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Determination of Scaled Wind Turbine Rotor Characteristics from Three Dimensional RANS Calculations

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Abstract. Previous studies have shown the importance of 3D effects when calculating the performance characteristics of a scaled down turbine rotor [1–4]. In this paper the results of 3D RANS (Reynolds-Averaged Navier-Stokes) computations by Make and Vaz [1] are taken to calculate 2D lift and drag coefficients. These coefficients are assigned to FAST (Blade Element Momentum Theory (BEMT) tool from NREL) as input parameters. Then, the rotor characteristics (power and thrust coefficients) are calculated using BEMT. This coupling of RANS and BEMT was previously applied by other parties and is termed here the RANS-BEMT coupled approach. Here the approach is compared to measurements carried out in a wave basin at MARIN applying Froude scaled wind, and the direct 3D RANS computation. The data of both a model and full scale wind turbine are used for the validation and verification. The flow around a turbine blade at full scale has a more 2D character than the flow properties around a turbine blade at model scale (Make and Vaz [1]). Since BEMT assumes 2D flow behaviour, the results of the RANS-BEMT coupled approach agree better with the results of the CFD (Computational Fluid Dynamics) simulation at full- than at model-scale.

1. Introduction
Experiments in combined wind and waves are necessary to validate numerical models of floating offshore wind turbines (FOWTs) but scaling for such model tests is challenging [5], especially because of the low Reynolds number flow at model scale. At MARIN (Maritime Research Institute Netherlands) both experiments and numerical simulations are conducted. For the experimental investigations a performance-matched wind turbine, the MARIN Stock Wind Turbine (MSWT), was developed and tested in collaboration with the University of Maine (e.g. Martin et al. [6], Fowler at al. [7] and Kimball et al. [8]). This model scale turbine is designed to match the performance coefficients of the NREL 5MW baseline turbine at full scale. Fernandes et al. [2] used this turbine for comparison of thrust and power coefficients between results from XFOIL, 2D RANS computations and basin tests. These investigations revealed discrepancies of the 2D computations to the experimental results. Additionally, a direct three-dimensional RANS (Reynolds-Averaged Navier-Stokes) computation of the thrust and power coefficients with ReFRESCO (http://www.refresco.org) achieved a better agreement with the experiments than these two-dimensional calculations (Make et al. [3]). The comparison of
the different methods investigated are shown in Figure 1 for the thrust and power coefficient. Three-dimensional effects, such as radial flow along the blade and flow separation, were suspected to be the cause of these discrepancies.

Figure 1: Thrust (a) and power (b) coefficients of the MSWT at model scale computed by different methods [2] showing model tests in red, FAST+2D ReFRESCO in green, FAST+XFOIL in blue and 3D ReFRESCO in black.

In addition, an optimization of the load coefficients of the scaled rotor to reproduce the measured rotor loads was performed by Gueydon et al. [4]. Three different optimization methods were applied to the MSWT mounted on the 1/50\textsuperscript{th} scale DeepCwind semi-submersible floating platform. The paper showed the differences between these three methods and their effect on the motions of the floater. The importance of a correct estimation of the rotor characteristics for the surge and pitch motions of the floating support structure was emphasized. The aerodynamic damping of the motions is greatly influenced by the thrust coefficient. Hence, the current work pays special attention to the thrust coefficient.

In its current state, ReFRESCO cannot conveniently be used to simulate a floating wind turbine (i.e. a spinning rotor on a moving platform in waves and wind). Instead it is solely used for the determination of the aerodynamic characteristics (thrust and power) of the rotor at low Reynolds numbers, which are encountered during model tests. FAST (Fatigue, Aerodynamics, Structures and Turbulence [9]) is an engineering tool that accounts for the coupling of the rotor aerodynamics and the floater hydrodynamics. In order to reproduce the model tests, it is intended in the present study to supply FAST with aerodynamic coefficients of the rotor’s blades (lift and drag) at model scale by using RANS calculations. The thrust and power coefficients are calculated with FAST by simulating steady wind condition and fixed rotor speed for each TSR (Tip Speed Ratio). The effect of a controller for the wind turbine rotor is not included in this paper.

More ways to extract aerofoil coefficients from 3D RANS calculations can be found in the literature [10,11]. Four different techniques were applied on: the MEXICO (Model Experiments in Controlled Condition) turbine a 4.5m diameter rotor using CFD and experimental data [10]; the UAE (Unsteady Aerodynamics Experiment) phase-VI 10.058m turbine rotor with
experiments [12]; and the Nordtank NTK 500/41 turbine having a 41 m diameter rotor in full
scale using CFD and experimental data [11].

