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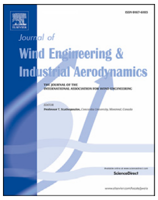

Aerodynamic design methodology for wind tunnel tests of wind turbine rotors

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ABSTRACT

This paper illustrates the methodology and the experimental verification of the design of a 1/75 aero-elastic scaled rotor of the DTU 10 MW reference wind turbine for wind tunnel tests. The aerodynamic design was focused on the minimization of the difference, in terms of thrust coefficient, with respect to the full scale reference. From the Selig low-Reynolds airfoils database, the SD7032 one was chosen for this purpose and a corresponding constant section wing was tested at DTU red wind tunnel, providing force and distributed pressure coefficients for the design, in the Reynolds range $30- \ 250 \times 10^3$ and for different angles of attack. The aero-elastic design algorithm was set to define the optimal spanwise thickness over chord ratio (t/c), the chord length and the twist, in order to match at least the first flapwise scaled natural frequency. An aluminium mould for the carbon fibre autoclave process was CNC manufactured based on B-Splines CAD definition of the external geometry given as an output of the design procedure. Wind tunnel tests at were carried out Politecnico di Milano on the whole 1/75 wind turbine scale model, confirming the successful aerodynamic design and manufacturing approaches. The experimental modal analysis carried out to verify the structural consistency of the scaled blade is also reported.

1. Introduction

Wind tunnel tests of wind turbine scale models represent an affordable and effective way for assessing the aerodynamics of wind turbines saving time, costs and uncertainties related to full scale experimentation. However, the main limitation in rotor scaling procedure for wind tunnel tests is the impossibility of matching Reynolds number with respect to full scale. This paper illustrates the non-trivial aero-elastic optimal design, the realization and the experimental verification of the wind tunnel 1/75 scale rotor of the DTU 10 MW wind turbine. More specifically, this work was developed for floating offshore wind turbine (FOWT) applications (Lifes50+, Bayati et al., 2013, 2014); nevertheless, the methodology reported and the conclusions drawn are of general validity in scaling rotors of wind turbines.

Similar efforts in scaling wind turbines have been recently made (Bredmose, 2014). Furthermore, a deep analysis of the scaling effects can be found in (Bottasso et al., 2014) regarding previous activities at Politecnico di Milano wind tunnel: this work deals with the definition of a procedure for aero-elastic model design, and good results, in term of thrust and torque value matching, were obtained as well as a correctly scaled blade structural behaviour also considering bend-twist scaling (Campagnolo et al., 2014).

A further study on the scaling effect of the turbine rotor aerodynamics was carried out in (Make, 2014), where it was found, both numerically and experimentally, that the Reynolds discrepancy caused a different behaviour of the model scale rotor, and by adjusting the chord length by an increment of 25% was obtained so that the model rotor matched target scaled thrust.

Similar results were obtained by DTU in (Bredmose et al., 2015), also in this case the rotor blades were geometrically adjusted in order to overcome the Reynolds scaling limit which, together with the use of low Reynolds airfoil and turbulence generators, allowed to obtain good results for the rotor aerodynamic performance.

The Reynolds scaling problem is even more important when dealing with offshore related testing, in this case Froude scaling is mandatory (Bredmose, 2014) worsening the Reynolds mismatch.

The DTU 10 MW wind turbine, which is the reference of this work, was firstly designed in the framework of the Light Rotor project in 2012 (Bak et al., 2012), starting from the upscaling of the reference 5 MW turbine from NREL (Jonkman et al., 2009). Later the Light Rotor project design evolved in the nowadays publicly available reference design, released by DTU (Baket al, 2013). The DTU 10 MW is being used as reference design in numerous current research activities related to wind energy development, ranging from wind farm optimization to offshore

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Table 1
DTU 10 MW turbine specifications.

Parameter	value	units
Cut in wind speed	4	m/s
Cut out wind speed	25	m/s
Rated wind speed	11.4	m/s
Rotor Diameter	178.3	m
Hub Diameter	5.6	m
Hub Height	119.0	m
Minimum Rotor Speed	6.0	rpm
Maximum Rotor Speed	9.6	rpm
Blade Prebend	3.332	m
Rotor Mass	228,0	tonn
Nacelle Mass	446,0	tonn
Tower Mass	628,4	tonn

Table 2
Wind Tunnel Model turbine specifications.

Parameter	value	units	scale
Cut in wind speed	2	m/s	$\lambda_V = 2$
Cut out wind speed	12.5	m/s	$\lambda_V = 2$
Rated wind speed	5.7	m/s	$\lambda_V = 2$
Rotor Diameter	2.37	m	$\lambda_L = 75$
Maximum Rotor Speed	360	rpm	$\lambda_f = \lambda_L \lambda_V^{-1} = 37.5$
Rotor Mass	0.54	kg	$\lambda_M = \lambda_L^3 = 4.22 \times 10^5$

wind turbine simulation or also for numerical tools benchmark and validation. Table 1 reports the main DTU 10 MW specifications in term of dimensions, masses and operating wind speed.

