+ MODEL
ARTICLE IN PRESS
+ MODEL
Available online at www.sciencedirect.com
ScienceDirect
Publishing Services by Elsevier
International Journal of Naval Architecture and Ocean Engineering xx (2016) 1—14
http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

Numerical optimization of Wells turbine for wave energy extraction

Paresh Halder [a], Shin Hyung Rhee [b], Abdus Samad [a,b,*]

[a] *Wave Energy and Fluid Engineering Laboratory, Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai 600036, India*
[b] *Research Institute of Marine Systems Engineering, Department of Naval Architecture and Ocean Engineering, Seoul National University, Seoul, South Korea*

Received 5 May 2016; revised 20 June 2016; accepted 27 June 2016
Available online ■ ■ ■

Abstract

The present work focuses multi-objective optimization of blade sweep for a Wells turbine. The blade-sweep parameters at the mid and the tip sections are selected as design variables. The peak-torque coefficient and the corresponding efficiency are the objective functions, which are maximized. The numerical analysis has been carried out by solving 3D RANS equations based on *k-w* SST turbulence model. Nine design points are selected within a design space and the simulations are run. Based on the computational results, surrogate-based weighted average models are constructed and the population based multi-objective evolutionary algorithm gave Pareto optimal solutions. The peak-torque coefficient and the corresponding efficiency are enhanced, and the results are analysed using CFD simulations. Two extreme designs in the Pareto solutions show that the peak-torque-coefficient is increased by 28.28% and the corresponding efficiency is decreased by 13.5%. A detailed flow analysis shows the separation phenomena change the turbine performance.

Keywords: Blade sweep; Wells turbine; Optimization; Wave energy; CFD

1. Introduction

In the recent years, various renewable energy sources have been explored, and devices to harness such energy are developed. One such device is an Oscillating Water Column (OWC) to harvest ocean wave energy. The device uses a Wells turbine for its power-take off. The turbine is an axial-flow self-rectifying low-pressure turbine and rotates continuously in a unique direction by the bidirectional action of air or working fluid. The turbine blades have a stagger angle of 90° and are constructed using symmetric aerofoils.

In the OWC, a reciprocating airflow is created by the action of ocean waves and the air transfers energy to the turbine blades. The air, which is the working fluid, reverses its direction with wave but the turbine rotation direction does not change. The effect of turbine design parameters have been investigated based on the experimental and numerical analysis by several researchers (Brito-Melo et al., 2002; Raghunathan, 1995; Taha et al., 2010; Torresi et al., 2004; Halder et al., 2015). However, there exists a limited number of systematic optimization works to improve its design and performance. One of such design parameters is the aerofoil shape of the turbine blade, which is optimized to increase the power output and efficiency (Mohamed et al., 2011).

The power output and the efficiency of the turbine depend on the design parameters and nature of flow over the blade Suction Surface (SS). The power transferred to the blade is higher for the flow attached to SS. A backward swept blade has a higher efficiency and torque over a wider operating range (Webster and Gato, 2001, 1999a). The blade efficiency or performance can be altered by modifying its shape (Kim et al., 2002; Mohamed and Shaaban, 2013, 2014).

Modifications of blade shape have been reported for gas turbine, steam turbine and hydro turbine, where the researchers achieve the asymptotic enhancement of turbine

* Corresponding author. Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai 600036, India.
E-mail address: samad@iitm.ac.in (A. Samad).
Peer review under responsibility of Society of Naval Architects of Korea.

http://dx.doi.org/10.1016/j.ijnaoe.2016.06.008

Please cite this article in press as: Halder, P., et al., Numerical optimization of Wells turbine for wave energy extraction, International Journal of Naval Architecture and Ocean Engineering (2016), http://dx.doi.org/10.1016/j.ijnaoe.2016.06.008

