Active separation control on a very thick wind turbine airfoil - A URANS and DDES perspective

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Abstract. The present works aim to investigate the effectiveness of active separation control by means of combined suction and vortex generator jets on the suction side of a very thick airfoil (40%) under tripped conditions. Fully resolved two-dimensional URANS and three-dimensional DDES simulations were carried out to assess the consistency of the results. It is observed for the baseline case that 2D URANS simulations are too optimistic while 3D DDES delivers an excellent agreement with the available experiment in the post stall region at $\alpha = 20^\circ$. The studies reveal that the proposed system is able to delay separation significantly, increasing the overall aerodynamic performance of the airfoil.

1. Introduction

With increasing demand of wind energy, the size of wind turbines increases significantly nowadays to enhance the power generation for each individual turbine. This especially takes place in the area where the available spaces for multiple rotors in wind parks are limited. The current trend for wind turbine even reaches up to 10-20 MW [1, 2]. Accordingly, the blade size increases and the need of the higher inertial moment at the blade root becomes increasingly important [3]. The inboard section of the blade is constructed by thick airfoils with the maximum thickness of more than 35%. The airfoils with excessive thickness often show reduced aerodynamic performances compared to the thinner sectional airfoils. This has been reported, for example, by Baker et al. [4] using experiment and Bangga et al. [3] by means of numerical simulations. A strong adverse pressure gradient (APG) occurs on the suction side of the airfoil, even at a small angle of attack, and hence promotes stronger separation [3, 4]. Furthermore, the leading edge is often contaminated by insects and dirt during the rotor operation leading to premature laminar to turbulent transition. Experimental data from [4] and [5] demonstrated that a significant impact on the maximum lift coefficient ($C_L$) and stall can be observed for premature transition (tripped) conditions. Moreover, the separated flow causes increased load fluctuations that can harm the stability and strength of the structure itself.

Many attempts have been done to delay the occurrence of separation by modifying the local behaviour of the flow for thin airfoils especially for aircraft applications, but not so many studies were conducted on very thick airfoils designed for the root area of wind turbine. Passive vortex generators (VG) are widely used, but fluidic VGs are less often. The studies for fluidic VGs showed that the method has a potential for separation delay, and was confirmed by several authors such as Ball [6], Johnston & Nishi [7] and Sullerey & Pradeep [8]. Combining the jet
influence with a boundary layer suction improves the flow stability and, thus, separation can be more effectively delayed. The present investigations aim to numerically assess the capability of the combined steady suction and vortex generator jets for separation delay on the DU 00-W2-401 airfoil with 40% relative thickness at a Reynolds number of 3 million. This airfoil is applied on the root area of the generic 10 MW AVATAR wind turbine [1]. Though the steady vortex generator jets was reported to be less effective than the synthetic jets in [9], the approach still renders feasible and worth investigating. Furthermore, the application of the method for excessively thick airfoils at the high Reynolds number requires a consideration and deeper studies are necessary, becoming the main novelty of the present paper. The knowledge gained from the present works can be transferred into a consideration for designing efficient large wind turbine rotors dealing with the complex 3D flow separation in the root area.

2. Computational setup
The computational studies employ the computational fluid dynamics (CFD) code FLOWer from the German Aerospace Center [10]. The spatial discretization scheme uses a central cell-centered Jameson-Schmidt-Turkel finite volume formulation because it provides high robustness and is well-suited for parallel applications. The method utilizes the central space discretization with artificial viscosity and explicit hybrid 5-stage Runge-Kutta time-stepping schemes. The dual time-stepping approach with the second order accuracy in time was applied. A time-step size of $3.47 \times 10^{-4}$ s was applied in the simulations. Two turbulence modelling approaches, Unsteady Reynolds-Averaged Navier-Stokes (URANS) and Delayed-Detached Eddy Simulation (DDES), were examined. Both models use the same turbulence closure for the wall bounded flow namely the Shear-Stress-Transport (SST) $k-\omega$ as the model is able to predict flows with a strong APG.

Figure 1: Three dimensional CFD mesh showing the blanked-overset region used in the simulations. The black colour indicates the airfoil mesh, red is for the suction plane and blue is for the blowing channel.
The same model was used in preceding works either as pure URANS [2,11–15] or as DDES [14–16] with good accuracy.

The overset approach was employed to simplify the mesh generation without sacrificing its quality. The illustration of the 3D mesh for all structures embedded each other is shown in Figure 1. The airfoil is discretized with [281x129] grid points in chordwise and normal directions with 32 cells within the boundary layer. The distance of the first grid layer to the wall was set to meet the non-dimensional wall distance of $y^+ < 1$ in order to properly capture the laminar sub-layer characteristics as no wall model was employed. The grid sensitivity study for the airfoil was carried out in advance [2]. A relatively large span extrusion of 0.4 times the chord length ($c$) was chosen and discretized by 41 grid points. The cell size in the wake area near the airfoil excluding the boundary layer is about 0.01$c$ which is suitable for eddy resolving based simulations. It shall be noted that a 2D grid was used for the URANS computations and a fully resolved 3D grid was applied for the DDES simulations. Both 2D and 3D meshes have exactly the same streamwise and normal grid distributions. The URANS approach was not applied in the 3D case because the resulting vortices from the vortex generator jet are intended to be resolved. The preceding studies [14] demonstrated that the DDES approach was able to resolve the complex 3D flow in the root area of wind turbine blade consisting of thick airfoils better than the URANS method. On the other hand, the DDES approach was not applied for the 2D case due to the 3D nature of the eddies.

