

COMPUTATIONAL AERODYNAMICS MODELING OF A 5MW NREL WIND TURBINE

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Received: December 10, 2019; Revised: March 29, 2020; Accepted: April 12, 2020

Abstract

Aerodynamic performance of a large-scale 5MW offshore wind turbine rotor designed by National Renewable Energy Laboratory (NREL) is investigated numerically using a hybrid Navier-Stokes/free wake method. This method simulates the flow over wind turbine rotor blade in the near-field region using RANS technique while models the rotor blade wake located far field by a Lagrangian wake representation. The results obtained from hybrid methodology at design condition show a good agreement with predictions from the blade element momentum theory and more computationally expensive wake-capturing simulations. In addition, a new offshore wind turbine of the same rating as NREL turbine has been created based purely on aerodynamic considerations. The performance of the two wind turbines are compared to assess the efficacy of different design approaches.

Keywords: Aerodynamics, wind turbine, computational fluid dynamics, renewable energy

Introduction

With increasing awareness of greenhouse gases emission and potential shortage of fossil fuel, renewable energy technology has been extensively explored and developed over the past several decades. Wind turbine technology, along with growing utilization of wind power, has advanced rapidly leading to a continuous increase in wind turbine size and power production.

A number of studies have been underway in recent years to obtain a better understanding of the underlying flow physics (Butterfield *et al.*, 1992; Xu and Sankar, 2000; Siddiqui *et al.*, 2016), as well as to advance multidisciplinary design and modeling of wind turbines (Tangler and Somer, 1995; Giguere and Selig, 1999; Malcom and Hansen, 2006; Schubel and Crossley, 2012). These efforts have been

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complemented by experimental investigations (Hand *et al.*, 2001; Cho and Kim, 2012). A number of researchers have also performed computational fluid dynamics (CFD) studies of wind turbines of various sizes and operating conditions (Duque *et al.*, 1999; Xu and Sankar, 1999; Benjanirat *et al.*, 2003; Tongchitpakdee *et al.*, 2005; Herraes *et al.*, 2014). Coupled effects of wind turbine aerodynamics with other disciplines such as aeroelasticity and aeroacoustics have also been investigated (Yu and Kwon, 2014; Wasala *et al.*, 2015).

In this study, 5MW offshore wind turbine developed by the National Renewable Energy Laboratory (NREL) in the United States is investigated computationally using hybrid method in-house CFD code. In this work, this design will be referred to as “5MW NREL wind turbine”. CFD results from an in-house hybrid methodology are compared with the predictions from classical combined blade-element momentum (BEM) theory as well as from other CFD methodologies requiring greater computational resources. In addition, a new large-scale offshore wind turbine design of the same rating as 5MW NREL is presented from a purely aerodynamic perspective. Comparison of the two turbine designs are made in order to examine effects of different design methodologies on aerodynamic performances of wind turbine.

Methodology

5MW NREL Wind Turbine Rotor Geometry and Operating Conditions

The design specifications of the 5MW NREL wind turbine selected as baseline design in this study are summarized in Table 1 below. The NREL 5MW wind turbine rotor blade has a tapered planform consisting of 7 different aerodynamic profiles (Jonkman *et al.*, 2009). The blade geometry, and the airfoils used at various radial locations are given in Table 2.

Computational Method: Hybrid Methodology

All CFD analyses of NREL 5MW wind turbine in the present study are conducted using an in-house flow solver, GT-Hybrid. The

hybrid method implemented in the code beneficially combines an accurate RANS solver for the flow region near the rotor blade with a computationally less expensive Lagrangian wake model for the wake region located far field. A spatially third order accurate upwind scheme is used for inviscid flux computation, while the time integration is performed by an approximate LU-implicit time-marching scheme. A variable turbulence models include Baldwin-Lomax, $k-\omega$ -SST, and the Spalart-Allmaras Detached Eddy Simulation (SA-DES). The SA-DES is employed as a turbulence closure for all computational cases in the present study.