Nomenclature

Abbreviations

CFD	computational fluid dynamics
CV	cross validation
FC	flow coefficient
KRG	Kriging method
LE	leading edge
MOO	multi-objective optimization
NSGA	non-dominated sorting of genetic algorithm
OWC	oscillating water column
PBA	PRESS-based average
PoF	Pareto optimal front
PS	pressure surface
RANS	Reynolds-averaged Navier−Stokes
RB	rotor blade
RBF	radial basis function
Ref	reference
RSA	response surface analysis
SS	suction surface
SST	shear stress transport
TC	tip clearance
TE	trailing edge
TKE	turbulent kinetic energy
WAS	weighted average surrogate

Symbols

B	rotor axial length
C	rotor blade chord length
d_1	constant of equation (2)
d_2	constant of equation (2)
E	error
F	objective function
$h = \frac{R_{hub}}{R_{tip}}$	hub-to-tip ratio
N	speed of rotor, rpm
N_{sm}	the number of basic surrogate model
$T^* = \frac{T}{\rho\omega^3 R_{tip}^5}$	torque coefficient
$\Delta P^* = \frac{\Delta P^o}{\rho\omega^2 R_{tip}^2}$	pressure drop coefficient
ΔP^o	static pressure drop
Q	volume flow rate
$r^* = \frac{R}{R_{tip}}$	non-dimensional radius
R	radius
$R_{mid} = \frac{(1+h)}{2} R_{tip}$	mid-span radius
$s = \frac{ZC}{2\pi R_{mid}}$	turbine solidity
T	blade thickness
T	shaft torque
U_{tip}	rotor velocity
$U^* = \frac{V}{U_{tip}}$	flow coefficient
Ω	rotational speed
$U*$	flow coefficient
V	axial velocity
W	weight
z	number of rotor blades
Θ	camber angle
Λ	sweep angle
P	density
$\eta = \frac{T\omega}{Q\Delta P^o}$	efficiency
Ω	angular velocity

Subscript

1	inlet
2	outlet
A	axial
avg	average
Cv	cross validation
hub	hub
mid	mid
Sm	surrogate models
Tip	tip
was	weighted average surrogate
*	non-dimensional parameter

performance. The Wells turbine is relatively newer development and the references available on the application and performance enhancement by modifying blade shape is limited. Some key references (Table 1) show that the modifications are performed basically for blade sweep and aerofoil profile. Some researchers focused on bi-plane Wells turbine, guide vane angle, tip clearance, duct geometry modifications.

Several efficient search optimization techniques are easily available to solve the optimization problems. One such optimization technique is the surrogate based modelling, which considerably reduces the design time to optimize a system (Samad et al., 2008; Badhurshah and Samad, 2015; Goel et al., 2007; Myers and Montgomery, 1995). In the surrogate base technique, a limited number of data points are used to construct multiple surrogates to obtain the optimal design. Goel et al. (2007) developed a Weighted Average Surrogate (WAS) model to identify the regions of high uncertainty. The WAS is basically a weighted sum of basic surrogates; namely, the Response Surface Approximation (RSA) (Myers and Montgomery, 1995), the Kriging (KRG) (Jeong et al., 2005; Martin and Simpson, 2005; Sacks et al., 2012; Simpson et al., 2001; Wang et al., 2014) and the radial basis function (RBF) (Orr, 1996). Several other articles (Valipour and Montazar, 2012a, 2012b, 2012c; Valipour et al., 2013, 2012)also reports several surrogates, but those do not contain WAS model.

The real life engineering problems have multiple objectives (Deb, 2001). A Multi-Objective Optimization (MOO) consists of two or more objectives which provide better understanding about the objectives and the variables in terms of performance enhancement. This also assists the designers to determine the best design or several design alternatives. In some design problems, conflicting objectives are correlated via Pareto optimal Front (PoF) of MOO (Collette and Siarry, 2003; Marjavaara et al., 2007). Another widely used approach based on a meta-heuristic algorithm includes a non-dominated sorting of a genetic algorithm (NSGA-II). The WAS model has been implemented for NSGA-II population generation for

Please cite this article in press as: Halder, P., et al., Numerical optimization of Wells turbine for wave energy extraction, International Journal of Naval Architecture and Ocean Engineering (2016), http://dx.doi.org/10.1016/j.ijnaoe.2016.06.008