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Review

Analyzing scaling effects on offshore wind turbines using CFD

Michel Make [a], [*], [1], Guilherme Vaz [b]

[a] Maritime Research Institute Netherlands Academy, Wageningen, The Netherlands
[b] Maritime Research Institute Netherlands, Wageningen, The Netherlands

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ABSTRACT

In this paper the flow over two (floating) wind turbines has been studied using RANS CFD calculations at model and full-scale Reynolds numbers conditions. The well-known NREL 5 MW and MARIN designed turbines (MARIN Stock Wind Turbine or MSWT) have been analysed. The MSWT was designed to have the same thrust at model-scale as the NREL turbine at full-scale conditions. The thrust was the major driver since it is more important for the behaviour of the floating platform. Numerical sensitivity studies were done to minimize all possible uncertainties: domain size, iterative convergence, grid refinement, and turbulence model sensitivity was studied. Modern verification and validation procedures were used to assess those uncertainties and to perform a validation of the numerical results against experimental data coming from constant uniform inflow, fixed turbine experiments. Furthermore, the flow around the turbines and its performance, both for model and full-scale, have been scrutinised, compared, and insights into their behaviour and Reynolds/scale effects gained. A good agreement between the CFD results and the experimental data has been obtained, with low uncertainties for thrust but large uncertainties for power. The large Reynolds effects on the flow of these turbines have been also shown and explained. Finally, it has been confirmed that the MSWT performs as intended at model-scale conditions.

1. Introduction

Floating offshore wind turbines (FOWT) are becoming attractive within the renewable energy world. Several FOWT have been deployed with success [1–3]. Other than bottom fixed offshore wind turbines, FOWT are subject to complex dynamic loads. While the wind turbine is exposed to aerodynamic loads generated by wind, the floater is subject to loads such as those generated by waves, currents and mooring systems. The combination of the latter results in a complex coupled system, which requires thorough analysis in order to formulate suitable legislation and for optimisation of FOWT designs before construction can begin.

The complexity of FOWT systems led to the development of modelling tools, capable of modelling the fully coupled response of FOWT such as FAST [4]. These tools, based on the Blade-Element-Momentum-Theory (BEMT), predict the aerodynamic performance of the wind turbine by using 2D airfoil data to predict the 3D wind turbine performance. As a consequence, the accuracy of these BEMT-based tools depends on the accuracy of the input data and 2D nature of the flow over the turbine. BEMT-based tools can provide good preliminary performance predictions, however, they may be very inaccurate when used to consider off-design, wide range Reynolds-numbers, highly dynamic and three-dimensional flows that arise on an FOWT [5].

Recent developments in computer technology allows for the analysis of wind turbines using more advanced, and theoretically more accurate, viscous-flow computational fluid dynamics (CFD) codes. Several studies have been published in which the aerodynamic behaviour of wind turbines are studied using these more advanced methods with varying complexity (e.g. see Refs. [6–8]). Yet the complete simulation of a full-scale free-floating wind turbine under wind and waves using viscous-flow CFD codes is still nowadays very costly, if not impossible.

An alternative method to study the dynamic response of FOWT is simultaneous wind and wave model testing, at smaller scales than the real prototype. However, conducting combined wind and wave tests, in which floater and turbine are modelled simultaneously, can be challenging. Several floating wind turbine model tests have been performed before: in 2006, a $\lambda = 47$ (1:47) scale experiment was performed in which a spar-buoy 5 MW floating

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[*] Corresponding author.

E-mail addresses: make@cats.rwth-aachen.de (M. Make), g.vaz@marin.nl (G. Vaz).

[1] Currently: Chair for Computational Analysis of Technical Systems, RWTH Aachen University, Schinkelstrasse 2, 52062 Aachen, Germany.

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Nomenclature

λ	Scale factor [−]
$\mathbf{\Omega}$	Vorticity vector [1/s]
$\mathbf{S}$	Strain-rate vector [1/s]
μ	Dynamic viscosity [kg/ms]
ν	Kinematic viscosity [m^2/s]
Ω	Rotational velocity [rad/s]
ρ	Density [kg/m^3]
τ_w	Wall shear-stress [kg/ms^2]
A	Sectional area πR^2 [m^2]
C_P	Power coefficient $\frac{Q\Omega}{\frac{1}{2}\rho V_\infty^3 A}$ [−]
C_T	Thrust coefficient $\frac{T}{\frac{1}{2}\rho V_\infty^2 A}$ [−]
$c_{0.7}$	Turbine chord at radial section r/R°=°0.7 [m]
C_{pn}	Pressure coefficient $\frac{p-p_\infty}{\frac{1}{2}\rho(nD)^2}$ [−]
D	Turbine diameter [m]
n	Rotational velocity [rad/s]
p	Pressure [N/m^2]
p_∞	Free stream pressure [N/m^2]
Q	Torque [Nm]
R	Turbine radius [m]
r	Turbine radial coordinate [m]
$R_{c_{0.7}}$	Reynolds number $\frac{\rho V_{wind} c_{0.7}}{\mu}$ [−]
T	Thrust [N]
U	Uncertainty [−]
V_∞	Undisturbed (free-stream) velocity [m/s]
V_{wind}	Inflow wind velocity [m/s]
$y+$	Dimensionless nominal distance to the wall $\frac{y_n\sqrt{\tau_w/\rho}}{\nu}$ [−]
TSR	Tip-Speed-Ratio $\frac{\Omega R}{V_\infty}$ [−]

