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Computational aerodynamic optimisation of vertical axis wind turbine blades

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ABSTRACT

The approach and results of a parametric aerodynamic optimisation study is presented to develop the blade design for a novel implementation of a vertical axis wind turbine. It was applied to optimise the two-dimensional cross-sectional geometry of the blades comprising the turbine. Unsteady viscous computational fluid dynamic simulations were used to evaluate blade performance. To compare geometries, the non-dimensional coefficient of power was used as a fitness function. Moving meshes were used to study the transient nature of the physical process. A new parameterisation approach using circular arcs has been developed for the blade cross sections. The optimisation process was conducted in two stages: firstly a design of experiments based response surface fitting was used to explore the parametric design space followed by the use of a Nelder–Mead simplex gradient-based optimisation procedure. The outcome of the optimisation study is a new blade design that is currently being tested in full-scale concept trials by a partnering wind energy company.

1. Introduction

1.1. Background and motivation

In recent years, environmental and economic pressures to reduce society's dependence on fossil fuels in power generation has led to significant research investment into sustainable power generation. A leading contender in this field is the extraction of energy from the wind using turbines, often co–located as large wind farms, which can be based on either land or at sea.

A vast array of academic and industrial optimisation studies have been performed on wind turbines. Tu et al. conducted an optimisation study on a Horizontal Axis Wind Turbine (HAWT) using a combination of CFD simulations and neural networks to evaluate turbine performance [1]. This was incorporated into a genetic algorithm for optimisation. However, not every study utilises CFD simulations for performance evaluations. This is because they require a significant computational resource. Instead, some studies such as those carried out by Cencelli et al. and Dossing et al. [2,3] have performed optimisations on HAWTs using Blade Element Momentum Theory (BEMT) which places a much lower demand on computational resource. However, BEMT cannot readily be applied to Vertical Axis Wind Turbine (VAWT) studies. This is because BEMT fundamentally relies on the concept of an actuator disk and known lift and drag blade properties. While the first shortcoming can be circumvented through

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Nomenclature

BEMT	Blade Element Momentum Theory
CFD	Computational Fluid Dynamics
C-FEC	Cross Flow Energy Company
DoE	design of experiments
HAWT	horizontal axis wind turbine
LHS	latin hypercube sampling
RMSE	root mean square error
VAWT	vertical axis wind turbine
A	turbine frontal area
C_p	coefficient of power
R_0	blade outer arc radius (X_1)
A_0	blade half arc angle of outer arc (X_2)
T_L	blade left thickness (X_3)
T_C	blade centre thickness (X_4)
T_R	blade right thickness (X_5)
Y	blade yaw angle (X_6)
Ψ	blade azimuthal angle
Ω	turbine rotational speed
U_∞	freestream wind speed
P	power
T_i	torque on blade i

the use of the double multiple stream tubes method [4], a prerequisite knowledge of the blade's lift and drag properties is incompatible with a numerical optimisation of its aerodynamic behaviour.

This work builds upon this knowledge and uses CFD tools to develop an automated optimisation program that does not require human interaction to search for a potentially optimal geometry. The focus of the optimisation study is on the two-dimensional blade cross section of a VAWT. The rest of this section outlines the problem and clearly defines the objectives of the research. Following this an insight into geometry parameterisation is given with the developed scheme shown in detail. Then, different aspects of the CFD simulations such as geometry meshing and the flow field solver are introduced. A sample is taken of the almost infinite number of possible blade shapes (design space) and an analysis is conducted to identify any possible trends in an attempt to gain a basic understanding of what is to be expected. Finally, the results obtained are presented and analysed.

1.2. Design overview of C-FEC vertical axis wind turbine

The research study presented in this paper was undertaken to assist a wind turbine design company, Cross-Flow Energy Company Ltd (C-FEC Ltd), in the development of a blade optimisation method for their wind turbine design. The concept turbine developed by the company is a Vertical Axis Wind Turbine (VAWT) using both lift (Darrieus effect) and drag (Savonius effect) to extract energy from the wind and produce the torque necessary to generate an exploitable form of energy. A limited number of optimisation studies are provided in the literature on the geometric optimisation of VAWTs that are designed specifically to take advantage of both lift and drag on the turbine blades for torque generation. Gupta et al. [5] have considered the efficiency improvements in the combination of Darrieus and Savonius effects in the design of a VAWT compared with a pure Savonius design . Manohar [6] have considered using the centrifugal effect to rotate a turbine's blades to move from operation in Savonius mode to operation in Darrieus mode to avoid the problem with self-starting in Darrieus turbines whilst taking advantage of the usually higher efficiency of Darrieus turbines operating at high speed. The C-FEC turbine design includes an additional and novel, as far as the authors are aware, asymmetric shield. This feature, which moves dependent on the oncoming wind direction, is not commonly seen in commercial wind turbines and increases turbine efficiency by shrouding the returning blades and thus minimising the negative torque that they would otherwise be generating. Fig. 1 shows a top-down view of the turbine designed by C-FEC Ltd with key components labelled. The azimuthal angle (ψ) is used to give reference to blade positions. In this paper it is defined as the angle between the direction of the free stream flow and the centre of the blade being considered. The green arrows indicate positive torque that is used in generating power and the red arrows indicate negative torque that hinders the production of power.

As the blades move perpendicularly to the wind direction (at ψ approaching 90°) drag becomes the dominant force. As the blades then move to become parallel to the flow (at ψ approaching 180°) the drag reduces and lift increases, making it the dominant force in this position. It is this combined use of lift and drag to create torque that potentially makes this machine very efficient. To further improve the design, the shield that is in place aids in reducing the drag on the retreating blades ($180° < \psi < 360°$) by redirecting the freestream flow. It is the hybrid nature of this design that provided the motivation for exploring a new method for blade shape parameterisation.