A distributed boundary layer suction was defined within $0.4 < x/c < 0.5$ and a square-duct blowing plane was introduced at $x/c = 0.65$ (Figure 1) acting as the fluidic vortex generator jets upstream of the expected separation location as recommended in [6]. The mesh of these additional components were generated using an automated script developed at the institute. The mesh was refined near the wall area maintaining the $y^+$ value less than unity.

3. Mass Flow Rate Influence

In the present studies, several combinations of the continuous suction ($\dot{m}_s$) and blowing mass flow rates ($\dot{m}_b$) are evaluated in advance till maximum effects of the flow control are achieved. The non-dimensional mass flow rate ratio $C_\mu$ is defined as $C_\mu = \frac{V_{jet/suction} L}{U_\infty c}$, where $V_{jet/suction}$ is the blowing or suction velocity, $L$ is the length of the blowing (0.005$c$) or suction (0.1$c$) area (see Figure 1) and $U_\infty$ is the freestream velocity.

Figure 2 presents the 2D URANS simulation results for the effects of the mass flow rates, $C_{\mu s}$ (suction) and $C_{\mu b}$ (blowing), on the aerodynamic performances of the airfoil in terms of $C_L$, $C_D$ and $C_L/C_D$. The forces are obtained from the pressure and skin friction coefficients by excluding the blowing patch and a linear interpolation within this area is carried out before the integration. Note that effects of the jet momentum on the drag coefficient is not considered and $C_D$ is obtained directly from the integration. It can be seen that the lift coefficient changes as the active flow control is applied, resulting in $C_{\mu s} = 0.00373$ and $C_{\mu b} = 0.00746$ (Case 5) as the most optimum one for the examined combinations. It shall be noted that $C_{\mu b}$ is larger than $C_{\mu s}$. This was set on purpose as the additional flow rate given, $\Delta C_\mu$, is able to effectively improve the performance. A possible configuration for this specific mass flow rate combination is illustrated in Figure 3 where $\Delta C_\mu$ is supplied from the nearby radial station of the blade span.

It can be depicted in Figure 2 that the load fluctuations are influenced by the proposed system. Case 3 shows the minimum fluctuations for all aerodynamic parameters presented in Figure 2 while Case 4 shows the strongest fluctuations. Figure 4 presents the frequency spectra of the load fluctuations for $C_L$, $C_D$ and $C_L/C_D$. It is shown that the locations of the peaks for the baseline case (Case 1) are similar to Case 2 and Case 4, but the magnitudes of the peaks are different. Stronger peaks at a larger frequency domain are observed for Case 2 and Case 4 that are originated from the vortex interactions between flow separation and the VG jets. On the other hand, the applied suction in Case 3 reduces the load fluctuations significantly. For Case 5,
the low frequency fluctuations vanish leaving a noticeable peak at 620 Hz, which is dominated by the generated vortices of the VG jets.

Figure 2: The effects of the mass flow rate on the aerodynamic characteristics of the thick DU 00-W2-401 airfoil at $\alpha = 10^\circ$. The transition was enforced at 2% and 10% on the upper and lower sides of the airfoil, respectively. The Reynolds number is 3 million. The error bars represent the amplitudes of the corresponding aerodynamic loads. The presented results were computed using the 2D URANS approach.

Figure 3: Design possibility of the suction-blowing system in the inboard blade region. The blade figure was obtained from the preceding CFD studies in [17]
To briefly resume the studies, Case 5 with $C_{\mu s} = 0.00373$ and $C_{\mu b} = 0.00746$ generates the maximum impacts compared to the other investigated cases. Therefore, this particular case is chosen for further simulations and evaluations.

4. AFC Devices Performances
In the present section, the characteristics of the aerodynamic polars influenced by the applied active flow control devices are investigated using 2D URANS and 3D DDES. Figure 5a presents the lift polar as resulting from the simulations. An additional inviscid XFOIL computation for the baseline case without active flow control (AFC) was performed for comparison. The experimental data from Rooij and Timmer [5] is also presented. The results show that URANS is too optimistic in the prediction, but an excellent agreement between DDES and the available experimental data for the baseline case at $\alpha = 20^\circ$ is obtained. It can be seen that $C_L$ for the AFC case increases considerably compared to the baseline case, becoming closer to its inviscid behaviour. The lift breakdown at $\alpha \approx 4^\circ$ is completely eliminated, and the stall angle is delayed up to around $28^\circ$ followed by a strong lift breakdown reaching the $C_L$ value similar to the

Figure 4: Frequency spectra for the DU 00-W2-401 airfoil at $\alpha = 10^\circ$. The inflow conditions and simulation parameters are the same as in Figure 2.
Figure 5: Aerodynamic coefficients as a function of the angle of attack ($\alpha$) computed using 2D URANS and 3D DDES approaches for the baseline case and the airfoil employing AFC.