fully functional wind turbine was studied [9]; a $\lambda = 64$ model experiment using a FOWT design with three wind turbines was tested some years later [10]; and in 2010, a $\lambda = 105$ scale model experiment involved modelling the turbine by means of a circular disk in combination with spinning weights to model the thrust and gyroscopic forces respectively [11]. Although these tests are valuable for the parties involved, the test methodologies varied significantly, and the detailed findings are not publicly available.

A unified model-testing methodology for Froude scale testing of FOWT was therefore proposed in Refs. [12], where a series of $\lambda = 50$ scaled model tests using the NREL 5 MW baseline turbine have been described in detail. These tests focused on the dynamic response of a fully functional FOWT, and were performed at the Maritime Research Institute in the Netherlands (MARIN). In these tests Froude (Fr)-scaling laws were applied to both wind and waves. This, since the main goal of these experiments was the proper modelling of the FOWT hydrodynamic response, and use of Froude-scaling (equal model and full-scale Froude numbers $Fr_M = Fr_F$ for setting the wind speed V_w; and geometry *just* scaled with $\lambda = 50$) is common practice. The same however, does not hold for modelling the turbine aerodynamics. As a consequence of Reynolds dissimilitude, the model-scale performance of the turbine (i.e. C_T and C_P) is compromised significantly. For proper modelling of the FOWT dynamic behaviour, it is desirable to have similar C_T and C_P values at model and full scale. However, since the dynamic response of the floater due to wind turbine loading is mostly dominated by the thrust force, it is more vital that C_T is similar at model and full scale. To obtain the correct model-scale C_T, a so-called *performance scaling* method [12,13] has been used ($Fr_M = Fr_F$ for V_w; and geometry *modified* and scaled with $\lambda = 50$), in which the turbine geometry was altered such that C_T was, as much as possible, similar for model and full scale. Using this methodology MARIN designed a new turbine denoted MARIN Stock Wind Turbine or MSWT [12,13].

As emphasised above, due to the very different scales of model and full-scale prototypes, the flow regimes can be very dissimilar and the performance of the turbines at model-scale may deteriorate. Also, all design and preliminary studies on FOWT have been done using BEMT tools that need accurate 2D aerodynamic data as input. While these tools have been applied with success for full-scale turbines [14] their application for model-scale cases is not very widespread, and due to their intrinsic assumptions questionable (see e.g. Refs. [13,15]). Therefore, in order to further improve FOWT designs and their model-scale experiments, it is imperative to fully understand in detail the all-scales physics of these turbines.

In the present work, a viscous-flow CFD approach is used to simulate fixed non-floating turbines, this being the basis for any further studies on floating turbines. Model- and full-scale conditions are studied and the scaling effects on the flow field and aerodynamic performance coefficients scrutinized. Both the NREL 5 MW baseline turbine [16], and the MSWT turbines [13] are analysed. Special attention is paid to the numerical accuracy of the CFD calculations by: 1) studying the influence of several numerical settings and schemes (domain size, boundary conditions, grids, iterative convergence, convergence residuals, turbulence models, etc); 2) using verification and validation (V&V) procedures [17] and techniques. The uncertainty of the numerical calculations on the different quantities of interest will be estimated and used for all comparisons between numerical and experimental results, with the aim of increasing the trustworthiness of the results, remarks and conclusions presented in this work. Although used for comparison and validation, the BEMT simulations and experiments are not part of the current work. A detailed description including the numerical and experimental setup used for the latter is given in Refs. [12–15].

The paper is structured as follows. The two turbines studied are introduced in Section 2. Afterwards, the CFD solver ReFRESCO, the computational settings, as well as the applied verification and validation procedures are presented in Section 3. Next, in Section 4, the major results are presented and discussed: first all numerical studies performed using the MSWT, then the analysis of the flow and performance of the NREL and the MSWT turbines and finally a comparison between all results obtained. A summary of conclusions is given in Section 5.

2. Geometries and flow conditions

While for the NREL 5 MW baseline turbine [16], a chord-based Reynolds number at 70% blade span ($Re_{c_{0.7}}$) is around 1×10^7, at model-scale it of order of magnitude of 5×10^4 when using Froude-scaled wind [12]. As it will be shown in this paper, the critical or sub-critical regime at these low model-scale Reynolds numbers results in a laminar boundary layer at the blades of the turbine, which is able to withstand only small adverse pressure gradients before separation occurs. The high level of flow separation reduces the lift-drag ratio of the turbine blade, with reduced C_T and C_P values. The poor aerodynamic performance at model-scale required extra measurements in order to improve and match the full-scale thrust and power.