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Aerodynamic modeling methods for a large-scale vertical axis wind turbine: A comparative study

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A B S T R A C T

Vertical axis wind turbines (VAWTs) are experiencing a renewed interest for large-scale offshore wind energy generation. However, the three-dimensional (3D) modeling of VAWT aerodynamics is a challenging task using computational fluid dynamics (CFD), owing to the high computational costs entailed. To alleviate this computational burden and improve design process efficiency, an alternative low-order model (LOM) is presented that incorporates key VAWT aerodynamic effects. These coupled sub-models account for the influence of dynamic stall, tower shadow, parasitic drag, flow curvature and finite blade effects.

A two-step approach is adopted to investigate two-dimensional (2D) and 3D VAWT aerodynamics separately with experimental data. A CFD model was created and both modeling strategies were compared. The LOM showed good agreement with the CFD model and the measurements with a low computational cost requirement. The CFD results identified that as the tip-speed ratio (TSR) was increased, the tower's downwind wake became increasingly more skewed.

Finally, both the LOM and the CFD model were employed in predicting the VAWT aerodynamic efficiency. It was established 3D effects must be included to provide an accurate prediction of VAWT performance especially at high TSRs. For VAWT analysts, modeling recommendations and limitations are discussed regarding the LOM.

1. Introduction

1.1. Background

In recent years, there has been a growing interest in the development and commercialisation of offshore floating wind turbine technology. Floating wind turbines are a viable design solution for deep water sites (>50 m) and can provide the opportunity to exploit superior offshore wind resources. These turbines can be separated into two primary configurations, the horizontal axis wind turbine (HAWT) and the vertical axis wind turbine (VAWT) [1]. The former has received an abundance of research reinforced by its considerable success for onshore installations and subsequently has been selected to be most suitable for a floating dynamic system [2]. Although, the latter remains highly underdeveloped, it has the potential to provide a more practical low-cost alternative due to its desirable offshore design attributes. The VAWT has considerable advantages over its horizontal axis counterpart such as its omnidirectionality and its higher range of structural scalability [3,4]. Furthermore, the placement of the turbine's generator at sea level improves the system's stability and therefore can reduce the size of the floating foundation structure required considerably. An important requirement for a floating VAWT is to restrain the floating platform from the yaw moment such that the aerodynamic torque is neutralised sufficiently [5,6]. The resurgence of interest in VAWT technology has recently led to studies investigating aerodynamic performance in an offshore environment [1,4,7–12].

Despite the VAWT's simplistic structural design, its aerodynamics are very complex and pose an analyst with significant modeling challenges. Particularly, at low tip-speed ratios (TSRs), a VAWT blade experiences dynamic stall due to the continuous high variation in its angle of attack. These large angular excursions produce highly unsteady coherent structures on the blade's lifting surface and are subsequently shed into its wake [13]. As the turbine's TSR increases its efficiency is dictated primarily by parasitic drag losses created by the VAWT's structural elements, while dynamic stall effects are mitigated. Furthermore, the rotor encounters

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vortex interactions whereby the retreating blade impinges on its own wake and the wakes of other preceding blades [14]. Fig. 1 shows a typical performance curve for a VAWT depicting its pertinent aerodynamic performance regions. The net result indicates that VAWTs operate in an adverse, unsteady aerodynamic environment with many complex interdependent flow features that must be captured to accurately model the turbine's performance [15].

1.2. Aerodynamic modeling

It is widely perceived that current VAWT designs are not as efficient as HAWTs and a strong contributing factor to this supposition is the deficiency of suitable models available for design optimisation. Many simplistic low-fidelity models utilised for HAWTs have been modified for VAWTs without taking into consideration their inherent differences and can lead to poor predictions [16]. A literature survey of numerical models can be found from Borg et al. [2] which can be broadly placed into three categories (1) Momentum model, (2) Vortex model and (3) Cascade model. At the other end of modeling spectrum exist computational fluid dynamics (CFD) methods that numerically solve the Navier-Stokes equations. These higher-order approaches have shown good success as reflected in the studies by Refs. [13,17–22]. Furthermore, its ability to give a very detailed insight into the VAWT's flow field and inherent versatility shows this approach gaining popularity for future VAWT aerodynamic investigations. However, the high computational run-times, large memory requirements and the user prowess required for CFD methods has so far delayed its regular application in the wind turbine industry [23]. Notwithstanding the major advancements in distributed computing, numerical simulations of wind turbine aerodynamics are still demanding, possibly requiring several days on powerful sophisticated parallel hardware architectures [24]. Moreover, this requirement can be severely exacerbated in cases where repeated solutions are needed for multidisciplinary design studies. Subsequently, at present the utilisation of CFD remains a topic of much debate and discussion within the offshore VAWT design community.