The far-field where wake is modeled using Lagrangian wake representation, a free wake model comprising of 15 wake trailer segments which make up the blade span is used for computing wake geometry. Shed wake may also be modeled as needed. Self-induced velocity due to presence of wake and induced velocity at the boundary separating CFD domain and outer wake region are computed using the Biot-Savart law.

Table 1. Design specifications of NREL 5 MW wind turbine

Rated Power	5MW
Roto orientation	Upwind
Number of blades	3
Rotor/Hub diameter	126 m/3 m
Rated wind speed	11.4 m/s
Cut-in/Cut-out wind speed	3 m/s / 25 m/s
Rated rotor speed	12.1 RPM
Overhang/Shaft tilt/Precone	2 m / 5 deg / 2.5 deg

Table 2. NREL 5 MW wind turbine rotor geometry

r/R	Airfoil/Profile	Chord (m)	Twist (deg)
0.0455	Cylinder	3.542	0
0.1322	Cylinder	4.167	0
0.1865	DU40-A17	4.557	13.308
0.2516	DU35-A17	4.652	11.480
0.3817	DU30-A17	4.249	9.011
0.4468	DU25-A17	4.007	7.795
0.5770	DU21-A17	3.502	5.361
0.7071	NACA64-A17	3.010	3.125
1.000	NACA64-A17	0.7	0

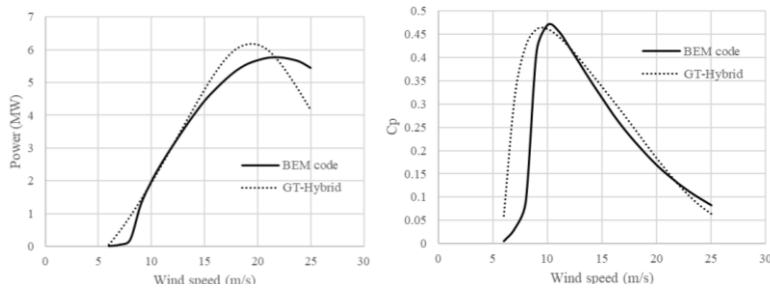


Figure 1. Comparison of hybrid CFD and BEM methodologies for a 2 MW offshore wind turbine (Pichitkul and Sankar, 2019)

It has been shown the hybrid method is economic yet effective in predicting flow field over the wind turbine rotor (Banjanirat and Sankar, 2004). In (Tongchitpakdee, 2007) computational results from the hybrid method are validated against experimental data for the case of NREL Phase VI rotor. In (Pichitkul and Sankar, 2019), simulations of a 2 MW offshore wind turbine using GT-Hybrid is compared against the result from the classical combined blade element-momentum (BEM) theory. The comparisons shown in Figure 1 indicate a very good agreement between the two methods for the power production and the coefficient of power, particularly near the rated speed of 10 m/s.

Computational Domain and Grid Generation

GT-Hybrid solver includes a standalone module for grid generation. Figure 2 depicts a graphical representation the C-H mesh that encapsulates the rotor blade whereas the wake is modeled outside the mesh. In the present

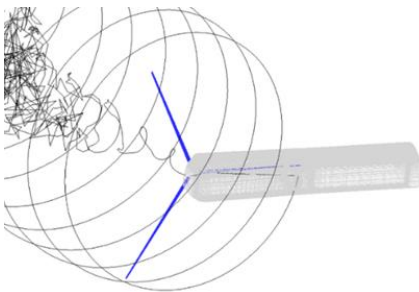


Figure 2 Schematic diagram of the hybrid method

study, all computational cases employ the mesh settings described in Table 3.

