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High performance ocean energy harvesting turbine design–A new casing treatment scheme

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ABSTRACT

Delaying a stall improves the performance of any turbomachinery system. TC (tip clearance), which is used in a bi-directional flow Wells turbine of an ocean wave energy device, changes the flow pattern on the turbine blade suction surface, while changing or modifying the TC zone can help obtaining a delayed stall. In the present work, a new tip grooving scheme is introduced and the performance is compared for different tip groove depths and TCs of a Wells turbine. The performance is defined in terms of wider operating range or stall delay, power production and efficiency. The problem was solved by a numerical analysis technique. A multi-block meshing scheme was employed to generate structured and hexahedral elements in the computational domain and the flow was solved in ANSYS CFX® v14.5 by solving Reynolds-averaged Navier Stokes equations. It was found that the grooves improve the turbine operating range and power production as compared to those of the turbine without a groove. The groove depth of 3% of the chord length produced highest power and widest operating range. Using the circumferential groove, 26% increase in turbine power output for a particular operating point is achieved.

1. Introduction

Oceans contain a large amount of energy, and harnessing the energy is a challenging task because of several factors such as uncertainty of the sea wave or current and natural calamities, etc. OWC (oscillating water column), which is a wave energy system, uses an impulse or a reaction turbine to extract energy from the waves. The OWC has an air chamber similar to an upside down bucket with a hole in the bottom. If a wave crosses the bucket, the bucket starts breathing (inhaling and exhaling) through the hole. If a turbine is placed in the hole, the turbine rotates. Similarly, in OWC, a duct is placed above the air chamber so that air can be breathed during wave action. An air turbine or a bi-directional turbine inside the duct extracts energy from the air and the energy is finally converted into electrical energy.

A Wells turbine [1], which is a reaction turbine and having symmetric blades, rotates unidirectionally by the alternating or oscillating axial flow of air. The turbine has a 90° angle of attack. The advantage of the turbine is that it is the simplest system that can be used in an ocean energy conversion system. It has no moving parts, except the rotor and electric generator-shaft assembly. On the other hand, the turbine has poor starting characteristics and has low efficiency and a low operating range.

The wave energy systems have poor efficiency and hence these are still not economically viable. The system components need to be redesigned to obtain the best performance. Some discrete and limited efforts are being made to enhance the performance of wave energy systems such as OWC chamber optimization, etc. The turbine is the heart of the OWC and has a peak efficiency of ~60%. If the entire system losses are included (wave to air loss, duct loss, turbine loss, generator loss etc.), the OWC system becomes inefficient. Again, the variability in wave height and period gives different flow velocities through the turbine duct. The Wells turbine can only produce power for a limited period because of its small operating range.

Efforts have been made to increase the performance of the Wells turbine by changing duct geometry [2], designing monoplane and biplane Wells turbine [3], optimizing blade profile and thickness [4], modifying airfoil profile [5–7], making non-symmetric airfoil blade shape [8] and non-uniform tip gap [9], inserting end plate

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Nomenclature

Abbreviations

GD	Groove depth
FC	Flow coefficient
LE	Leading edge
PS	Pressure surface
RANS	Reynolds-averaged Navier Stokes
SIMPLE	Semi-implicit method for pressure-linked equations
SS	Suction surface
SST	Shear stress transport
TC	Tip clearance
TE	Trailing edge
TKE	Turbulent kinetic energy

Symbols

B	Rotor axial length
C	Chord length
C_p	Pressure coefficient
H	Height of the groove
$h_1 = \frac{R_{hub}}{R_{tip}}$	Hub-to-tip ratio
N	Speed of rotor, rpm
Pw	Power output
$\Delta P* = \frac{\Delta P^o}{\rho\omega^2 R_{tip}^2}$	Pressure drop coefficient
ΔP^o	Stagnation pressure drop
Q	Volume flow rate
$r^* = \frac{R}{R_{tip}}$	Non-dimensional radius
R_{tip}	Tip radius
$R_{mid} = \frac{(1+h)}{2} R_{tip}$	Mid-span radius
$s = \frac{ZC}{2\pi R_{mid}}$	Turbine solidity
$T* = \frac{T}{\rho\omega^3 R_{tip}^5}$	Torque coefficient
t_{max}	Maximum blade thickness
t	Blade thickness
T	Shaft torque
U_{tip}	Rotor velocity
$U* = \frac{V}{U_{tip}}$	Flow coefficient
w	Width of the groove
z	Number of rotor blades
ρ	Density
$\eta = \frac{T\omega}{Q\Delta P^o}$	Efficiency
ω	Angular velocity
v	Average axial velocity

