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Experimental lift control using fluidic jets on a model wind turbine

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Abstract. This study focuses on the experimental implementation of a fluidic lift control strategy on wind turbine blades with the objective of reducing the aerodynamic load fluctuations experienced by the rotors. Blades are equipped with a row of blowing jets located in the vicinity of the rounded trailing-edge of the airfoil. Two configurations are performed: a translational configuration (2D configuration with free blade tip), and a rotational case where the blades are mounted in the wind turbine bench of the laboratory. The actuation modifies the flow near the trailing-edge and changes the whole pressure distribution around the airfoil as well as the spanwise lift distribution on the blade. Load, flapwise bending moment and pressure measurements as well as Particle Image Velocimetry (PIV) show respectively the actuation effectiveness in terms of load modification and flow topology alteration.

1. Introduction and work objectives

Wind turbine blades are permanently subjected to incoming wind variations that provoke severe load fluctuations on the rotor. These fluctuations may damage the blades and reduce the turbine operating life. Wind changes are due to the inhomogeneity and the unsteadiness of the flow in the atmospheric boundary layer and are characterized by both wind velocity and wind direction variations. This study is part of the French national project SMARTEOLE that aims at reducing the aerodynamic load fluctuations as well as the blade fatigue to therefore increase the rotor lifetime. SMARTEOLE project investigates load alleviation at three different scales: the farm scale, the wind turbine scale, and the blade scale. The present study deals with overloads reduction at the blade scale and is performed at a wind-tunnel scale.

Nowadays, horizontal axis wind turbines (HAWTs) load fluctuation reduction is mainly carried out with collective or individual pitch control. However, this strategy acts on the whole blade and may have a long time response towards wind fluctuations with small time scales (<10 s) leading to a more curative than preventive actuation. Active load control techniques (flaps, microtabs, fluidic devices...) have small time responses and are able to operate on just some areas of the blade, specially on the areas generating the higher torque. By adding information on the turbine controller about the incoming wind conditions thanks to LiDAR devices or blade pressure measurements, wind turbines could compensate in real time the rotor overloads. Up to now, no active flow control devices are used in industrial HAWTs. Passive devices such as vortex generators are however employed at the blade roots to reduce flow separation in this low torque production area. The most mature strategy of active load control concerns trailing-edge flaps

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1 and tabs as can be read in [1], [2] and [3]. High deflection flexible flaps show a lift coefficient gain ΔC_L up to 0.8 as can be read in [4].

To obtain faster time responses and be devoid of moving mechanical parts, more innovative flow control concepts are investigated such as fluidic jets or plasma actuators. Active flow control is mainly implemented to perform either a boundary layer separation control, a circulation control or both at the same time. Separation control actuation is located on the first third of the airfoil suction side (or all along it) and its effect delays stall towards higher blade angles of attack. Circulation control is performed by an actuation at the trailing-edge of the blade and its effect shifts the lift curve towards higher (or lower) lift forces. As with trailing-edge flaps, the actuation efficiency can be quantified in terms of lift coefficient gain or loss $\pm \Delta C_L$. Concerning flow separation, the resulting ΔC_L is usually between +0.1 and +0.3 for active flow control applications: authors in [5] and [6] obtain gains of 0.3 and 0.12 respectively with Dielectric Barrier Discharge (DBD) plasma actuators, synthetic jets show a gain equal to 0.12 [7] and fluidic jets perform a lift coefficient gain of 0.2 [8]. Regarding circulation control, fluidic jets have shown an increase of 0.25 of the lift coefficient as seen in [9] and plasma actuators can increase or decrease the lift coefficient by around ± 0.1 ([10] and [11]). A complete review of wind-turbine oriented active flow control strategies can be read in [12].

In the present work, the experimental load control is carried out via an active fluidic control strategy applied on a wind turbine model and at a wind-tunnel scale. All the tests are carried out in an open-loop configuration. The explored technique aims at modifying the flow near the trailing-edge of the airfoil (separation and stagnation points in the linear part of the lift curve) by operating blowing jets along the blade. It has been chosen to perform lift modification with a rounded trailing-edge that allows a monitoring of the circulation around the airfoil and thus of the lift force that can either be increased or decreased. Figure 1 shows how this circulation control may allow to maintain a constant lift force when incoming wind conditions vary in direction and in terms of incoming velocity. The figure also shows the active separation control principle of stall delay.