Table 3. Computational Grid Settings

Grid Parameter	Value
Number of airfoil wrap-around grid lines	131
Number of above/below airfoil grid lines	45
Number of spanwise grid lines	70
Dimensionless wall distance, y^+	3.25

Aerodynamic Design Approach for Large-Scale Wind Turbine

The 5MW NREL wind turbine was designed from a multi-disciplinary perspective, taking into consideration structural loads and vibrations, in addition to aerodynamic considerations. In this study, a purely aerodynamic approach is presented for a comparable 5MW wind turbine.

Preliminary Sizing

The first design parameter to be determined is the number of blades, B . For a large-scale upwind turbine of larger than 1MW-rating type, it is a common practice to use 3-blade configuration (Malcolm and Hansen, 2006). The rated wind speed of the new wind turbine is set to be the same as for the 5MW NREL turbine (11.4 m/s). The turbine rotor radius can be obtained using a definition of wind turbine power coefficient, C_p given in Equation (1). For a large-scale wind turbine, it is reasonable to assume C_p of 0.5.

$$C_p = \frac{P}{\frac{1}{2} \rho V_{rated}^3 (\pi R^2)} \quad (1)$$

The sizing process described above yields a rotor radius of 60.977 m.

After the rotor radius is found, a rated RPM of the wind turbine is subsequently to be determined. According to (Malcolm and Hansen, 2006) earlier studies suggested that the optimal tip speed ratio, TSR defined by Equation (2) is in a range of 10-12. By considering the rated wind speed along with selecting a TSR of 11.5, the rotational speed of 20.53 RPM is obtained.

$$TSR = \frac{\Omega R}{V_{rated}} \quad (2)$$

Airfoil Selection

To reduce substantial disparities in aerodynamic characteristics among different airfoil families attributable to profile power losses, the same family of airfoil shapes used in the 5MW NREL design is used for the new design.

Blade Twist and Chord Design

To achieve optimal aerodynamic performances from selected airfoil families, a radial twist distribution is selected such that a local angle of attack at each radial station yields the maximum possible lift-to-drag ratio of a given airfoil shape. As depicted by Figure 3, at zero pitch operation, the local blade twist β is related to the local flow angle ϕ , and the local angle of attack α via Equation (3). In this context, ΔV denotes local induced inflow velocity and takes the value of $V_{rated}/3$ for maximum efficiency rotor. Using this definition, the local flow angle ϕ may be approximated using Equation (4).

$$\beta = \phi - \alpha \quad (3)$$

$$\phi = \arctan\left(\frac{V_N}{V_T}\right) \approx \arctan\left(\frac{2}{3} \frac{V_{rated}}{\Omega r}\right) \quad (4)$$

The local blade chord at each radial location is next computed by comparing the local rate of change of flow momentum through an annulus of width Δr on the rotor disk to the aerodynamic forces exerted by the corresponding sections of the blades as described in Equation (5). This relationship can be further simplified to yield Equation (6).

$$\rho(2\pi r \Delta r)(V_\infty - \Delta V)(2\Delta V) = B(L' \cos \phi + D' \sin \phi) \Delta r \quad (5)$$

$$4\pi r V_\infty^2 \left(\frac{2}{9}\right) = B \frac{1}{2} \rho (\Omega r)^2 c C_l \quad (6)$$

After local chord values are determined using the technique described above, the radial chord distribution is replaced with a linear regression fit to allow blade manufacturability.

Design Configuration Summary

The specifications of the new 5MW turbine and a comparison between 5MW NREL and the new design blade geometry are presented in Table 4 and Figure 4, respectively.

