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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. Its performance has been analysed extensively, both experimentally and numerically. A number of these studies highlighted a difference between steady and unsteady operation, caused by an apparent variation in performance between acceleration and deceleration. This phenomenon has been diffusively discussed in the last 15 years, and its causes have been always placed in the interaction between trailing edge vortices and blade boundary layer. The same scientific community always failed to reconcile this explanation 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.

Nomenclature

ω	rotational speed
Ω_t	tangential component of vorticity
$\overline{f}$	non-dimensional piston frequency
ϕ	global flow coefficient $\left(\frac{V_{piston}}{\omega r_{tip}} \frac{A_{piston}}{A_{rotor}}\right)$
ϕ_l	local flow coefficient
ρ	density
c	blade chord
f	piston frequency
P	static pressure
P^{**}	local non-dimensional static pressure drop
P^{*}	non-dimensional static pressure drop
r	radius
r^*	non-dimensional radius $(r - r_h)/(r_{tip} - r_h)$
r_h	hub radius
r_{tip}	tip radius
T	torque
T^*	non-dimensional torque
T^{**}	local non-dimensional torque
V_a	absolute axial velocity
V_t	absolute tangential velocity
W	relative velocity
W_a	relative axial velocity
W_t	relative tangential velocity

1. Introduction

The Wells turbine [22] is a self-rectifying axial flow turbine employed, with a Oscillating Water Column (OWC) system, to convert sea wave energy in mechanical energy [4]. Its performance has been studied extensively, both experimentally [6, 3, 18, 20, 15, 16] and numerically [11, 13, 5, 21, 10, 19]. 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.* [18]. 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 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), while counter-clockwise loops do develop at lower-incidence-angle excursions, with the flow still attached to the surface [1].

Setoguchi *et al.* [17] and Kinoue *et al.* [13, 12] 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.* [18] is studied numerically, initially with the geometrical simplification of [17, 13, 12] and then by 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 [18]. 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 ($sigma = 0.67$).

Table 1. Wells turbine geometry analyzed in [18]

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.* [17] and Kinoue *et al.* [13, 12] 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 [17, 13, 12]. 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 results of Ghisu *et al.* [7, 9], the $k-\omega$ SST model has been selected for turbulence closure. The SIMPLEC algorithm has been used for pressure-velocity coupling, a second-order upwind scheme for discretizing convective terms and a second-order centered scheme for pressure and viscous terms.

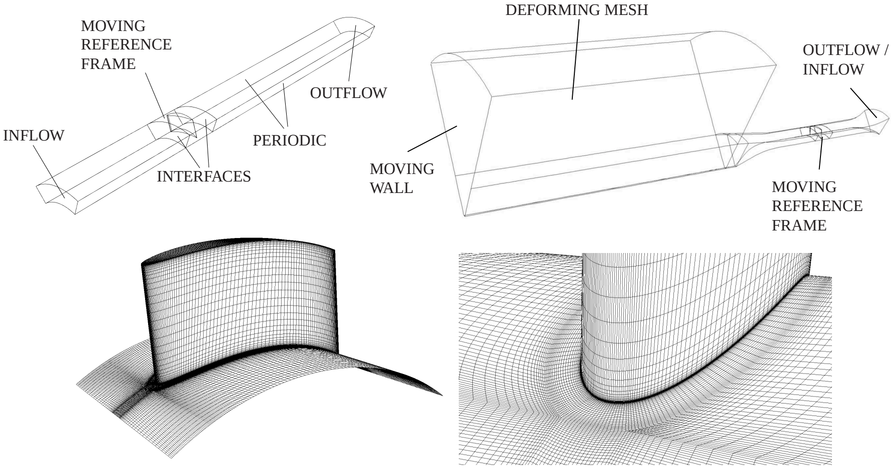


Fig. 1. Simplified (top left) and full (top right) computational domains, and computational mesh (bottom)

The motion of the piston has been simulated by means of a moving wall, controlled by an user-defined-function (UDF), in combination with a dynamic mesh. One passage has been simulated, with periodic boundary conditions.