After an explanation of the experimental set-up and the employed methodology, the second section is devoted to the results corresponding to the blade implemented in a translational configuration as well as the first preliminary results obtained in the wind turbine bench of the laboratory.



Figure 1: Principle of active circulation control in response to a sudden gust modifying the incoming flow speed and/or angle of attack (left), principle of active separation control (right)

2. Approach and methods

2.1. Blades and fluidic jets actuation

The blade airfoil is a rounded trailing-edge NACA65₄-421 circulation-control oriented airfoil named NACA65₄-421-CC (see figure 2) with a curvature radius at the trailing-edge of 2% of the

chord. Blades are not twisted, have a constant chord c equal to 100 mm, and can be mounted on the two-bladed wind turbine bench of the laboratory whose rotor radius R is equal to 700 mm.

Regarding the flow control implementation, blades are equipped with a row of 72 micro jets (hole diameter d = 0.6 mm and spaced of e = 4.8 mm) that blow compressed air in the vicinity of the trailing-edge at $\frac{x}{c} = 0.96$ over the upper side of the blade. The actuation takes place on the second half of the blades from $r \approx 0.5R$ to $r \approx R$. Both stationary and rotating tests are carried out in the "Lucien Malavard" closed return-circuit wind-tunnel of the University of Orléans (France) where two test-sections are available to testing.



Figure 2: Original NACA65₄-421 airfoil (dotted line) and lift control airfoil (solid line) (from [13])

2.2. Translational configuration

Before implementing the blades on the rotor bench and testing the flow control on a rotating configuration, blades are first tested in a translational configuration meaning that the blade is mounted in a 2D-configuration but with a free blade tip as shown in figure 3a. This configuration will be called in the following *translational configuration*. Tests are performed in the main test-section that is 2 m high, 2 m wide and 5 m long. The model is mounted on a 6-component platform balance that provides time averaged lift and drag forces as well as the aerodynamic moments. Mean pressure distribution around the airfoil is measured with twenty pressure taps implemented on the blade between the leading-edge and 70% of the chord and located at r = 0.63R or r = 0.88R. Measurements are made with a 32-channel differential pressure scanner ESP-32HD (GE, ± 0.361 PSI) embedded in a MicroDAQ system (CHELL). The reference pressure is the static pressure measured with a Pitot probe near the upper wall of the test-section.

Time-averaged velocity fields of the trailing-edge flow and the blade wake are obtained via PIV (Particle Image Velocimetry) measurements at r = 0.62R. PIV field is in a slice between two jets, but close to a jet hole. Performing PIV measurements exactly over a jet was difficult due to laser reflections. PIV system consists of a Nd:Yag laser $(2 \times 200 \text{ mJ})$ emitting pulses with a 2.5 Hz emission rate. The light sheet is oriented in order to visualize simultaneously both pressure and suction sides of the airfoil. Seeding particles are micro-sized olive oil droplets sprayed by a PIVTEC seeding system and the particle diameter is of approximately 1 µm. Images are acquired with a Imager LX11M camera $(4032 \text{ px} \times 2688 \text{ px})$ with a 200 mm lens. The final resolution of the velocity fields is of one vector every 0.8 mm with a $32 \text{ px} \times 32 \text{ px}$ final interrogation window and an overlap of 50%. One thousand image pairs are recorded for time-averaging.

In this configuration, wind-tunnel tests are performed with an incoming flow velocity U_{∞} of 20 m/s corresponding to a chord Reynolds number Re of 130000. At this Re, low Reynolds effects appear and the boundary layer developing along the suction side of the airfoil separates from the wall for a large range of angles of attack. To avoid these laminarity effects and enhance

turbulence, experimental testing is performed with a 4.4% turbulence grid settled in the testsection entry instead of working with the natural turbulence of the wind-tunnel equal to 0.5%.