The objective of the present work is to create a link between RANS and BEMT calculations of
wind turbines that are typically used for the testing of FOWTs in combined wind and waves
in hydrodynamic testing facilities. This method aims at producing lift and drag coefficients for
the description of a rotor used in a Froude scaled wind. Froude scaling of a wind turbine rotor
results in low Reynolds number flow (typically \( < 10^5 \)).

The RANS-BEMT coupled approach to calculate the thrust and power coefficients is presented
in this paper. This approach is similar to the inverse BEMT method mentioned in [10]. The
results of this technique are validated and verified with two different turbines. Model test data
and model scale CFD data of the MSWT in 3D (small scale rotor with a 2.52 m diameter,
Reynolds number range from \( 2.2 \cdot 10^4 - 5.4 \cdot 10^4 \) at 70% of the rotor) and full scale CFD data of
the NREL 5MW baseline turbine in 3D (rotor diameter of 126 m, Reynolds number range from
\( 5.16 \cdot 10^6 - 1.24 \cdot 10^7 \) at 70% of the rotor) are used as a reference.

More information about the geometrical data, blade profile and development of the MSWT
can be found in Martin [13] and Make [14]. The NREL 5MW baseline turbine is specified by
Jonkman et al. [15].

Nomenclature

| Variable | Description | Unit |
|----------|-------------|------|
| \( a \)  | Axial flow induction factor per section | \([-\) |
| \( a' \) | Tangential flow induction factor per section | \([-\) |
| \( c \)  | Chord length | \( m \) |
| \( C_d \) | Sectional drag coefficient | \([-\) |
| \( C_l \) | Sectional lift coefficient | \([-\) |
| \( C_P \) | Power coefficient | \([-\) |
| \( C_p \) | Pressure coefficient | \([-\) |
| \( C_T \) | Thrust coefficient | \([-\) |
| \( d \)  | Drag force per section | \( N \) |
| \( f_t \) | Tangential force per section | \( N \) |
| \( f_x \) | Axial force per section | \( N \) |
| \( f_r \) | Resultant force per section | \( N \) |
| \( l \)  | Lift force per section | \( N \) |
| \( p \)  | Pressure | \( N/m^2 \) |
| \( R \)  | Radius of the rotor | \( m \) |
| \( Re_c \) | Reynolds number based on chord \( (Re_c = (w \cdot c)/\nu) \) | \([-\) |
| \( r \)  | Local radial distance | \( m \) |
| \( s \)  | Planform area of a section | \( m^2 \) |
| \( TSR \) | Tip speed ratio \( (TSR= \Omega \cdot R/V) \) | \([-\) |
| \( V \)  | Wind inflow velocity | \( m/s \) |
| \( w \)  | Relative inflow velocity at a blade section | \( m/s \) |
| \( \alpha \) | Angle of attack (AoA) per section | \( ^{\circ} \) |
| \( \beta \) | Twist angle of the blade | \( ^{\circ} \) |
| \( \theta \) | Angle between relative inflow velocity \( w \) and rotation plane | \( ^{\circ} \) |
| \( \nu \)  | Kinematic viscosity | \( m^2/s \) |
| \( \rho \) | Fluid density | \( kg/m^3 \) |
| \( \tau \) | Shear stress | \( N/m^2 \) |
| \( \Omega \) | Angular velocity | \( rad/s \) |
2. Numerical tools
For the work of this paper two numerical tools are used to obtain the RANS-BEMT coupled approach. These tools are ReFRESCO, a RANS code, and FAST with its subroutine AeroDyn [16] applying the Blade Element Momentum Theory.

2.1. ReFRESCO
ReFRESCO (http://www.refresco.org) is a community based open-usage CFD code for the Maritime World. The code solves multiphase (unsteady) incompressible viscous flows using the Navier-Stokes equations, complemented with turbulence models, cavitation models and volume-fraction transport equations for different phases [17]. The equations are discretized using a finite-volume approach with cell-centered collocated variables, in strong-conservation form, and a pressure-correction equation based on the SIMPLE algorithm is used to ensure mass conservation [18]. Time integration is performed implicitly with first or second-order backward schemes. At each explicit time step, the non-linear system for velocity and pressure is linearized with Picard’s method and either a segregated or coupled approach is used. A segregated approach is adopted for the solution of all other transport equations. The code is parallelized using MPI and subdomain decomposition, and runs on Linux workstations and HPC clusters.

The computations selected for this work were carried out using a RANS approach together with the $k-\omega$ SST (shear stress transport) two equation turbulence model by Menter [19]. The momentum equations were discretized using the QUICK 2nd order scheme for convection and a central 2nd order scheme for the diffusion terms. For the turbulence equations a 1st order convection scheme was used. For efficiency and simplicity the turbine tower was neglected. By doing so there is no need for sliding interfaces, or overlapping grids, and the rotational motion of the turbine can be described by means of an Absolute-Formulation (AFM). By using the AFM approach the RANS equations are solved in the moving reference frame but the variables written in terms of the absolute, earth-fixed inertial reference frame quantities. As a result, steady calculations can be considered. More information about the ReFRESCO computations can be found in [1], who used it to compute the flow around turbine blades.