A grid sensitivity study similar to the one of [8] has been conducted to verify the choice of the numerical mesh. As a result, a mesh with 260 points around the blade profile, 70 between successive blades (in the wake region) and 35 in spanwise direction was obtained. 10 points have been employed in the tip gap region, for a total of about 10^6 cells, and the maximum y^+ was maintained of the order of 1 to ensure a good resolution of the boundary layer.

3. Results

3.1. A Comparison with Unsteady Forces in Rapidly Pitching Airfoils

A Wells turbine blade, during its normal operation, experiences a periodic change in incidence angle, due to the periodic and bi-directional airflow generated by the motion of the (water) piston inside the OWC. This is not dissimilar to what happens to rapidly pitching (or plunging) airfoils, where the presence of a hysteretic loop for the force coefficients has been known for many decades and analyzed with great level of details since the 1970s [2, 14], for its importance in various applications. The phenomenon is dominated by two parameters: maximum incidence angle and reduced frequency, while the importance of Reynolds number is limited. The maximum incidence angle defines whether and to what extent the airfoil experiences stall, while the reduced frequency determines the importance of the dynamic effects that generate the difference between force coefficients during pitch-up and pitch-down. Figure 2 presents a comparison between the experimental data of McCroskey [14] and computational results obtained in this work using unsteady RANS ($k-\omega$ turbulence model). The NACA0012 airfoil is sinusoidally pitching with an incidence range of 20 degrees around different mean angles, at a fixed reduced frequency of 0.1, in different stall conditions. In no-stall conditions (i.e. if the maximum incidence angle is lower than the static stall angle) the motion determines a counter-clockwise hysteretic loop, while in deep-stall conditions the loop is clock-wise. In intermediate situations, the loop is distorted, and in some cases (light-stall) a bow appears in the lift coefficient loop. These dynamic effects have been know for decades and studied in detail both experimentally [2, 14] and numerically [1]. They are generally considered negligible at reduced frequencies lower that $4 \cdot 10^{-3}$ [2]. The lower reduced frequencies Wells turbines operate at are not sufficient to produce hysteretic effects in isolated airfoils and wings.

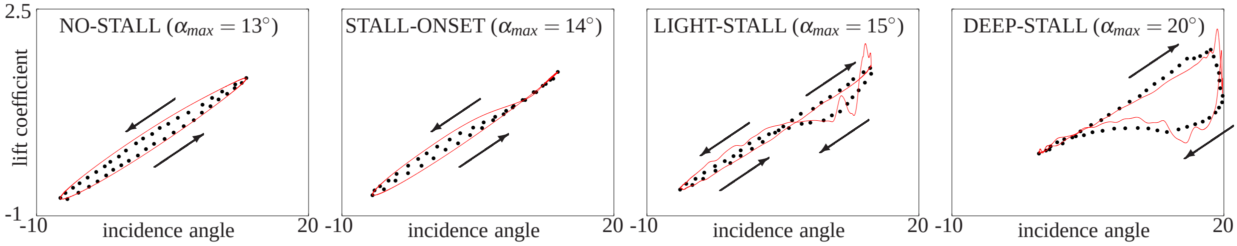


Fig. 2. Unsteady forces in rapidly pitching airfoils

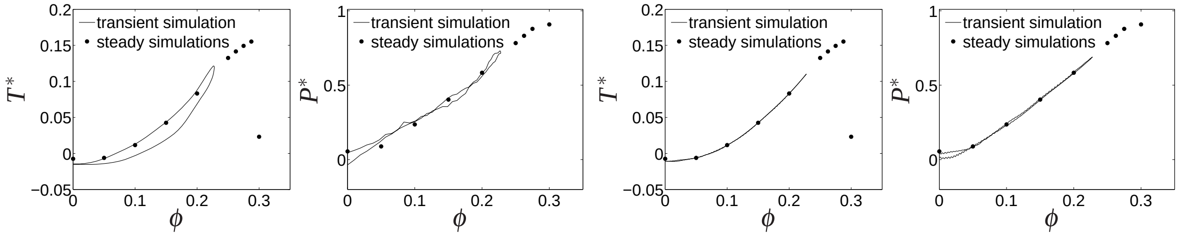
3.2. Simplified Geometry

Wells turbine performance is reported in terms of non-dimensional pressure drop and torque as a function of the flow coefficient ϕ. ΔP is the pressure difference across the rotor, ρ is the flow density, ω the rotational speed, r_{tip} the tip radius, T the torque and V_a the axial velocity upstream of the rotor. In the experimental analysis of Setoguchi *et al.* [18], V_a is not directly measured, but its value is calculated from piston velocity and area ratio (ratio between piston area and rotor inlet area), neglecting capacitive effects. This makes ϕ a theoretical flow coefficient:

$$T^* = \frac{T}{\rho \omega^2 r_{tip}^5}; \quad P^* = \frac{\Delta P}{\rho \omega^2 r_{tip}^2}; \quad \phi = \frac{V_a}{\omega r_{tip}} \equiv \frac{V_{piston}}{\omega r_{tip}} \frac{A_{piston}}{A_{rotor}} \tag{1}$$

Following the approach of [17, 13, 12], V_a is imposed as an inlet boundary condition, together with turbulence intensity (3%) and viscosity ratio (10), while ambient static pressure is imposed at exit.

A transient simulation has been run, with a first-order implicit approach in time and different values for the time step, keeping the number of sub-iterations fixed and equal to 20. The inlet velocity has been varied using a sinusoidal law, to obtain the same flow coefficient that would have been caused by the motion of the piston and neglecting capacitive effects in the OWC system. The simulations, initialized with the steady solution at $\phi = 0$, have been run for half a period (corresponding to the outflow phase). Figure 3 highlights the importance of a correct choice of the time-step in transient simulations: when selected appropriately, these simulations do not show any hysteresis between acceleration and deceleration phases, and no difference between the steady and transient performance.



(a) $\Delta t = 2 \cdot 10^{-2} s$ (b) $\Delta t = 1.25 \cdot 10^{-3} s$

Fig. 3. Influence of time-step size in transient simulations

3.3. Full Geometry

The simulations with the full geometry (Figure 1, top right) have been run for three piston periods to verify that periodically stable results had been obtained. A time step of $5 \cdot 10^{-4}$ s has been used. Figure 4 compares the non-dimensional coefficients of torque and static pressure drop with the experimental data of [18].

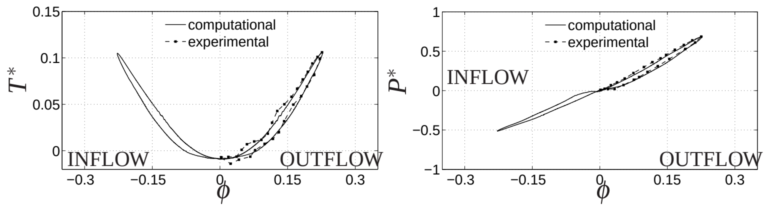


Fig. 4. Comparison between experimental and computational results

The flow coefficient ϕ is calculated from piston velocity and system geometry (equation (1)), assuming the flow at inlet to the turbine to be axial and neglecting capacitive effects (as in [18]). The experimental data are available only during outflow, while numerical results are available both for inflow (negative flow coefficient) and outflow (positive flow coefficient). The hysteresis of the real OWC system is evident and is correctly reproduced.

In order to isolate the turbine aerodynamic performance (and possible hysteretic behaviors), performance should be correlated to flow characteristics in the proximity of the blade. Torque and pressure drop across the rotor have been non-dimensionalized as in equations (2), with local values of (tangentially-averaged) relative velocity evaluated $0.5c$ upstream of the rotor rather than with blade tip speed as in equations (1), and plotted as a function of a local flow coefficient ϕ_l, calculated at mid-radius. The results, reported in Figure 5, do not show significant differences between performance during acceleration and deceleration.

