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Experimental and numerical study on a model of offshore vertical axis wind turbine with pitching blades

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Due to growing interest in offshore wind energy, vertical axis wind turbines (VAWTs) have recently received renewed interest. Their low center of gravity, omni-directional capability, and ability to rotate even if the platform base is not strictly horizontal, make them a very interesting option for suitable large floating wind turbines. However, because of the lack of research and the complexity of the flow, lift-driven VAWTs require further investigations to be competitive with horizontal axis wind turbines (HAWTs). One potential improvement is to pitch the vertical blades during their rotation (Figure 1) in order to have a better angle of attack, thus increasing lift, decreasing drag, and enhancing rotational speed [1]. Pitching the blades allows also an easier initial rotational starting procedure [2], and the ability to slow down the rotation in strong wind conditions.

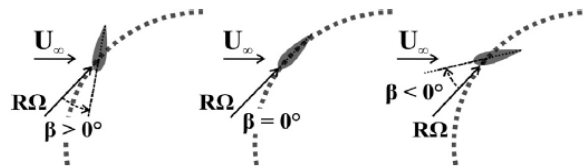


Figure 1: view from above: examples of pitch angle β for a VAWT blade.
 U_∞ is the incoming wind speed, R is the turbine radius, Ω is the angular velocity

In this context, we built a simple 1/100 scale model of a large three blade H-type Darrieus vertical wind turbine with active pitch-control (c.f. EOLFI SpinFloat project¹).

First, numerical simulations have been performed on various NACA 4-series, 5-series and Selig airfoil profiles at different chord Reynolds numbers using double multiple stream-tube model (DMST) with tip loss correction [3] [4] [5]. Based on the power coefficient, the best suitable airfoil Selig1046 has been selected. The measured polar of the lift coefficients C_L and drag coefficients C_D of the experimental blades are shown on figure 2 for different chord Reynolds numbers. Besides the blade profile, the turbine design parameters such as aspect ratio $A_R = L/D$ and solidity ratio $\sigma = nC/D$ (with L : the blade length, D the turbine diameter, n : the number of the blades, C the chord length), have also been investigated through the QBLADE model [6] [7] by varying the turbine diameter and the chord of the blades. Figure 3 is a view of the turbine we finally designed.

¹ <https://www.eolfi.com/en/eolfi-research-development/spinfloat>

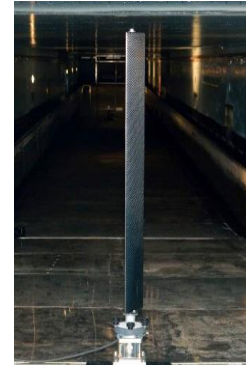
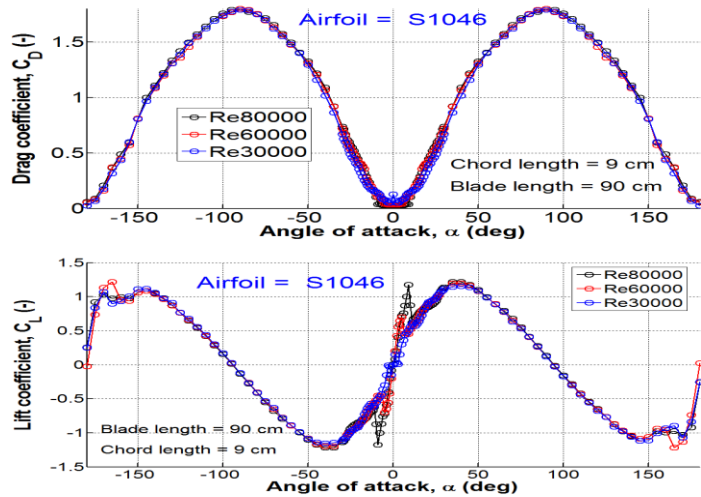


figure 2: Measured lift and drag coefficients with the Selig-1046 blade for 0° to 360° angle of attack.