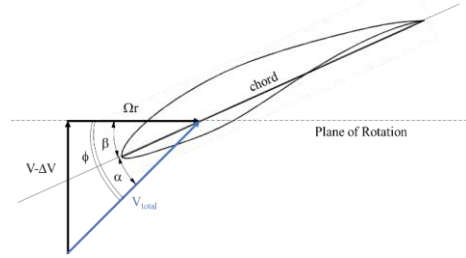


Figure 3. Schematic diagram of a local blade and related angles

Table 4. Design specifications of the NEW 5MW wind turbine

Rated Power	5MW
Roto orientation	Upwind
Number of blades	3
Rotor/Hub diameter	121.95 m/3 m
Rated wind speed	11.4 m/s
Cut-in/Cut-out wind speed	3 m/s / 25 m/s
Rated rotor speed	20.53 RPM
Overhang/Shaft tilt/Precone	0 m / 0 deg / 0 deg

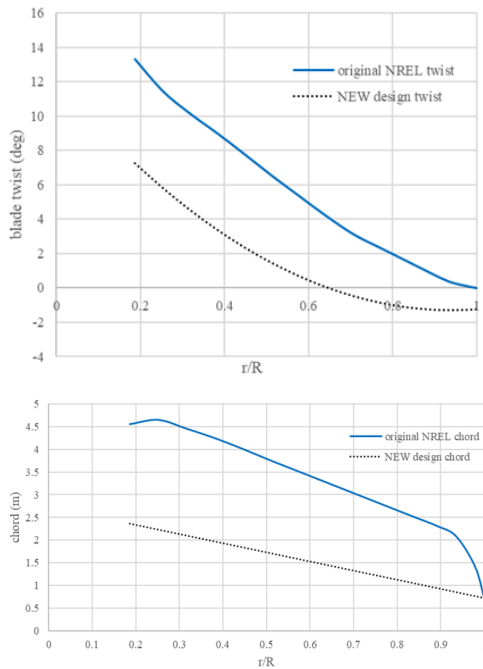


Figure 4. Comparison of blade geometry between 5 MW NREL and the new design

It is seen that the blade chord from the present is considerably shorter than the NREL design where interdisciplinary considerations such as bending and torsional loads on the blade were considered. As a result, the profile power is reduced with the present design leading to some improvements in the rotor performance. The twist distribution is comparable between the two designs, if the NREL rotor is rotated by a non-zero blade pitch.

Results and Discussion

5MW NREL Wind Turbine Prediction by the Hybrid Method

Figure 5 below shows a comparison between power production at rated condition as predicted by GT-Hybrid and industrial standard BEM code WT_PERF (Buhl, 2004). It is seen that the rated power is realized at the rated wind condition.

5MW NREL Blade Load Distributions

In Figure 6, the radial distributions of normal and tangential forces from GT-Hybrid for the 5MW NREL are shown at the rated condition, and compared with predictions from the NREL BEM analysis (WT_PERF). The sectional thrust force, which gives rise to power production was comparable with both approaches. However, the normal forces from

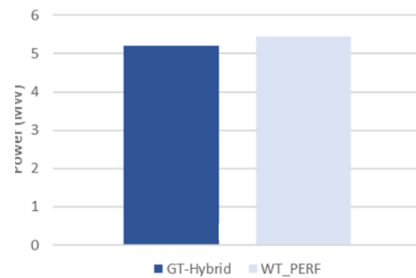


Figure 5. Comparison of power production at rated condition from the hybrid method and BEM

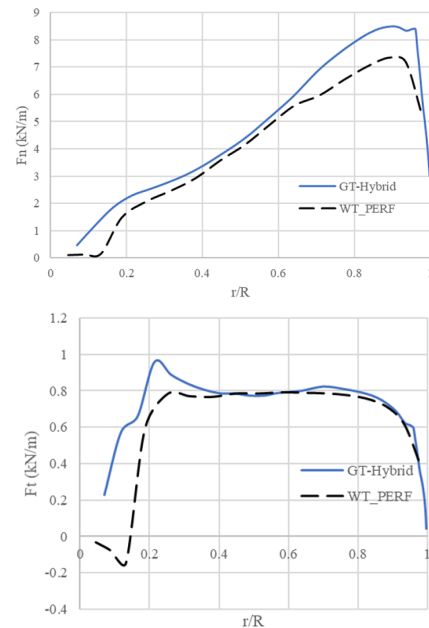


Figure 6. Comparison of normal and tangential forces between the hybrid method and BEM at rated condition