[10], sweeping [11,12], changing blade pitch angle [13,14], etc. Other efforts involve modification of guide vane angle [15–17], bi-directional flow [18], variable chord [19], bi-plane unidirectional blade [20], counter rotating blade [21,22], hysteretic behavior with unsteady flow [23], etc. In a simpler design, the turbine has limited moving elements but a larger separated zone makes the turbine less efficient.

Several authors have investigated the TC (tip clearance) effect on Well turbine performance and found that 1% TC is optimum. Torresi et al. [24] reported that 1% TC reduces the flow separation near the blade tip and improves the turbine performance. The hysteresis curve size was decreased by the increase in TC [25,26]. Taha et al. [27] reported a uniform TC with different chord length ratios. Although a non-uniform TC has a better performance [9], the manufacturing difficulty may arise.

The other types of turbomachines with casing grooves or casing treatment studies have been reported by many researchers [28–37]. The turbomachines are basically used in the gas turbine system. Two common types of casing treatment scheme are available: axial skewed slot and circumferential groove. The casing groove changes the flow separation profile and operating range. The above grooving schemes cannot be implemented in the Wells turbine as the turbine has a 90° stagger angle. Again, an advantage for Well turbine grooving is that a continuous groove can be cut in the entire casing circumference of the turbine and the blades can rotate inside it. To control the tip leakage flow, only the tip gap modification and end plate scheme were reported in the literature for the Wells turbine [24–27].

In the present study, a new casing treatment or casing grooving scheme for a Wells turbine was introduced and numerical analyses were performed to get a high performance turbine for wave energy extraction. A Reynolds-averaged Navier Stokes (RANS) solver was used for the simulations. The geometry was meshed using structured elements and a multi-block concept. A detailed description of the design, solution procedure, and analysis of the results with and without grooving is presented.

2. Wells turbine performance parameters and stall delay

To design a high performance turbine, it is required to reduce the losses in the turbine. The losses include flow separation and several vortices formation in the passage. The vortices act in terms of flow separation or entropy generation and turbine performance drops. Singular separation or ordinary separation is created by stall in a turbine blade. In the stall condition, the flow is retarded along the wall because of adverse pressure gradient and viscous shear stresses. As a result, the fluid element near the wall can no longer proceed in a forward direction. Several studies have been reported to improve the stalling (or delaying the stall condition) in the compressor and turbine by using circumferential casing grooves which gives a wider operating range and higher power or efficiency [30,36].

Low velocity air over an airfoil at a zero-incidence angle does not initiate flow separation. If the air velocity slowly increases, the flow separation starts from the blade TE (trailing edge). If the velocity or the incidence angle increases further, the separation point or stall point moves towards the blade LE (leading edge). If the stall point can be pushed towards the TE, the airfoil performance or the turbine blade performance increases as the attached flow transfers more energy to the blade. This phenomenon is called delay of separation or delay of stall point or stall delay.

In the Wells turbine, the blades are constructed using symmetric airfoils and the incidence angle is too high; i.e., the flow separation occurs at a low velocity. This is the reason for having a low operating range in the Wells turbine. The low operating range implies that the flow is not attached to the blade surface for a longer period during inhaling or exhaling of air by the OWC and the turbine produces power only for a short duration. The attached flow transfers more energy to the turbine and hence the performance of the turbine increases.

The flow is assumed to be sinusoidal and in each wave sequence, the wave gradually pushes the air through the turbine annuli. The air attains a peak speed and finally the speed becomes zero at the