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On the Hysteretic Behaviour of Wells Turbines

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Abstract

The Wells turbine is a self-rectifying axial flow turbine employed in Oscillating Water Column systems to convert low-pressure airflow into mechanical energy. A number of studies highlighted a variation in turbine performance between acceleration and deceleration phases, generally ascribed to the interaction between blade trailing edge vortices and blade boundary layer. This explaination is in opposition with the large existing literature on rapidly pitching airfoils and wings, where it is generally accepted that a hysteretic behavior can be appreciated only at non-dimensional frequencies significantly larger than the ones typically found in Wells turbine.

This work presents a critical re-examination of the phenomenon and a new analysis of some of the test cases originally used to explain its origin. The results demonstrate how the behavior of a Wells turbine is not dissimilar to that of an airfoil pitching at very low reduced frequencies and that the causes of the alleged hysteresis are in a different phenomenon.

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Nomenclature

μ	fluid viscosity	r	radius
ω	angular velocity	r^*	non-dimensional radius $(r-r_h)/(r_{tip}-r_h)$
Ω_t	tangential component of vorticity	r_h	hub radius
ϕ	global flow coefficient	r_{tip}	tip radius
ϕ_l	local flow coefficient	T	torque
ρ	density	T^*	non-dimensional torque
σ	solidity at tip radius	T^{**}	local non-dimensional torque
τ_w	wall shear stress	V_a	absolute axial velocity
c	blade chord	V_t	absolute tangential velocity
c_p	pressure coefficient	W	relative velocity magnitude
$\underline{f}$	piston frequency	W_a	relative axial velocity
f	non-dimensional piston frequency	W_t	relative tangential velocity
P	static pressure	x	blade coordinate in the direction of the chord
P^*	non-dimensional static pressure drop	y	wall distance
P^{**}	local non-dimensional static pressure drop	y^+	non-dimensional wall distance $(y\sqrt{\rho\tau_w}/\mu)$

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1. Introduction

The Wells turbine [1] is a self-rectifying axial flow turbine employed, with a Oscillating Water Column (OWC) system, to convert sea wave energy in mechanical energy [2]. Its performance has been studied extensively, both experimentally [3, 4, 5, 6, 7, 8] and numerically [9, 10, 11, 12, 13, 14]. One peculiar aspect mentioned in this research is the apparent difference in performance during the accelerating and decelerating phases of the normal operation. The first investigation of this phenomenon was presented by Setoguchi *et al.* [5]. Their facility employed a large cylinder with a moving piston connected to the turbine duct, so as to reproduce the OWC system dynamics and a realistic bi-directional airflow. Different rotor geometries were studied, highlighting the lower performance of the machine during piston acceleration than during deceleration (counter-clockwise hysteretic loop). The hysteresis was present even with a maximum angle of attack significantly lower than the one corresponding to static stall.

They concluded the phenomenon (a) unlikely to be caused by three-dimensional effects, because of the independency from blade aspect ratio, and (b) to be dissimilar to the one present in airfoils and wings, because of the opposite rotation of the hysteresis cycle. However, they did not mention that counter-clockwise loops do develop in airfoils at lower-incidence-angle excursions, with the flow still attached to the surface [15], while clockwise hysteretic loops are present in pitching wings only at large angles of attack (when vortex burst or stall are enclosed in the pitch excursion).

Setoguchi *et al.* [16] and Kinoue *et al.* [10, 17] employed Computational Fluid Dynamics (CFD) to explain the origin of the phenomenon, studying a simplified geometry (a blade passage of the straight annular duct housing the turbine rotor, neglecting the piston chamber). They identified different vortical structures during acceleration and deceleration, and attributed the different performance to their interaction with trailing edge vortices shed by the blade.

In this work, the Wells turbine of Setoguchi *et al.* [5] is studied numerically, initially with the geometrical simplification of [16, 10, 17] and then with a geometry more representative of the experimental setup. This allows the performance of the turbine to be isolated from that of the OWC system and verify whether the difference in performance highlighted in the experiments is caused by a real hysteresis of the turbine, or by some other phenomenon.

2. Methodology

The experimental set-up and the details of the investigation are reported in [5]. The experimental facility is composed of a cylindrical chamber (1.4 m diameter) with a piston moved by an electric motor. The airflow is conveyed in an annular duct where the Wells turbine is placed. Main geometric and flow characteristics are reported in Table 1. During the experiment, the turbine operated at Reynolds numbers between 1.3×10^5 and 3.1×10^5 ($Re = \frac{\rho W c}{\mu}$), while the reduced frequency ($\overline{f} = (\pi f c)/(\omega r_{tip})$) ranged between 8×10^{-4} and 1.4×10^{-3}. In this work, the analysis focuses on the NACA0020 turbine, with 1 mm tip clearance and 90 mm chord length (solidity at tip radius $\sigma = 0.67$).

Table 1. Wells turbine geometry analyzed in [5]

Airfoil	NACA 0015/0018/0020	Rotor Tip Diameter	300 mm
Rotor hub diameter	110 mm	Tip clearance	1/2/3 mm
Chord length	60/90/108 mm	Number of blades	5/6/7
Solidity at tip radius	0.48-0.67	Sweep ratio	0.420 (37.5/90)
Rotational speed	2500 rpm	Piston period	6 s

Setoguchi *et al.* [16] and Kinoue *et al.* [10, 17] conducted a numerical study on a simplified geometry (a straight annular duct enclosing the turbine rotor, as in Figure 1, top left) to simulate the performance of the machine. This geometry has been used in this work to verify the hysteresis reported by [16, 10, 17]. Then, a more realistic geometry (including moving piston, chamber and actual duct) has been employed to verify the effects of the previous simplification both on flow distribution and on the hysteretic characteristics of the machine.

The numerical simulations have been conducted with the commercial CFD software Ansys Fluent® 15.0, while Ansys IcemCFD® has been used to generate the multi-block structured grid (Figure 1). A C-grid around the blade was able to capture the complex boundary layer flow, with a H-mesh structure in the rest of domain. The unsteady Reynolds-Averaged Navier-Stokes (RANS) equations have been solved for a compressible ideal gas. Based on the