2.3. Rotational configuration

Rotational testings are performed in the return test-section of the wind-tunnel as described in [13] and shown in figure 3b. The turbine is located at the exit of a convergent $(4 \text{ m} \times 4 \text{ m} \text{ to})$ $3 \text{ m} \times 3 \text{ m}$) that allows flow conditioning. Honeycombs and a turbulence grid are also employed to ensure flow homogeneity. The turbine is positioned normal to the flow (yaw angle $\gamma = 0^{\circ}$) and is centered in the homogeneous flow area at 3.8 m from the turbulence grid. In the present study, the incoming wind velocity is fixed at $U_{\infty} = 10 \,\mathrm{m/s}$ with a turbulence intensity level of around 4%. The wind turbine bench is made up of a reversible motor Phase Ultract 509 that enables the monitoring of the turbine rotational velocity Ω up to 1000 rpm. The servomotor provides energy when the working point of the turbine is propulsive and dissipates energy when the working point is extractive (present case). Torque and thrust of the turbine are measured with a Scaime M2392 transducer. Pressure distribution is measured on one of the two blades with a similar system as used in the translational configuration (ESP-32HD, GE, ± 1 PSI). The pressure transducer is embedded in the rotor and the reference pressure is the static pressure measured with an embedded Pitot probe measuring 400 mm upstream from the rotor hub. Root bending moment on both blades is measured with a strain gage full bridge circuit (Kyowa gages, $120\,\Omega$). Two pressure sensors (Sensortechnics $0-5\,\mathrm{bar}$) measure the total pressure inside the blade pressure chamber that supplies the blowing jets. Measurements from pressure transducers and strain gauges are transferred to the ground thanks to a through-bore slip ring Servotecnica SRH3899. A Pacquet rotary joint allows the transmission of compressed air from the stationary state to the rotor of the turbine.



(a) Blade mounted in the translational configuration



(b) Blade mounted in the wind turbine bench (rotational configuration)

Figure 3: Pictures of the experimental set-ups

3. Results

3.1. Blowing jets characterization

First, the blowing jets are characterized in quiescent air conditions, that is, outside the windtunnel and without an external flow. The objective is to characterize the blowing homogeneity along the blade span and to have an idea of the jet diffusion downstream of the jet exit. Also, this characterization permits to have the jet velocity evolution as a function of the applied flow rate which is necessary for the calculation of the momentum coefficient C_{μ} . The momentum coefficient quantifies the strength of the actuation and is defined as the ratio between the injected momentum with the actuation and the momentum of the free stream such as $C_{\mu} = \frac{\rho_j S_j U_j^2}{\frac{1}{2}\rho U_{ref}^2 S_{ref}}$, where ρ_j is the jet density, S_j the surface of the blowing jets, U_j the jet velocity, ρ the density of the incoming flow, U_{ref} a reference velocity and S_{ref} a reference surface. Figure 4 shows the coordinate system used for the jet characterization that was performed with a thin total pressure probe (inner diameter of 0.25 mm).

Figure 5a shows the jet velocity U_{x^*} distribution along the blade span for several abscissas i.e. distances from the trailing-edge located at $x^* = 0 \text{ mm}$ and a flow rate $Q_{fm} = 180 \text{ L}_n/\text{min}$. The theoretical jet location is shown by the black lines and the model parts intersections are represented by the red lines. Figure 5b is a zoomed view of figure 5a that permits to better visualize the micro jets resolution and the flow between them. The mean jet exit velocity at $x^* = -2 \text{ mm}$ is equal to 174 m/s and 72% of the jets show a jet velocity below this average. The blowing homogeneity is satisfying except at some locations at the joints between blade sections where the jet velocity seems significantly weaker than on the rest of the blade.

