Ocean Engineering 169 (2018) 202–214

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Optimization of blade profiles for the Wells turbine

Tim Gratton[a], Tiziano Ghisu[b,*], Geoff Parks[a], Francesco Cambuli[b], Pierpaolo Puddu[b]

[a] Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, United Kingdom
[b] Department of Mechanical Engineering, Chemistry & Materials, University of Cagliari, Cagliari, 09123, Italy

ARTICLE INFO

Keywords:
Wells turbine
Optimization
OpenFOAM
Tabu search
Free form deformation

ABSTRACT

A Wells turbine, when coupled with an oscillating water column, allows the generation of power from the energy in waves on the surface of the ocean. In the present work, a tabu search is used to control the process of optimising the blade profile in the Wells turbine for greater performance, by maximising the torque coefficient. A free form deformation method is used as an efficient means of manipulating the blade profile and computational fluid dynamics in *OpenFOAM* are used to assess each profile in both two and three dimensions. Investigations into both the flow coefficient at which the optimization is performed and the number of control variables in the free form deformation tool are performed before optimisations are done on a two-dimensional blade at the hub and tip solidities. This results in increases to the torque coefficient of 34% and 32% at the tip and hub solidities, respectively. These results are then applied to the three-dimensional turbine, giving a 14% increase in the torque coefficient. The results are assessed and an improved method of optimising the blade in two dimensions is proposed.

1. Introduction

As the world moves into an age where it can no longer be reliant on fossil fuels to meet our energy needs, renewable sources of electrical power are being explored more thoroughly than they have been in the past. While solar and wind energy is available around 20–30% of the time, energy from waves on the surface of the ocean is available up to 90% of the time in a suitable location (Pelc and Fujita, 2002). One method of harvesting this energy is through the use of oscillating water column (OWC) systems equipped with a Wells turbine, proposed by Prof. Alan Arthur Wells (1980).

A reciprocating airflow through a duct is produced when waves reach an OWC system built on the shore (Heath, 1959; Falcao and Henriques, 2016) or floating in water (Luo et al., 2014). A turbine installed in the duct creates a torque that is used to drive a generator which produces electrical power. Due to the nature of the task, the turbine must be able to generate power from airflow in both directions (inflow and outflow) and, as a result of this, it usually has a symmetric layout. The rotation of the blade combined with the axial flow effectively create a wing at incidence, and the associated lift and drag forces can be resolved in the axial (F_A) and tangential (F_T) directions. The Wells turbine therefore shares many of the features of a symmetric wing: the low lift at low angles of attack requires the axial flow to be sufficiently large for the lift component of the tangential force to overcome the drag in order to produce power. There is also an upper limit, above which stall reduces the tangential force. These two features of the Wells turbine limit the values of the flow coefficient (ϕ), defined as the ratio of axial velocity to blade speed, where the device is useful to those immediately preceding stall.

Increasing the performance of the Wells turbine would provide greater power output to the electrical grid for a device of the same size. There are two key measures of the performance of the Wells turbine: non-dimensional torque (C_T) and efficiency (η) which are defined in equations (1)–(3). The non-dimensional torque, or torque coefficient, is a measure of the useful work produced by the turbine blades. An increase in the torque (T) supplied to the generator will allow more power to be produced. The efficiency takes the torque coefficient and divides it by the non-dimensional axial force on the blade, a measure of the pressure drop across it, and the flow coefficient. If the efficiency is increased, it means that, for the same pressure drop, there is a greater torque driving the generator. This parameter is important, as if in the process of increasing the torque coefficient the efficiency is lowered, a greater pressure difference will be required across the blade. Due to effects in the OWC, the peak axial flow velocity will be reduced, decreasing the peak flow coefficient and subsequently the peak torque. This would negate some of the improvements that have been made (Simonetti et al., 2017).

* Corresponding author.
E-mail address: t.ghisu@unica.it (T. Ghisu).

https://doi.org/10.1016/j.oceaneng.2018.08.066
Received 16 April 2018; Received in revised form 1 July 2018; Accepted 30 August 2018
0029-8018/ © 2018 Elsevier Ltd. All rights reserved.

$$C_T = \frac{T}{\frac{1}{2}\rho\Omega^2 r_{\text{tip}}^5} \tag{1}$$

$$C_A = \frac{\Delta p}{\frac{1}{2}\rho\Omega^2 r_{\text{tip}}^2} \tag{2}$$

$$\eta = \frac{C_T}{C_A\phi}\frac{1}{\pi\left(1-\frac{r_h^2}{r_t^2}\right)} \tag{3}$$

There are many parameters that can affect the performance of the Wells turbine. A summary of previous studies on the effects of blade sweep, solidity and profile is presented below.

Three-dimensional (3D) simulations in *ANSYS Fluent* (ANSYS, 2013a) have been used to consider the effect of sweep on a Wells turbine blade with both NACA0020 and CA9 profiles by Kim et al. (2002). A blade sweep ratio of 0.35 was found to improve the mean efficiency and stall point, and the NACA0020 profile was found to perform better than the CA9 profile. A formal optimization on the blade sweep parameter at the mid and tip sections has been completed by Halder et al. (2017a). Simulations of a monoplane turbine with a NACA0015 profile were done in *ANSYS CFX* (ANSYS, 2013b) and used to create surrogate models for the efficiency and torque coefficient. These models were then used with a genetic algorithm to identify a Pareto-optimal front for the problem. Two designs were selected for evaluation: the first increased the torque coefficient by 28% and the operating range by 18% at the expense of a 14% decrease in efficiency, while the second increased the efficiency by 6% but decreased the peak torque coefficient by 36% and decreased the operating range by 22%. These results illustrate the trade-off that is often found in real-world multi-objective optimization problems.