2.2. FAST
FAST is a computer aided engineering code designed for the simulation of coupled dynamic responses of floating wind turbines [9]. This code is developed and maintained by NREL (National Renewable Energy Laboratory). The aerodynamics are modelled within the AeroDyn subroutine. It uses quasi-steady BEMT (Blade-Element-Momentum Theory) or a generalized dynamic inflow model (see Moriarty and Hansen [16]). BEMT consists of two principles: a permeable actuator disc in a closed stream tube and a collection of independent two-dimensional aerofoil elements (see Togneri et al. [20]). From the first principle the changes in axial and rotational momentum across the face of the actuator disc can be obtained. Equating this first principle with the forces of the second principle, a relationship between the gross flow velocities and the aerodynamic forces at any radial position along the rotor blades can be derived. An integration along the radius of the blade results in the performance characteristics of the rotor. More information about BEMT can be found e.g. in Burton et al. [21]. The theory of the AeroDyn subroutine is described by Moriarty and Hansen [16]. For this work FAST version 7 is used.

3. Coupling method
There are four techniques named in Guntur and Sørensen [10] to conduct the extraction of aerofoil coefficients from three-dimensional RANS computations. These techniques are:
• An inverse BEMT (Blade Element Momentum Theory) method using previously determined local forces to calculate the local induction
• Obtaining the annular average of the axial velocity at a given radial position in the rotor plane by the usage of CFD
• Obtaining the axial velocity at a given radial position in the rotor plane at the location of the blade by the usage of CFD
• Determining the angle of attack (AoA) by comparison of high-pressure side $C_p$ distributions of a 3D case with a 2D case with a known AoA

The RANS-BEMT coupled approach presented here is similar to the first of the four techniques mentioned above. The steady three-dimensional RANS computations of the MSWT at model scale and the NREL 5MW at full scale [1] are taken as a starting point for the calculations. In the work of Make and Vaz computations of the two turbines in a TSR number range from three to eight were carried out. The calculation procedure within the RANS-BEMT coupled approach is illustrated with the flowchart in Figure 2.

![Flow chart of RANS-BEMT coupled approach.](image)

To create a link between the three-dimensional CFD computations and the Blade-Element-Momentum Theory tool FAST, the 3D wind turbine blade is divided into equidistant sections. Every section is assumed to be two-dimensional. Then the pressure $p$ and shear stress $\sigma$ distribution are integrated to obtain the axial and tangential forces of every cross section along the blade, $f_x$ and $f_t$, respectively. Since the model scale turbine has a poor lift/drag performance, the drag and therefore the shear stress is an important factor to calculate the thrust correctly. In a first step the induction, represented as $a$ and $a'$ within BEMT, is neglected. Thus, the angle of attack $\alpha$ is directly calculated by the far upstream wind inflow velocity, $V$, and the local blade
velocity, $\Omega r$. The axial and tangential forces are used to calculate the lift and drag coefficients, $C_l$ and $C_d$, respectively. These results are used as an input for the BEMT computations done with FAST. In this calculation, $C_l$ and $C_d$ of a given section are restricted to the values which were obtained from $f_x$ and $f_t$. The output of FAST provides the thrust and power coefficients as well as the induction factors. These axial and tangential induction factors are taken to calculate new input data ($C_l$, $C_d$, $\alpha$), which can be used for new FAST calculations. FAST is called iteratively until the thrust and power coefficient of each iteration is less than 0.1%. The next two subsections detail the calculation procedure of the RANS-BEMT approach.

3.1. Axial and tangential forces
The first step consists of the force calculation using the pressure and shear stress distributions from the three-dimensional RANS-computations. The pressure and shear stress distributions have been resolved into axial and tangential components. These components are integrated separately to obtain the axial and tangential forces.

3.2. Inverse BEMT calculations
To calculate the lift $l$ and drag $d$, the velocities and forces acting on a 2D section have to be defined. These forces and velocities are depicted in Figure 3. The forces are presented in red, the velocities in blue and all other quantities in black.

