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Study on start-up characteristics of H-Darrieus vertical axis wind turbines comprising NACA 4-digit series blade airfoils

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A B S T R A C T

Installation of H-type vertical axis wind turbines is in many cases limited by the inherent start-up issues associated with this type of turbine. This could be crucial in environments with low wind speed. The aim of this study is to provide an appropriate CFD modeling setup for investigation of the start-up behavior associated with this class of turbines. For this purpose, a series of transient CFD simulations were carried out using ANSYS Fluent. In contrast with the conventional approach, whereby a constant angular velocity is specified for the rotor, in the present work, the turbine was left free to accelerate based on the torque experienced over time. Careful considerations were made regarding turbulence modeling and grid generation, which are key to ensuring accuracy in this investigation. The result of this simulation, in the form of an accelerating time series, demonstrates good agreement with the published experimental data, and the method yields a high level of accuracy, proving its usefulness for similar problems. In another attempt, the validated CFD setup was utilized to evaluate the effects of several geometric attributes of the turbine rotor on the starting characteristics. Symmetric and cambered airfoils of different thicknesses with a wide range of pitch angles were examined. The optimum start-up characteristics were observed with the use of a medium-thickness cambered airfoil, NACA2418, put to use with an outward pitch angle of 1.5°; this configuration decreased the start-up time while retaining the turbine's peak performance.

1. Introduction

Policies enacted in recent decades to reduce dependence on fossil fuels, and a growing interest in renewable energy, particularly wind energy, have encouraged researchers to develop various types of wind turbines. Although horizontal axis wind turbines (HAWT) continue to be the most popular for large-scale power production, their counterparts, vertical axis wind turbines (VAWT), especially Darrieus turbines, have received much attention in recent years for stand-alone applications [1,2]. Ease of maintenance, simplicity of blade fabrication, and lower operating noise are just some of the advantages of VAWTs over conventional propeller-type turbines. Additionally, their operation is independent of wind direction and they demonstrate higher efficiency in turbulent flow fields, making them highly attractive [3–6].

In spite of the stated advantages of VAWTs, some researchers [7] have claimed that Darrieus-type turbines with fixed rotor geometry and straight blades parallel to the rotation axis (Fig. 1) are not capable of self-starting. Watson and Mays et al. have pointed out the effects of the Reynolds number on self-starting behavior [8,9].

To resolve the self-starting issue, researchers have proposed various rotor geometries, including various types of active/passive pitching mechanisms that have been designed by Nahas [10], Kirke [3] and other researchers and reviewed in depth by Pawsey [11] and Kirke and Lazauskas [12]. Moreover, Kirke [3] pointed out that self-starting can be assisted with careful airfoil selection, by optimizing the thickness and camber. Although assisted Darrieus rotors have received a great deal of recent attention, in an experimental study, Dominy et al. [13] showed that for three-bladed H-Darrieus turbines, self-starting is possible even when fixed-pitch and symmetrical airfoils are used. In an open section wind tunnel test, their low-solidity turbine succeeded in escaping the dead band of operating speeds stated by Baker [14]. This provided a new resolution to a historical concern related to the use of Darrieus turbines without active controls. Nevertheless, VAWTs still suffer from a considerable lag in development compared to HAWTs due to the

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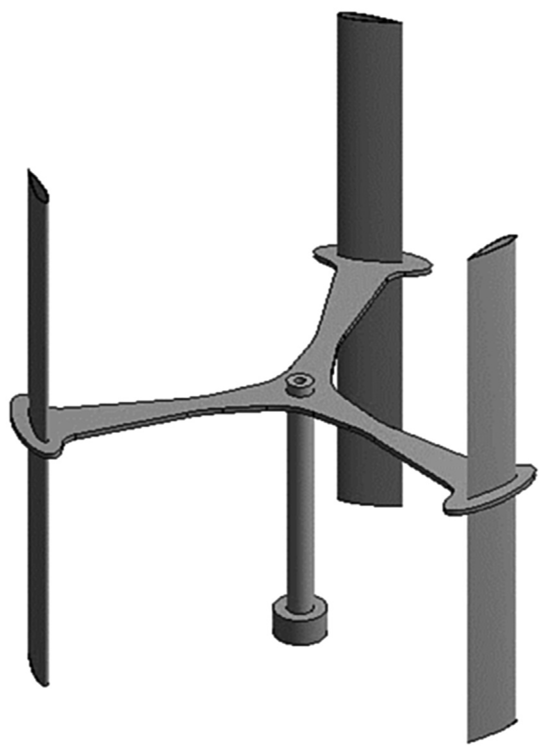

Fig. 1. Straight-bladed Darrieus (H-Darrieus) rotor schematic.