A computational investigation using the *NEWT* solver (Dawes, 1992) on three different solidities of Wells turbine has been presented by Watterson and Raghunathan (1998). This work found that increasing the solidity of the turbine increased the operating range. A new, variable chord length, Wells turbine design is suggested by Soltanmohamadi and Lakzian (2016). A blade profile varying from NACA0020 at the hub to NACA0012 at the tip is used for aerodynamic and structural reasons. A 26% reduction in entropy generation was achieved. Solidity was further considered by Shaaban (2017a) by combining a genetic algorithm with computational fluid dynamics in *ANSYS Fluent*. Pareto solutions were found that could either increase the efficiency by up to 5% with a 3% decrease in torque coefficient or increase the torque coefficient by 11% while also increasing the efficiency by 2%.

Studies into the effects of the blade profile on the turbine performance have been also carried out. Among standard symmetric profiles, the NACA0020 blade appears the most suitable for low Reynolds number turbines (Setoguchi et al., 2004) while the NACA0015 profile displayed better performance at larger Reynolds numbers; however, due to the nature of the experimental approach taken, these studies were only able to consider four blades from standard families. To the authors' knowledge, the only work that studies the use of generic blade profiles (i.e. not from standard families) in a Wells turbine is the one from Mohamed et al. (2011), who combine a multi-objective genetic algorithm with a parameterization of the blade profile using a spline fit of a series of 12 control points. The evaluations were completed using two-dimensional (2D) simulations in *ANSYS Fluent*. This led to an increase in torque coefficient of 12% and a 1% increase in efficiency for the optimized blade when compared to the datum NACA0021 profile. No verification of the applicability of these results to the 3D turbine is presented. A similar optimization algorithm has been used by Shaaban (2017b), but applied to the biplane turbine, using a 3D evaluation in *ANSYS Fluent*. Due to the significantly larger time require by 3D simulation, the description of the blade profile has been simplified significantly, by dividing a NACA0015 profile at the point of maximum thickness, and allowing only a scaling the two sections. This led to a 9% improvement in the peak torque coefficient.

This work presents an optimization of the blade profiles for a Wells turbine, using a free form deformation tool to modify the blade shape and a tabu search optimization algorithm to explore the design space. The objective is to maximise the torque coefficient, as evaluated by computational fluid dynamics (CFD). Initially, an investigation is conducted to find the optimal number of control variables in the free form deformation (FFD) tool. Then, the profiles used for the hub and tip sections are optimized in 2D. A 3D turbine has been generated by applying a linear variation of the hub and tip profiles and then evaluated to verify the actual gain in performance. A choice has been made to keep the blade solidity fixed at the datum value, in order to avoid a significant variation of the pressure drop vs flow coefficient curve (i.e. the turbine damping), which affects the water level displacement in the OWC and therefore the turbine working conditions (Torres et al., 2016; Simonetti et al., 2017, 2018; Bouali and Larbi, 2017; Elhanafi et al., 2017; Mahnamfar and Altunkaynak, 2017).

The rest of the paper is organized as follows. Section 2 presents the optimization system (i.e. optimizer, parameterization approach, and evaluation system), Section 3 presents the results from the two-dimensional optimization of the blade profiles, and Section 4 verifies the proposed modifications in three dimensions. Finally, Section 5 presents some conclusions and suggestions for future work.

2. Optimization system

The optimization system involves three main components. A tabu search routine, described in Section 2.1, is used to explore the design space, represented by the control point locations that are used in the FFD tool presented in Section 2.2. These control points are used to modify the blade shape and, accordingly, the simulation domain. The performance of the new profile is then assessed using CFD to evaluate the objective function. This component is outlined in Section 2.3. A flow chart for this system is shown in Fig. 1.

2.1. Tabu search

The tabu search (TS) algorithm (Glover, 1989) is a metaheuristic optimization method with a local search at its core, but with routines to escape local minima and explore further regions of the search space. While this method cannot guarantee that the global minimum will be found, the progressive nature of the search should ensure that some improvement is made, making it suitable for the task of optimising the blade profile of the Wells turbine. The algorithm is well suited to parallelization, by evaluating the objective function of each candidate non-tabu move simultaneously across multiple computing nodes. This has a direct influence on the choice of CFD software that is best suited to the task. In previous research, the commercial code *ANSYS Fluent* has been used to great effect (Ghisu et al., 2015; Kim et al., 2002). However, licences must be purchased for each individual node that is to be used simultaneously and this would severely limit the extent to which the search could be carried out in parallel. Open source codes do not have this limitation, making them a better choice for this work. Of all the

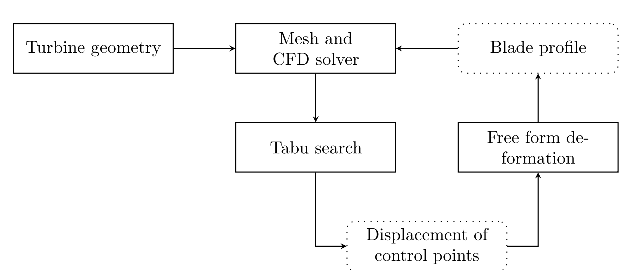

Fig. 1. Interaction of the system components.

Download English Version:

https://daneshyari.com/en/article/10156184

Download Persian Version:

https://daneshyari.com/article/10156184

Daneshyari.com