The wind turbine blade rotates with a local velocity of $\Omega r$. Hence, the relative velocity at the blade $w$ can be obtained as:

$$w = \sqrt{(V^2 \cdot (1-a)^2) + \Omega^2 r^2 \cdot (1 + a')^2}$$

(1)

The induction factors $a$ and $a'$ for the flow in axial and tangential directions are a consequence of the actuator disc concept [21]. This concept assumes a change of axial and rotational momentum in the flow. The change of momentum results in an alteration of the velocities which is represented by the induction factors. Together with the angle of attack $\beta$ forms $\theta$ (see Figure 3): $\theta = \alpha + \beta$. For the MSWT the lift and drag forces can be calculated as:

$$l = -f_x \cdot \cos \theta - f_t \cdot \sin \theta$$

(2)
\[ d = -f_x \cdot \sin \theta + f_t \cdot \cos \theta \]  

Then, the corresponding lift and drag coefficients are estimated as:

\[ C_l = \frac{l}{0.5 \cdot \rho \cdot w^2 \cdot s} \]  
\[ C_d = \frac{d}{0.5 \cdot \rho \cdot w^2 \cdot s} \]  

$s$ is the planform area of a section and $\rho$ is the fluid density. The lift and drag coefficients as well as the angles of attack are used to fill the aerofoil data files of FAST. Since one angle of attack is provided per 2D section (per TSR), the aerofoil data files are restricted to take the calculated lift and drag coefficients. FAST computes the force transmitted across the shaft between the rotor and gearbox including aerodynamic, gravity and inertia loads. This is important for the turbine design. However, for this paper the aerodynamic properties of the blade are of interest. In addition, the CFD simulations did not take into account the gravity and inertia loads. Therefore, these contributions are subtracted to obtain the aerodynamic thrust coefficients. The procedure is also applied to the full scale NREL 5MW turbine. In the next section the results of this RANS-BEMT coupled approach are presented.

4. Results

The results of this coupled approach show the thrust and power coefficients ($C_T$, $C_P$) for two different turbines. The MSWT is tested at model scale (rotor with a 2.52 m diameter, Reynolds number range from $2.2 \cdot 10^4 - 5.4 \cdot 10^4$ at 70% of the rotor) and the NREL 5MW turbine at full scale (rotor diameter of 126 m, Reynolds number range from $5.16 \cdot 10^6 - 1.24 \cdot 10^7$ at 70% of the rotor). For each of these quantities, calculations with different amount of sections (11, 21, 42, 63) are conducted. The results for the NREL 5MW turbine at full scale are shown in Figure 4 for a wind inflow velocity of $V = 11.4$ m/s. Figure 5 presents the results for the MSWT at model scale for a wind inflow velocity of $V = 2$ m/s. In both figures the thrust coefficient is shown on the left and the power coefficient on the right. The direct CFD calculation from Make and Vaz [1] is given as a reference (CFD 3D). Additionally, experimental data of the MSWT [22] are presented in Figure 5.

![Figure 4: Thrust (a) and power (b) coefficients of the NREL 5MW baseline turbine at full scale.](image-url)
The results of the RANS-BEMT approach show a better agreement with the original direct CFD computation, with increasing number of spanwise sections. The studies of Make and Vaz [1] showed a greater two dimensional behaviour of the flow around a turbine blade at full scale than at model scale. Based on this observation the full scale RANS computations should be more appropriate for the RANS-BEMT approach than the model scale RANS computations. This statement is confirmed by the comparison of the CFD 3D and the RANS-BEMT results at full and model scale.

The results of the coupled approach and the direct CFD computation are similar. In all four graphs the trend and the magnitude of the values are similar. For the model scale rotor the RANS-BEMT results compare to the experiment almost as well as the direct CFD computation. Considering that the RANS-BEMT approach relies partly on the RANS results and partly on the BEMT results, the differences between CFD 3D and RANS-BEMT are acceptable.

5. Conclusions
The objective of this work was to create a link between RANS and BEMT calculations of wind turbines at low Reynolds number flows encountered at model tests in a basin. An approach was developed to use three-dimensional RANS results as input for the BEMT computations so that lift and drag coefficients can be determined resulting in similar $C_T$ and $C_P$. This RANS-BEMT coupled approach was then applied to computations of a turbine at full scale and a turbine at model scale.

It was shown that the results of this approach and the results of the direct CFD computations done by Make and Vaz [1] are similar for both turbines. At model scale, where other standard aerodynamic tools (e.g. XFOIL) fail to determine the force coefficients (see Fernandes et al. [2]), the RANS-BEMT approach is a valid alternative. However, the work of Gueydon et al. [4] showed that further improvement in the prediction of the rotor characteristics is needed for a correct numerical modelling of FOWT dynamics at model scale.

Perspectives for future work include the following points:

- A comparison with results using other ways of obtaining the angle of attack directly from CFD simulations.
- CFD computations with a wider range of angles of attack and more Reynolds numbers.
• Development of an approach that accounts for unsteady conditions (gust wind, varying speed, pitching blades) on moving foundations.

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