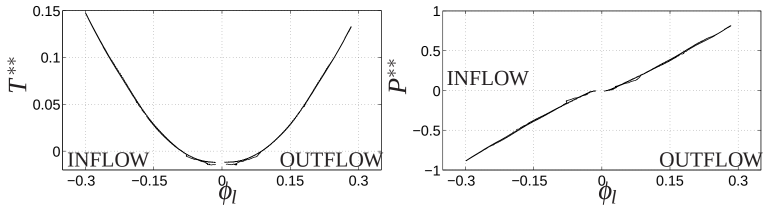


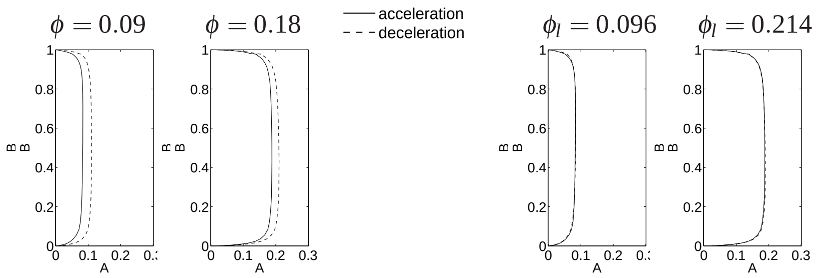
Fig. 5. Computational performance as a function of local flow variables

$$T^{**} = \frac{T}{\rho W_t^2 r_{tip}^3}; \quad P^{**} = \frac{\Delta P}{\rho W_t^2}; \quad \phi_l = \frac{W_a}{W_t}; \tag{2}$$

It is important to verify the flow behavior near the rotor and the presence of the flow separations and vortical structures highlighted by [17, 13, 12]. Figure 6(a) shows the difference in the radial distributions of axial flow velocity upstream of the turbine rotor between acceleration and deceleration, during outflow, for two values of the (global) flow coefficient based on piston velocity. The different velocity profiles are caused by capacitive effects the air maiss inside the chamber and are the real cause of the hysteresis. Figure 6(b) compares the axial velocity distributions for equal mass-flows entering the rotor during acceleration and deceleration. The velocity profiles are in good agreement: only comparing turbine performance under equal inlet conditions ensures other effects due to the presence of the OWC system to be filtered out, thus focusing the attention on the (eventual) real hysteresis of the turbine.

Figure 7 shows a comparison of pressure coefficient distributions at mid-span: at equal values of global flow coefficient ϕ, the different axial velocity determines a different pressure coefficient distribution and therefore the apparent hysteresis seen in Figure 4. When the local flow coefficents (ϕ_l) is the same, the mass-flow through the rotor is equal and the difference in pressure distribution between acceleration and deceleration vanishes.

Figure 8 compares relative velocity contours around the blade for the two values of the local flow coefficient ϕ_l. The differences are minimal, and not sufficient to produce appreciable variations in the pressure coefficient distributions or in the values of the integral forces. The flow is well attached to the turbine blade over most of the span, with the

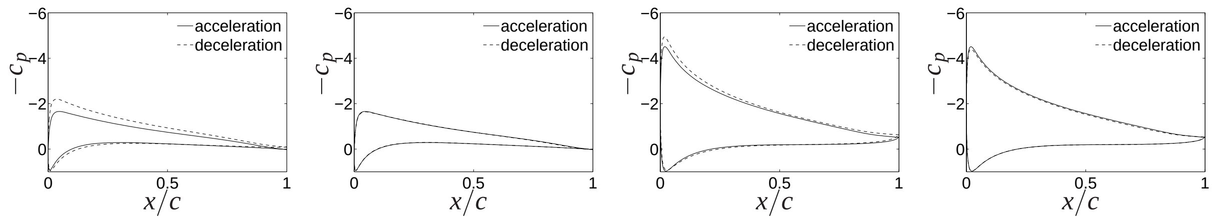


(a) Equal global flow coefficients (ϕ) (b) Equal local flow coefficients (ϕ_l)

Fig. 6. Spanwise distribution of axial velocity during acceleration and deceleration