In most cases, researchers resort to two-dimensional (2D) CFD models rather than three-dimensional (3D) models as the computational cost can be three orders of magnitude higher than that of a 2D CFD model [25]. However, 2D models have shown to overestimate the VAWT's efficiency as parasitic drag losses and finite blade effects are not simulated [18,19,25]. Interestingly, Siddiqui et al. [20] showed that a 2D simulation over-predicted VAWT performance by 32% in comparison to a full 3D simulation. In addition, Maître et al. [26] found that the blade tip vortices and the interference drag produced at the blade/strut junction were responsible for a 22% loss in the aerodynamic efficiency. Kinsey and Dumas [27] showed that the drop in performance relative to a 2D study can be limited to nearly 10% when endplates are used on blades with aspect ratios greater than ten. Balduzzi et al. [17] examined the important CFD modeling aspects regarding VAWTs and initially specifies that a 3D model is required when investigating the turbine power output. These studies highlight that care must be taken when making conclusions purely based on 2D models and Lam and Peng [19] confirm this by stating that *"a full-scale three-dimensional CFD model is undoubtedly necessary to capture realistic flow behaviors around VAWTs"*.

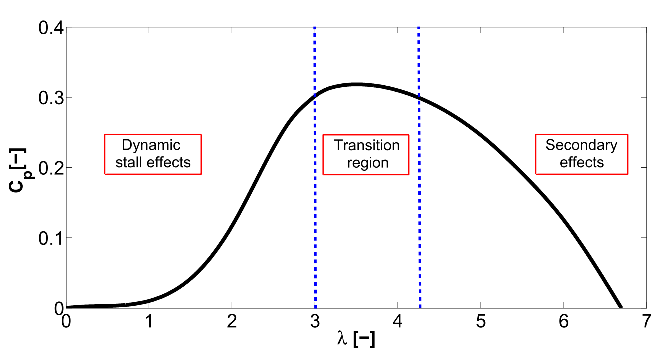

Fig. 1. Typical VAWT aerodynamic performance curve.

1.3. Aim of the present study

It is clear a 3D CFD model can provide better accuracy than a 2D model, but the CPU run-times involved are impractical and currently not affordable at the conceptual design stage. Therefore, in the interests of computational efficiency an alternative modeling strategy is needed to negate these high computational demands and accelerate the industrial design process. This paper presents designers with a low-order model (LOM) that can be utilised for simulating large-scale VAWT aerodynamic performance in a computational efficient manner. The objective of this design tool is to permit rapid design iteration to allow for the development of optimal turbines designs. The LOM incorporates salient characteristics of higher-order methods and is compared with a CFD model in predicting 2D VAWT aerodynamics. Additionally, the LOM's predictive ability is examined with the addition of 3D aerodynamic effects in comparison with experimental measurements and also CFD results.

2. Experiments

2.1. Survey of experiments

A multi-megawatt offshore VAWT will operate at high Reynolds numbers and its blades will experience a turbulent boundary layer during operation [11,13]. Table 1 provides a summary of the available experimental studies from the open literature, which meet the requirement of $Re_{avg} > 10^6$. As the VAWT's blades experience a continuously varying relative velocity during the turbine operation, the average Reynolds number (Re_{avg}) is used here to characterise each turbine and is expressed in Eq. (1).

$$Re_{avg} = \frac{\Omega R c}{\nu} \quad (1)$$

where Ω is the VAWT rotational velocity, R is the radius at the VAWT midspan, c is the blade chord length and ν is the air kinematic viscosity.

It is necessary to ensure the flow similarity to that of a large-scale offshore VAWT. This is important, as the blades of small-scale VAWTs experience a low Reynolds number flow regime and the boundary layer separates more readily from the blade's surface [13,28]. Moreover, as emphasised by Bachant and Wosnik [29], numerical models should be validated with physical data obtained at the same scale as the intended prototype. For each VAWT listed in Table 1, the corresponding available experimental dataset types are also stated. One cannot fail to notice that the VAWT power coefficient measurements (i.e. $C_p(\lambda)$) dominate at this scale and the availability of blade normal and tangential force coefficient measurements (i.e. $C_N(\theta,\lambda)$ and $C_T(\theta,\lambda)$) are scarce. Where θ is the blade azimuthal angle and λ is the tip-speed ratio defined as: