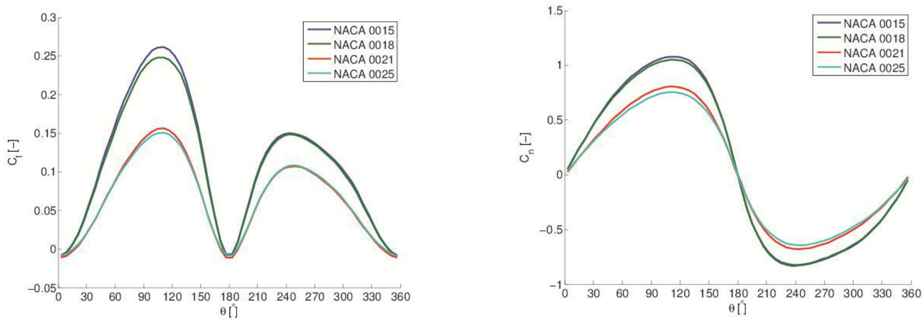


Figure 3: Power curves for different blade configurations for different airfoil configurations.

The loads are again of strong interest for the rotor design. The tangential and normal thrust coefficients for the single blade are shown in Figure 4.



a) Tangential force coefficient

b) Normal force coefficient

Figure 4: Single blade tangential and normal force coefficients computed by BE-M algorithm for different airfoil configurations.

The loads as well as the power production are reduced for blades with high thickness profiles: despite the increased profile drag, since the profile is mostly operating at low angles of attack, the loads are however reduced.

5. Conclusions

The present work has considered the FP7 DeepWind rotor and an aerodynamic benchmarking analysis on different blade aspects has been performed. In the baseline project, a two bladed rotor with NACA 0018 profiles was considered. The benchmarking shows the aerodynamic effect of a change in the number of blades. A blade number equal to two or three is equally a good choice with respect to the rotor loads. Further reduction in the loads can be obtained by adding one more blade, however this would increase substantially the rotor cost and therefore the cost of energy. The choice between two and three blades should be conducted considering the rotor basement, analyzing which vibration (thrust or lateral) is more dangerous from a turbine perspective.

Considering the different airfoils, NACA 0015 and NACA 0018 are the two best alternatives from a power production point of view. Increasing the airfoil thickness would lead to a sensible decrease in the performance, however linked to a decrease in the blade loads. The choice between the two selected profiles should be conducted based on structural considerations.

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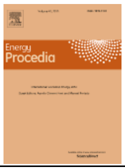

Biography

Mr. Gabriele Bedon is a Ph.D. Student in Energy Engineering at University of Padua, Italy. His main research topics involve the aerodynamic simulation of the Darrieus wind turbines and their. He graduated at University of Padua in Mechanical Engineering and at Denmark Technical University in M.Sc. in Engineering, Sustainable Energy.