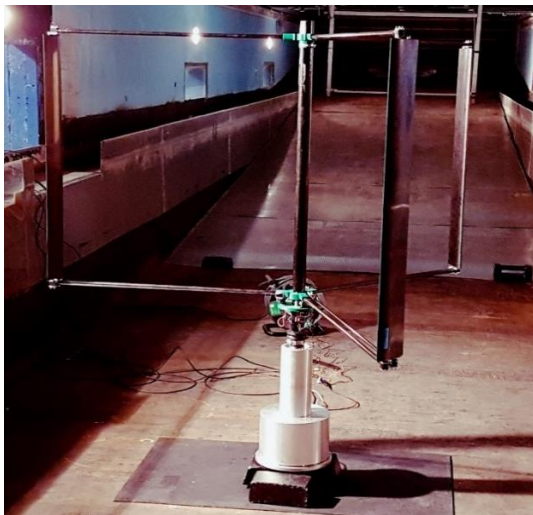


Figure 3: VAWT experimental model

VAWT characteristics:

- Diameter: 1.60 m
- Blade length: 0.90 m
- Blade chord: 0.09 m
- Blade max thickness: 0.015 m

Pitching performance:

- 3 servo motors
- Amplitude +/- 30° ,
- Celerity: 60°/0.1 s
- Max torque: 48 Kg.cm

Pitch Control:

- Control-command: every 0.3° in azimuthal rotation
- Teensy cards + computer + Arduino + Python programs

We used three active servo-motors to pitch the blades. These actuators have fast response time with quite high torque performance to pitch continuously the blades even when the turbine rotates rapidly. The control-command procedure is driven with two teensy cards, a computer, Python and Arduino software.

An important parameter is the Tip Speed Ratio $TSR = R\Omega/U_\infty$ with U_∞ , the incoming wind speed, R the turbine radius, Ω the angular velocity. At low TSR, a large pitch amplitude is needed in order to reduce the angle of attack and hence to enhance rotor performance. Conversely, while a small pitch amplitude is sufficient to produce good performance at high TSRs. We made a specific study to determine optimized pitch amplitude as the TSR changes.

DMST- and QBLADE- type models were first used to have a first guess of possible pitch laws that could be used to enhance the turbine performance. Then, we performed 2D numerical simulations with a Computational Fluid Dynamics (CFD) commercial finite element URANSE solver CFX [8] in order to have more information on the pattern of the flow associated with each pitch function used.

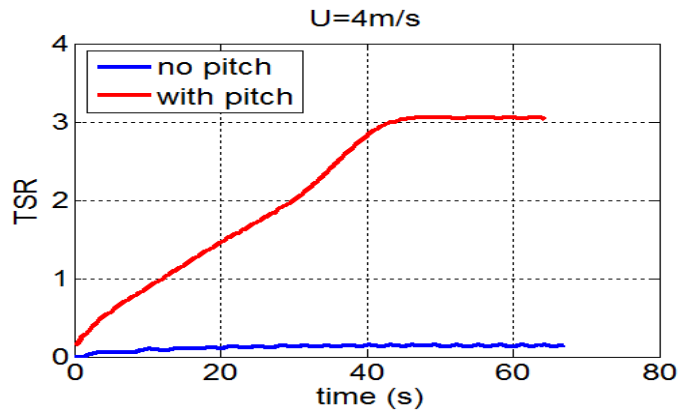


Figure 4: Time series of the recorded Tip Speed Ratio for the same incoming wind speed; blue: pitch off; red: pitch on.

Experiments were then conducted in the large IRPHE/PYTHEAS air-sea interaction facility² in Luminy Marseille, with force and moment evaluation, rotational sensors to detect the blade-azimuthal position and rotational speed, and particle image velocimetry (PIV) measurements. A particular care was taken on the control-command of the pitching laws to increase the aerodynamic performance and the turbine efficiency.