2. Scaling the reference design

The first step of model design was the comparison between the turbine specifications and the Polimi Wind Tunnel (GVPM) (Zasso et al., 2005) test section dimensions and flow performance. The GVPM is a closed circuit facility with two test rooms: a 4 × 4m high speed low turbulence and a 14 × 4m low speed boundary layer test section. The high speed section is characterized by very low turbulence, $Iu < 0.15\%$, and high speed, maximum velocity of 55 m/s, in the low speed section the turbulence index is higher, $Iu < 2\%$, with a reduced maximum velocity 15 m/s. The low speed section is 36 m long, 14 m wide and 4 m high, allowing very large scale wind engineering tests, useful for civil engineering application or low blockage aerodynamic related tests. Trying to avoid an excessive miniaturization of the turbine model components, the wind tunnel tests are performed in the low speed section.

In Eq. (1) the scale factor is defined as the ratio between a general DTU 10 MW turbine parameter and the corresponding wind tunnel model parameter.

$$\lambda = \frac{p_{reference}}{p_{model}} \tag{1}$$

The dimensional analysis technique is fundamental in model design for wind tunnel. A series of non-dimensional groups are usually taken into account, the most used are the Reynolds number, Froude Number, Strouhal Number, Cauchy number, etc. Usually the length scale, λ_L, is defined from simple considerations about the wind tunnel dimension, then one of the non-dimensional group is selected to be kept constant from full scale to model scale. The choice is made considering which are the most important parameters that influence tests results. For example Froude scaling is typically used for the presence of non-negligible gravity dependant loads (e.g. long-span bridges, hydrodynamic forces). In floating offshore wind turbine scale tests in ocean basins, Froude scaling is mandatory due to the presence of physical waves. Froude number is defined as in Eq. (2)

$$Fr = \frac{V}{\sqrt{gL}} \tag{2}$$

where V is the velocity, g is the gravitational acceleration and L is the length. Fixing the length scale factor λ_L due to the dimension of the model, the velocity scale factor λ_V is consequently defined as $\sqrt{\lambda_L}$, resulting in very low speeds for the tests.

For this particular project the λ_L has to be selected in the range: $70-90$, the lower limit comes from the maximum wind tunnel model diameter of 2.5 m, this ensures that the blade tip is far enough from the tunnel ceiling and floor during the rotor revolution, thus avoiding the wall boundary layer. The higher limit avoids to have an excessive miniaturization of the model components.

The λ_V has a fixed range of possible values: $1.5-3$, due to a comparison between the cut out speed, 25 m/s, of the DTU 10 MW and the maximum wind tunnel speed, 15 m/s.

A discrete number of possible combinations for the scales were evaluated, a good compromise was found in $\lambda_L = 75$ and $\lambda_V = 2$. Once defined the length and velocity scales, the scales of the principal physical quantities were derived from dimensional analysis. Table 2 reports the most important scaled turbine characteristics.

The blade design aims at matching as close as possible the scaled values of the turbine aerodynamic thrust and torque. It is worth mentioning that, since this scaled design is related to the study of a floating system, the thrust matching is of higher importance since the floating system dynamics is more influenced by thrust than torque (Bredmose et al., 2015).

3. Wind tunnel model blade design input

In this scenario, the main goals in the blade design can be summarized as follows:

- matching the reference thrust coefficient
- matching the scaled first blade flapwise natural frequency
- matching the scaled blade weight

It is pretty clear that the blade design is challenging both from an aerodynamic and structural point of view. In Fig. 1 the blade design procedure is reported.

3.1. Reference design input

The DTU 10 MW reference and wind tunnel model turbine operational parameters are reported in Table 3, as combinations of wind speed, V, rotor rotational speed, Ω and Tip Speed Ratio, TSR ($TSR = \Omega \cdot R/V$). The model wind speed operational value are reduced by λ_V and the model rotational speed is reduced by λ_V/λ_L, this ensures that the TSR does not change when scaling to wind tunnel dimensions. Keeping TSR similitude ensures to have the same aerodynamic kinematics, as it is discussed in the following.

3.2. Model airfoil

One of the most critical aspect in the model blade design is the airfoil selection, as a matter of fact, the main limitation in reproducing the reference aerodynamic performance is related to the Reynolds number reduction when working at wind tunnel scales.

Referring to Eq. (3), Renyolds number depends on the air density ρ, wind speed U, the blade chord length c and air dynamic viscosity μ. The scale factor for Reynolds number is therefore defined as $\lambda_{Re} = \lambda_L \lambda_V$ equal to 150 (i.e. the wind tunnel Reynolds number is 150 times smaller the full scale one). This could result in a completely different aerodynamic behaviour of the blade profile at model scale.

$$Re = \frac{\rho \cdot V \cdot c}{\mu} \tag{3}$$

The Reynolds discrepancy forces to use different airfoil shape than the

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