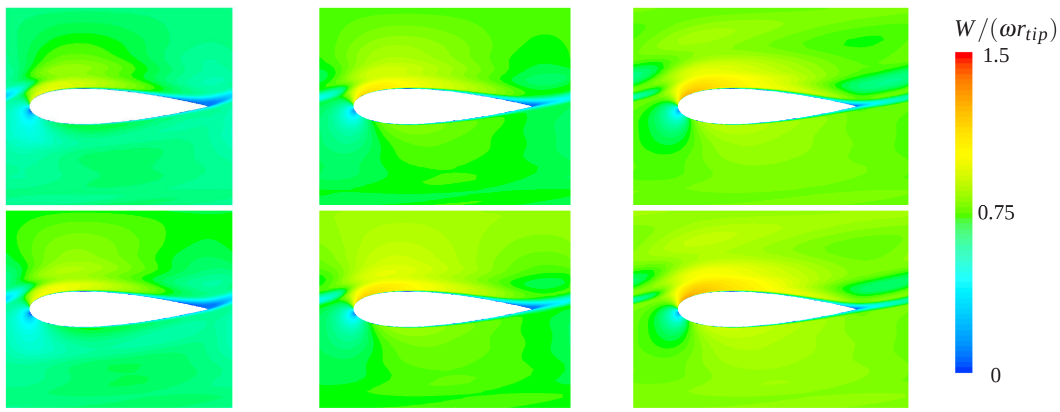
appearance of a confined corner separation near the hub. The large areas of flow separation presented in the numerical work of Setoguchi *et al.* and Kinoue *et al.* [18, 13, 12] have not been found in this work.

Figures 10 and 11 highlight the main secondary flow structures present in the flow during acceleration and deceleration, at $\phi_l = 0.096$ and $\phi_l = 0.214$, respectively. Tip leakage vortex and horseshoe vortices near the hub at either sides of the blade are evident for both flow coefficients, and their intensity increases at $\phi_l = 0.214$.



(a) $\phi = 0.09$ (b) $\phi_l = 0.096$ (c) $\phi = 0.18$ (d) $\phi_l = 0.214$

Fig. 7. Mid-span pressure coefficient distributions during acceleration and deceleration, for the same values of global and local flow coefficient



(a) $r^* = 0.2$ (b) $r^* = 0.5$ (c) $r^* = 0.8$

Fig. 8. Comparison of relative velocity contours during acceleration (top) and deceleration (bottom), at different radial positions (r^*), for $\phi_l = 0.096$

The strength of the horseshoe vortices decreases significantly towards the trailing edge, and vortices produced by previous blades are barely visible, while the larger intensity of the tip leakage vortex makes it visible also near the

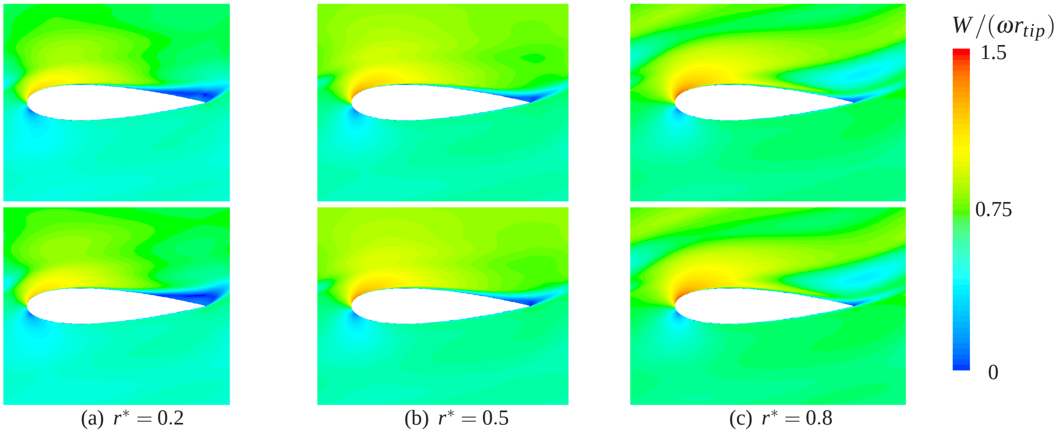


Fig. 9. Comparison of relative velocity contours during acceleration (top) and deceleration (bottom), at different radial positions (r^*), for $\phi_l = 0.214$

