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The performance of Wells turbine under bi-directional airflow

A. Thakker*, R. Abdulhadi

Wave Energy Research Team, Department of Mechanical and Aeronautical Engineering, University of Limerick, Limerick, Ireland

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Abstract

This paper presents the performance of a Wells turbine operating under unsteady bi-directional airflow conditions. In this study, four kinds of blade profile were selected, NACA0020, NACA0015, CA9 and HSIM 15-262123-1576. The experiments have been carried out for two solidities under sinusoidal and irregular unsteady flow conditions based on Irish waves (Site2). It was found that for a Wells turbine operating under bi-directional air flow, the rotor geometry preferred is the blade profile of CA9 with rotor solidity $\sigma = 0.64$. In addition, the efficiency curve of the Wells turbine under unidirectional flow conditions fails to present the rapid rise in the instantaneous efficiency which occurs at low flow coefficient of bi-directional flow condition. A comparative analysis between the numerical simulation results and experimental results was carried out. As a result, an excellent agreement was found between the numerical and experimental results. In addition, the effect of blade profile and rotor solidity on hysteretic characteristics of the turbine has been clarified experimentally under bi-directional airflow.

keywords: Fluid machinery; Wells turbine; Airfoil; Real sea condition; Wave power conversion.

1. Introduction

Over the last few decades, scientists have been investigating and defining different methods for power extraction from wave motion. The most successful and most extensively studied device for power extraction energy from ocean waves is the oscillating water column (OWC) device. OWC-based wave energy power plants convert wave energy into low-pressure pneumatic power in the form of bi-directional airflow. Self-rectifying air turbines are used to extract mechanical shaft power. Two different turbines are currently in use around the world for wave energy power generation, the Wells turbine, introduced by Dr. A.A. Wells [1] in 1976 and the impulse turbine by some authors [2,3]. Both of these turbines are currently in operation in different power plants in Europe. Ongoing research around the world is focused on improving the performance of both these turbines under different operating conditions.

The present investigation deals with the Wells turbine. There are many reports, which describe the performance of the Wells turbine both at starting and running characteristics [4–7]. According to these results, the Wells turbine has inherent disadvantages: lower efficiency, poor starting and higher noise level in comparison with conventional turbines [8,9]. In order to enhance the performance of the Wells turbine, some of its rotor blade profiles have been tested under steady flow inlet condition. It has been found by [10] that the optimum blade profile for small-scale Wells turbine, which is installed in wave energy plants such as the navigation buoy [11] (that is, the turbine is operated at a low Reynolds number) is NACA0020. On the other hand, for large-scale Wells turbines, which are installed in wave energy plants such as the LIMPT system [12], (that is, the turbine is operated at a high Reynolds number) it has been found by [16] that the optimum blade profile is NACA0015. Furthermore, until now, all experimental investigations have been carried out under steady unidirectional flow conditions. The latter are not representative of the turbine sea working conditions, where the flow is bi-directional and random in nature.

*Corresponding author. Tel.: +353 61 202223; fax: +353 61 202944.
E-mail address: Ajit.Thakker@ul.ie (A. Thakker).

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Nomenclature

H_s	significant wave height
K	non-dimensional period ($= r_t m/H_s$)
l	chord length of rotor blade
m	turbine to OWC open area ratio
r_t	tip span radius
T_s	mean period of incident wave
T	torque
U_t	circumferential velocity at r_t
v_a	axial flow velocity
W	relative inflow velocity
V_a	maximum value of v_a

Greek symbols

ϕ	flow coefficient
Φ	flow coefficient under sinusoidal flow ($= V_a/U_t$)
ρ	density of air
μ	viscosity of air

This paper presents an experimental investigation into the performance of Wells turbine operating under bi-directional airflow. Four kinds of blade profile were selected, i.e. NACA0020, NACA0015, CA9 and HSIM 15-262123-1576 (the last one is named HSIM15 in the following discussion). In order to determine the optimum rotor blade profile of the turbine, the experimental investigations were carried out using two solidities $\sigma = 0.48$ and $\sigma = 0.64$. In addition, the behavior of Wells turbine operating under bi-directional airflow was investigated. The numerical simulation results of the turbine operating under unsteady sinusoidal flow condition were compared to the experimental results. Also, the hysteretic characteristics of Wells turbine operating under bi-directional irregular inlet flow conditions have been clarified experimentally.

2. Experimental setup

A schematic layout of the experimental test rig used by the Wave Energy Research Team (WERT) at the University of Limerick is shown in Fig. 1. It consists of a 0.6 m turbine test section with a hub to tip ratio of 0.6, a bi-directional valve, a plenum chamber with honeycomb section, a calibrated nozzle joining the fan to the plenum chamber, ductwork, a centrifugal fan and two automated actuators (1) and (2). The first actuator (1) controls the flow rate while the second actuator (2) controls the direction of flow. Air is drawn in through the bi-directional valve either through side A or B depending on the position of automated valve. (A more detailed drawing of this bi-directional valve is shown in Fig. 2.) It then passes through the test section and into the plenum chamber. In the chamber the flow is conditioned through a calibrated nozzle and finally exhausted at the fan outlet. The flow rate is controlled using the automated valve.

For this study, four kinds of symmetrical blade profile with chord length l of 120 mm were used for the experiments. The blade profile and turbine specifications are shown in Table 1. All the blade profiles were investigated for two solidities, $\sigma = 0.48$ and $\sigma = 0.64$. The turbines were tested at different rotational speeds; 1700, 1500, 1300, 1100, 900, 700, 500 and 350 rpm, which correspond to Reynolds numbers of 4.44×10^5, 3.91×10^5, 3.4×10^5, 2.89×10^5, 2.38×10^5, 1.88×10^5, 1.41×10^5 and 1.077×10^5, respectively.

2.1. Experimental procedure

The sinusoidal and random (Irish sea climate) wave inlet conditions to the turbine have been generated by controlling the opening area of the centrifugal fan outlet of the test rig using an actuator valve. Initially, the actuator valve was calibrated to find the correlation between the open area of fan outlet and pressure drop across the nozzle (ΔP_n) located at the inlet to the fan. The relationship between the valve displacement and the flow rate through the test section was found using a nozzle calibration curve. In order to generate a given regular or random wave, time history of valve displacement was calculated using the above-mentioned method. The actuator valve controller was utilized to operate the valve according to the time history. For this purpose, a computer program was written [14] and the controller was interfaced with a computer. In order to create a bi-directional airflow, the controller controls the two actuators and a limit switch. The limit switch is positioned such that it closes when the valve that controls airflow rate closes. When this flow control valve closes, it presses the limit switch, causing the actuator (2) to move in the reverse direction, thus reversing the direction of airflow through the turbine.

The experimental procedure involves fixing the rotor at a set speed and generating the required flow pattern (sinusoidal flow or Site2 conditions). Performance parameters were recorded using a high-speed logger that is part of the data acquisition system [15].

The overall performance of the turbine was evaluated by the turbine angular velocity ω, generated torque T, flow rate Q and total pressure drop across the rotor ΔP_r. The results are expressed in the form of torque coefficient C_T, pressure coefficient C_A, efficiency η and mean average efficiency η_t. The definitions are given below:

$$C_T = \frac{T}{\rho\omega^2 r_t^5} \qquad (1)$$