Figure 4: Definition of the coordinate system for the jet characterization



3.2. translational configuration

Figure 6a shows the global lift coefficient C_L obtained with the platform balance as a function of the angle of attack α for the baseline case with a turbulence intensity $T_u = 4.4\%$ as well as for two controlled cases. Lift coefficient is defined as $C_L = \frac{F_L}{\frac{1}{2}\rho U_{\infty}^2 S_{ref}}$ where F_L is the lift force and S_{ref} the surface emerging from the streamlined fairing. For the controlled cases, the lift force is corrected by substracting the lift force obtained without an incoming wind but with the actuation powered. Momentum coefficient C_{μ} is calculated with U_{ref} equal to the incoming flow velocity $U_{\infty} = 20 \text{ m/s}$ and with the jet exit velocity U_j measured with the total pressure probe. The blowing jets action at the trailing-edge of the blade is mainly noticeable for the highest C_{μ} and the lift coefficient increase is more important for the angles of attack between 10° and 20° witnessing of a stall delay of the airfoil with the actuation. By looking more closely to the flow rate effect on the lift coefficient gain (figure 6b), two tendencies seem to be highlighted. In the linear part of the lift curve, between 0° and 7° the lift coefficient gain obtained goes no further than 0.1. However, it reaches 0.16 and 0.3 for 10° and 18° respectively and the highest C_{μ} . This indicates that our actuation seems to perform a weak circulation control when the flow is attached to the blade, and a separation control for the higher angles of attack, when the boundary layer separation point rises along the airfoil chord.

This lift modification is also demonstrated with pressure measurements. Figure 7 shows the pressure coefficient C_p distribution at a blade span r = 0.63R of the airfoil for several C_{μ} coefficients at $\alpha = 10^{\circ}$. Pressure coefficient is defined as $C_p = \frac{P - P_{\infty}}{\frac{1}{2}\rho U_{\infty}^2}$, where P is the measured pressure over the blade and P_{∞} is the static reference pressure. The actuation reduces the



Figure 5: Jet velocity distribution along the blade span as a function of x^* without external flow $(Q_{fm} = 180 L_n/\text{min} - C_\mu = 0.022)$

pressure level along the suction side of the blade whereas the pressure distribution remains unchanged along pressure side. This corresponds to an overall increase of the airfoil lift which is coherent with the previous load results.

Figure 8 shows the velocity fields around the airfoil trailing-edge with and without actuation and for an angle of attack $\alpha = 18^{\circ}$. The jets create a low pressure area in the vicinity of their exit and allow to partially reattach the flow over the airfoil. With the jets actuation, boundary layer separation is delayed over the airfoil chord and therefore the recirculation area becomes smaller. Flow visualization confirms load and pressure measurements because by reducing the separated area the lift coefficient is increased. The jet signature is also visible as a high velocity region downstream of the airfoil. As the jet exit velocity is an order of magnitude higher than the freestream velocity the PIV correlation might be altered in the region close to the jet exit.



Figure 6: Global lift coefficient C_L and its gain ΔC_L for Re = 130000 (translational configuration)



Figure 7: Pressure distribution at r = 0.63R and $\alpha = 10^{\circ}$ for Re = 130000 (translational configuration)

3.3. Rotational configuration

This section introduces the first preliminary results of flow control performed in the wind turbine bench. For this rotational configuration the momentum coefficient should be calculated with $S_{ref} = cR$ and the reference velocity U_{ref} equal to $\sqrt{U_{\infty}^2 + U_R^2}$, where U_R is the tip velocity and $U_{\infty} = 10 \text{ m/s}$. This definition implies that C_{μ} depends on the tip-speed ratio λ ($\lambda = \frac{\Omega R}{U_{\infty}}$) of the turbine as shown in figure 9 for the three different flow rates applied (Baseline¹, P1 and P2).

Figure 10a shows the power coefficient of the turbine C_{power} as a function of the tipspeed ratio λ for several pitch angles β and without actuation. Power coefficient is defined as $C_{power} = \frac{Q\Omega}{\frac{1}{2}\rho U_{\infty}^3 S_{rotor}}$ where Q is the torque generated by the turbine and S_{rotor} the blade swept area. The higher values of C_{power} are found for a pitch angle $\beta = 8^{\circ}$ but pitch angles 6° , 8° and 10° show very similar curves. The optimal operating point of the turbine is obtained for a tip-speed ratio λ_{opt} equal to 5.5 and corresponds to a maximum power coefficient $C_{power-max}$

¹ For the proper functioning of the rotary joint, a weak blowing is required for the baseline case



Figure 8: Time-averaged non dimensional velocity fields with and without actuation at $\alpha = 18^{\circ}$ (translational configuration)