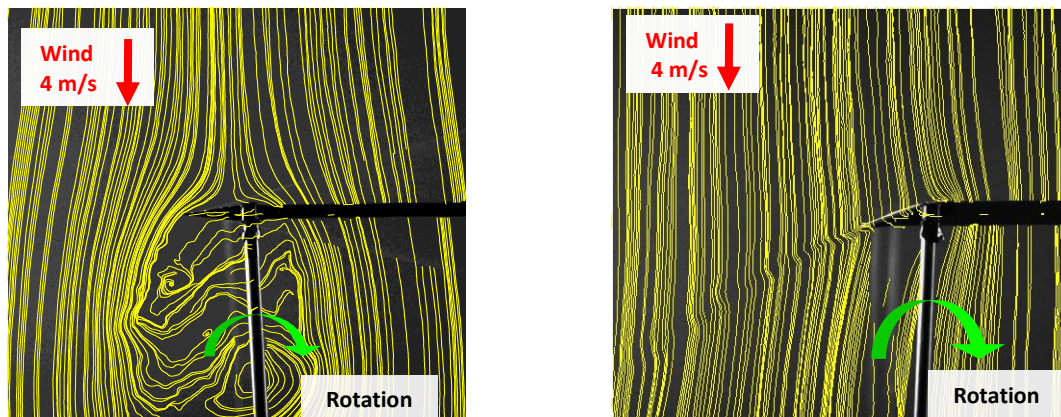


Figure 5: measured streamlines, same incoming wind speed: 4 m/s ; view from above. Left: Pitch Off; Right: Pitch On

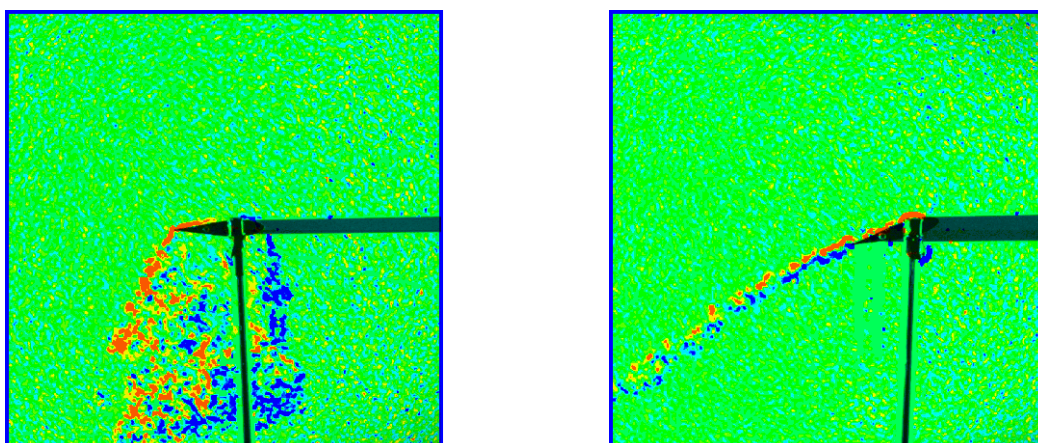


Figure 6: measured vorticity field, same incoming wind speed: 4 m/s ; view from above. Left: Pitch Off; Right: with Pitch On

An open source genetic algorithm optimization software, Dakota, was used to determine the best pitching laws, with input variables such as incoming wind speed, angular

² <https://www.osupytheas.fr/?-LASIF-Grande-Soufflerie-air-eau-de-Luminy->

velocity, blade azimuthal positions, TSR. Dakota contains algorithms with stochastic expansion methods, reliability, sensitivity variance analysis and advanced strategies with automatic direct real-time data exchange between on-going experiments and software [9] .

Finally, we found that at rather low wind speed, pitching the blade brings a considerable gain on the TSR (Figure 4). The rotational speed, in this example, is multiplied by 20 with the same incoming wind speed !

To better understand the positive gain obtained by those pitch laws, we then made PIV measurements of the flow around the blade in no-pitch and pitch conditions, for variable TSR. Figure 5 is an close-up example of the streamline field differences between no pitch and pitch on conditions for the same incoming wind speed $U = 4$ m/s. Figure 6 is the associated vorticity field. We see clearly the huge modification of the flow due to the blade pitching. The TSR (and by the way the blade velocity) is much higher when the pitch is on, thus generating visible better conditions for decreasing drag and increasing lift creating higher efficiency. Velocities, vorticity and streamlines were compared with the CFD numerical simulations.

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