complexity of their flow fields; the angle of attack undergoes large and rapid changes during operation, as discussed by Untaroiu et al. [4], particularly at low tip speed ratios (TSRs), in conditions of large-scale separation, and during interaction with turbulent wakes, as reported in the literature [15–17]. Due to these issues, investigations into the performance of VAWTs can be controversial. Major difficulties are also inevitable in studies associated with their starting behavior. According to a literature survey, the most widely used analytical models in the aerodynamic study of VAWTs can be categorized into momentum models, vortex models, and cascade models. Various extensions of the momentum model (also known as the blade element momentum model) tend to suffer from the inaccuracy of the predicted aerodynamic loads on turbine blades during their quasi-steady operation, and the inability to deal with some important details, such as the wakes produced by individual blades [8]. More importantly, the momentum equation is not valid for conditions of high TSRs, or for the study of rotors of high solidity [18]. Vortex models are considered to be the most accurate models among the three types, but the latest versions of these models still rely on significant simplifications, are highly time-consuming, and suffer from convergence problems [19]. The cascade model offers smooth convergence in all ranges of TSR and solidity, with quite reasonable accuracy [20]. In spite of the strength of the cascade model, it has not received as much attention as the momentum and vortex models.

Computational fluid dynamics (CFD) methods have been employed in a few works to investigate VAWT start-up behavior [4,20]; however, results from these works were not in general agreement with published experimental data, and some of the modeled VAWTs failed to pass the early plateau stage highlighted by Hill et al. [21] and Howell et al. [22].

Although these studies largely failed due to imprecise geometry, the application of less appropriate turbulence models, or poor grid generation, some precipitous conclusions were stated about the capability of numerical methods for such applications. As a result, future developments of VAWTs were left to high-cost experimental studies or deficient quasi-steady simulations.

Accordingly, the initial purpose of the present work is to discuss in detail the issues associated with CFD simulation of VAWT start-up performance, to criticize improper judgments in the literature, and to reintroduce CFD techniques to the community for this specific application. The present work includes careful investigations of grid generation, turbulence modeling, and time step size to overcome the complexity of flow acting on the turbine rotor over its entire operating range. These steps yield a precise model, whose output results are validated herein against empirical data from a wind tunnel test of a turbine with identical geometry. We showed that CFD techniques, in the form of transient simulations, are applicable in the accurate modeling of VAWT behavior from standstill until peak operating condition.

This work also included an effort to improve the start-up performance of this type of turbine by testing geometry variations using the validated CFD technique. Symmetric and cambered NACA airfoils of different thicknesses were examined, as well as a wide range of positive and negative fixed pitch angles, and the optimal configuration, based on this comprehensive study, is proposed herein.

2. VAWTs and CFD modeling

Several CFD simulations of VAWTs have been conducted to provide insight into rotor performance and to enhance the operation of this class of turbines [23–26]. The usual practice is to produce a power curve for the turbine rotor in a quasi-steady-state condition, in which the rotor is forced to run with a constant TSR. Following this practice, Ferreira et al. [27] have conducted extensive work to evaluate H-Darrieus rotor performance. Their work concentrated on the significance of turbulence modeling, and a variety of existing models have been compared in this way for the purpose of studying H-Darrieus machines. Although remarkable conclusions have been made based on such investigations, this approach does not provide data on turbine acceleration and thus cannot provide any insight into starting behavior. This fact has encouraged researchers to alternatively conduct fully time-dependent simulations to study turbine start-up.

Of crucial importance, in a CFD simulation the turbine rotor is not connected to any measurement system or any generator; therefore, there is no additional mechanical load or magnetic resistance. This is considered a significant advantage of CFD simulation. In contrast, in experimental studies the measurement system adds negative loads to the rotor and thus the results are valid only for generators identical to those used in the experiment. In CFD simulations, it is possible to actively update the setup based on generator operating charts or related calculations. This precise technique could therefore be beneficial for the testing of different turbine–generator configurations.

Although 3D CFD simulations, by their nature, can generally provide higher-accuracy results than 2D studies, they are considered impractical for VAWT simulations due to their excessive computational requirements even when coarse meshes are applied (which itself can lead to inaccurate results). Regardless of the fact that in 2D simulations some secondary effects as well as the contribution of blade tips and the resistance of the support arm are neglected, a recent review of the literature shows that 2D models are sufficient for these types of studies [22,28–32].

In the current study, the commercial CFD solver ANSYS Fluent was employed as a standalone simulation environment. A 2D transient CFD simulation, utilizing a sliding mesh capability, was run over time. A circular domain enclosing the rotor was allowed to undergo relative motion. Also, the 6DOF solver [33], which is