Figure 9: Momentum coefficient C_{μ} in the rotational configuration as a function of the tip-speed ratio λ

equal to 0.42 in agreement with the results obtained with Blade Element Momentum (BEM) theory and presented in [13] for the same turbine. When increasing the pitch angle β the power coefficient decreases as the aerodynamic performance of the blades is reduced. Figure 10b plots the thrust coefficient C_{thrust} as a function of λ . Thrust coefficient is defined as $C_{thrust} = \frac{D}{\frac{1}{2}\rho U_{\infty}^2 S_{rotor}}$ where D is the overall drag of the turbine. The pitch angle augmentation entrains a global thrust coefficient decrease as the blade surface facing the wind is reduced and also the rotor drag force. The maximum C_{thrust} is obtained for the lower pitch angle and is equal to 1.4. For the optimal working point of the turbine ($\beta = 8^{\circ}$ and $\lambda = 5.5$) thrust coefficient is equal to 0.76.

Actuation performance is shown in figure 11 for the blade flapwise bending moment (FBM) and in figure 12 for pressure measurements. Torque measurements with actuation still have to be post-processed as the use of a rotary joint to supply the rotor on compressed air added a frictional torque on the wind turbine shaft that made the measurements difficult. Figure 11 shows the FBM of one blade as a function of λ with and without actuation for $\beta = 10^{\circ}$. This variable is a resultant of the lift force all along the bladespan. FBM grows steadily up to a certain tip-speed ratio ($\lambda = 4$) after which the value seems to increase more slowly. The effect of the actuation is visible as the FBM value for both controlled cases is over the baseline case. As



Figure 10: Power coefficient C_{power} and thrust coefficient C_{thrust} for different pitch angles β and without actuation (rotational configuration)

expected, the greater the applied flow rate, the greater the effect on the FBM is. The effect of the blowing jets is more visible for the low λ (between 1 and 4) and gets weaker for the higher tip-speed ratios (from 4 to 6). The maximum FBM gain is of 0.9 N m and obtained for $\lambda = 2.93$.



Figure 11: Flapwise bending moment with and without actuation for $\beta = 10^{\circ}$ (rotational configuration)

Pressure coefficient is shown in figure 12 with and without actuation for a pitch angle $\beta = 10^{\circ}$ and a tip-speed ratio equal to 2.93 corresponding to $\Omega = 400$ rpm. Blue colors correspond to the pressure at radial blade position r = 0.63R and red colors to r = 0.88R. Pressure coefficient for the rotational configuration is defined as $C_p = \frac{P - P_{\infty}}{\frac{1}{2}\rho(U_{\infty}^2 + (\Omega r)^2)}$. Pressure distributions do not reach the maximal value of 1 because the axial and azimuthal velocity deficit is not taken into account in the reference velocity used in the C_p definition. First, baseline pressure distributions at the two radial positions 0.63R and 0.88R show the same tendency even if the pressure level over the pressure side of the blade for r = 0.63R is greater. The actuation changes the pressure distribution along the suction side of the blade by reducing the pressure level over this side. Pressure along the pressure side of the blade is not altered by the flow control. Again, the higher the applied flow rate, the higher the effect of the actuation on the pressure distribution is.



Figure 12: Pressure coefficient C_p distribution for $\beta = 10^{\circ}$ and $\lambda = 2.93$ with and without actuation (rotational configuration)

4. Conclusion

An experimental active control strategy is tested on a model wind turbine equipped with a row of fluidic jets blowing in the vicinity of the trailing-edge. The jet characterization shows that the blowing homogeneity is satisfactory for the employed blades. For the translational configuration, the flow control is effective and an increase of the lift coefficient up to 0.3 is achieved. Pressure measurements and PIV visualization confirm this lift coefficient gain. The actuation performs a weak circulation control on the linear part of the lift curve and a boundary layer separation configuration permits the understanding of the actuation mechanisms and performances. First results obtained in the wind turbine bench are also addressed. The effect of the actuation is visible on the flapwise bending moment as well as on the pressure distribution along the rotating blade. This study remains a preliminary investigation of fluidic active flow control on a model wind turbine and at a wind-tunnel scale. An eventual scaling-up of the proof of concept and a fatigue reduction quantification will be done with SMARTEOLE partners that analyse wind anticipation capabilities for industrial wind turbine control strategies as can be read in [14].

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