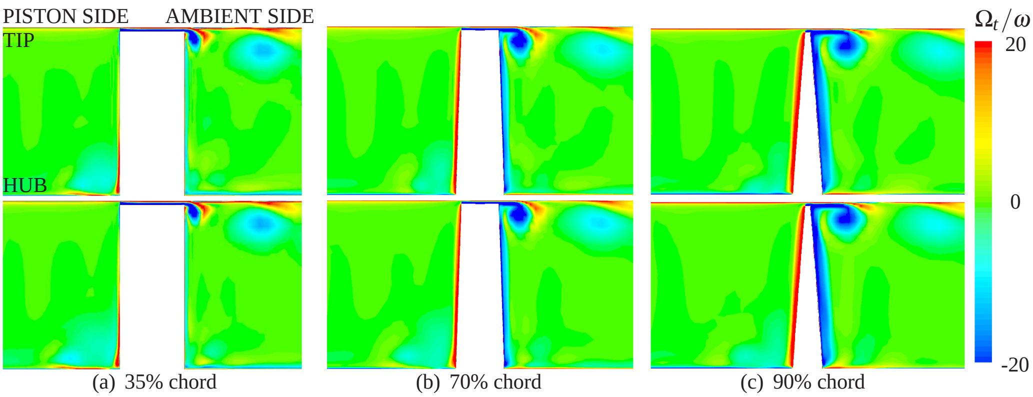


Fig. 10. Tangential vorticity contours at $\phi_l = 0.096$ during acceleration (top) and deceleration (bottom), at planes with different tangential positions.

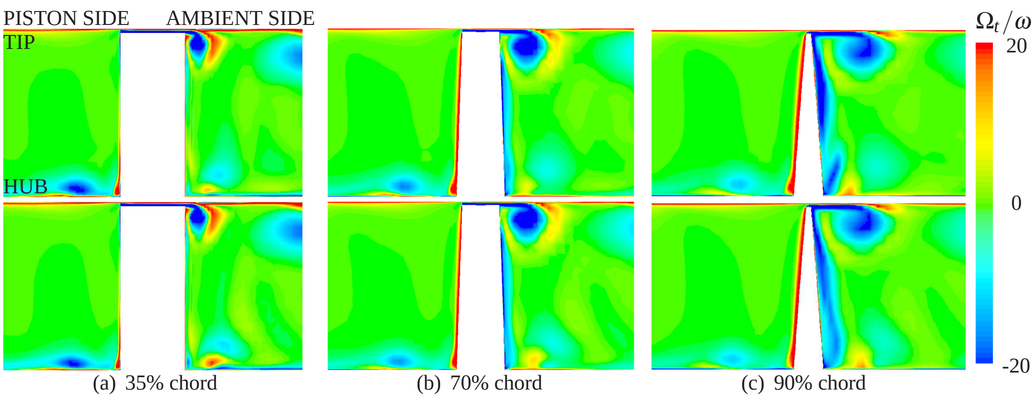


Fig. 11. Tangential vorticity contours at $\phi_l = 0.214$ during acceleration (top) and deceleration (bottom), at planes with different tangential positions.

following blade. The differences between acceleration and deceleration are minimal and confined to small regions, and do not produce appreciable variations in the integral forces produced by the blade.

4. Conclusions

The existence of a hysteretic behavior in Wells turbines has been recognized by several authors. Nevertheless, operating non-dimensional frequencies are significantly lower than the ones studied for pitching airfoils and wings, where the phenomenon has been investigated extensively. [17, 13, 12] used Computational Fluid Dynamics to analyze the problem and found its origin in the interaction between secondary flow structures and trailing edge vortices.

In this study, a numerical analysis of the same problem is presented, both using the same simplifications of [17, 13, 12] and with a geometry more representative of the actual experimental setup. The behavior of the Wells turbine has been isolated from the one of the OWC system, allowing the performance of the turbine to be studied in detail. The origin of the hysteresis has been demonstrated to be linked to capacitive effects within the OWC system rather than to dynamic effects in the turbine. These effects are negligible, at least at the non-dimensional frequencies and Reynolds number studied in this problem. The phenomena indicated by other authors as the causes for the hysteretic behavior have not been confirmed in this analysis.

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