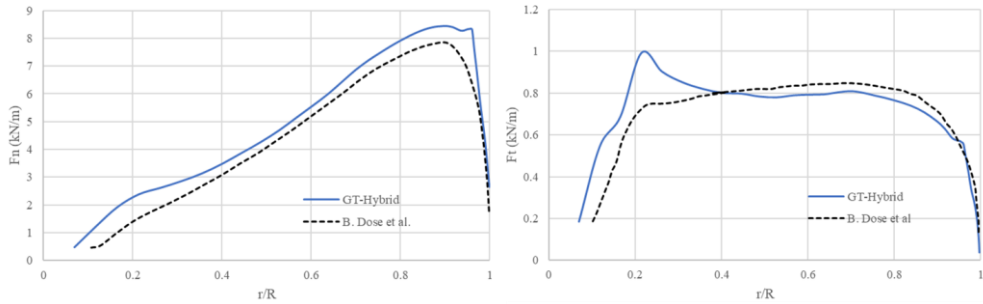


Figure 7. Comparison of normal and tangential forces between the hybrid method and fully unsteady RANS simulation at rated condition

the GT-Hybrid analysis were higher in the tip region, compared to the BEM theory.

To better understand and assess capability of the hybrid method in computing airflow over this large-scale wind turbine, comparisons of normal and tangential forces along blade span at the rated condition from the hybrid method have been compared with the more computationally expensive fully unsteady RANS computations by Dose *et al.* (2018) in Figure 7. The agreement is considered satisfactory, given the wide differences in the computational methodologies used in these two approaches.

Performance Comparison between 5MW NREL and NEW 5MW Rotor Design

A comparison between power production of 5MW NREL and the new 5MW design preliminarily assessed by BEM code WT_PERF is given in Figure 8. As stated earlier, the smaller chord of the present design yields a lower profile power penalty, and leads to a somewhat higher power coefficient at the rated wind speed of 11.4 m/s and at higher speeds.

Concluding Remarks and Future Works

The hybrid methodology presented in this study efficiently and effectively simulates the flow over 5MW NREL wind turbine rotor at rated condition. The current study thus serves as a validation that the present hybrid method

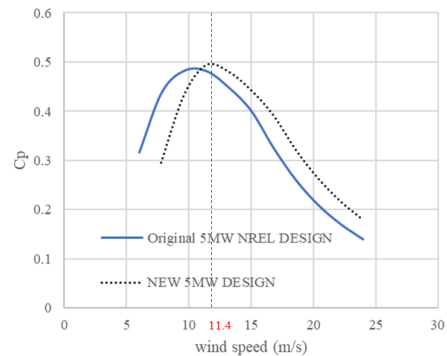


Figure 8. Comparison of power production of original 5MW NREL design and the new 5MW design

is applicable to large-scale wind turbine configurations. The hybrid CFD solver may be modified to take into account wind speed variation due to ground boundary layer effects. In addition, the solver may be modified to handle unsteady upcoming winds and hub motion attributable to wave loads, allowing wider variety of physical phenomena to be modelled.

Acknowledgments

The first author would like to express her gratitude toward the Royal Thai Government for the scholarship and financial support over the course of her study.

Appendix: Nomenclature

B	Number of rotor blades
c	Chord length
c_l	Sectional lift coefficient
C_p	Power Coefficient
D'	Drag force per unit blade length
L'	Lift force per unit blade length
P	Rotor power
r	Blade radial position
R	Rotor radius
V	Wind speed
ΔV	Local induced inflow velocity

Greek Symbol

α	Local angle of attack
β	Local element pitch angle
ϕ	Local flow angle
ρ	Air density
Ω	Rotor angular speed

Subscripts

N	Normal to plane of rotation
T	Tangential to plane of rotation
<i>rated</i>	Rated condition

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