Figure 6: Time- and spatial-averaged (over the span) pressure ($C_p$) and skin friction ($C_f$) coefficients at $\alpha = 20^\circ$ computed using the 3D DDES approach for the baseline case and the airfoil employing AFC.
Figure 7: Iso-surface plots of the Q-criterion (5000) coloured by the non-dimensional total velocity obtained from the DDES computations for the baseline and AFC cases at $\alpha = 20^\circ$.

Figure 8: Frequency spectra for the DU 00-W2-401 airfoil at $\alpha = 20^\circ$ computed using 2D URANS and 3D DDES approaches. The inflow conditions and simulation parameters are the same as in Figure 5.
Figure 9: Frequency spectra for the DU 00-W2-401 airfoil at various angles of attack computed using the 2D URANS approach. The inflow conditions and simulation parameters are the same as in Figure 5. The left figures show the baseline case and the right figures are the case employing the AFC devices.

baseline case. In Figure 5b, the drag polar obtained from the CFD simulations is presented. No experimental data is available for drag so that the assessment for the accuracy is not possible. Despite that, the drag characteristics influenced by the AFC devices can still be examined. It is shown that $C_D$ for the case employing AFC increases slightly at $-10^\circ < \alpha < 10^\circ$. A significant reduction of $C_D$ is observed at a higher $\alpha$ until the lift stall occurs at $\alpha = 28^\circ$, followed by a sudden augmentation of drag. The DDES computations at $\alpha = 20^\circ$ produce a similar behaviour that supports the observed effects for the 2D URANS simulations. The sliding ratio is improved
significantly by the AFC approach for a large range of the angle of attack at $2^\circ < \alpha < 28^\circ$ depicted in Figure 5c. The results of the DDES simulations show an even higher $C_L/C_D$ at $\alpha = 20^\circ$ indicating that an even greater benefit may be obtained by employing the proposed system than those predicted the URANS method.

The pressure and skin friction distributions in Figure 6 and flow visualization in Figure 7 reveal that separation is completely eliminated at $\alpha$ as high as $20^\circ$. This renders to a suggestion that the approach is feasible and can be beneficial for the power production of wind turbines, especially as the sliding ratio increases significantly as depicted in Figure 5c. It is shown in Figure 6a that the pressure levels on the upper and lower sides of the airfoil change significantly compared to the baseline case, becoming really close to the inviscid pressure distribution. In Figure 6b, a greater maximum $C_f$ is observed for the case employing the AFC devices at $x/c \approx 0.05$. The skin friction level gradually reduces up to $x/c = 0.4$ before the suction device increases its level up to $x/c = 0.5$, and then $C_f$ drops again. Downstream this position, the blowing device further enhances $C_f$ and the effect is present until the trailing edge. This combination of the flow manipulation effectively eliminates flow separation compared to the baseline case that shows massive separation as early as $x/c \approx 0.25$.

Figure 8 shows the frequency spectra of the aerodynamic load fluctuations computed using 2D URANS and 3D DDES at $\alpha = 20^\circ$. The locations of the peaks obtained from the 2D URANS computations are similar to the 3D DDES results even though the magnitudes of the fluctuations differ. The spectra obtained from the DDES computations are more broadband especially for the baseline case. In agreement with the evaluations given in Section 3, the employed AFC devices shift the peaks to a higher frequency. Despite that, the fluctuations are not necessarily smaller than the baseline case in contrast to what observed at $\alpha = 10^\circ$ in Figure 4. Further detail about this specific characteristic is presented in Figure 9. It is shown that the spectra are influenced strongly by the variation of the angle of attack. The amplitudes of the loads for the baseline case increase with increasing angle of attack, and the maximum peak is further shifted to a lower frequency domain. For the case employing the AFC devices, the characteristics of the fluctuations change. A dominant peak is observed at a frequency of about 60 Hz for the case at $\alpha = 0^\circ$. Note that no fluctuations are observed for the baseline case in Figure 9. This peak vanishes at $\alpha = 4^\circ$, but high frequency oscillations with low amplitudes are shown at the frequencies greater than 400 Hz. Further increase of $\alpha$ results in the generation of a dominant peak at 620 Hz that is observed for $\alpha \geq 10^\circ$. In the post-stall regime, at $\alpha = 40^\circ$, the vortices driven by flow separation cannot be suppressed any longer. This causes a generation of a noticeable peak at a lower frequency domain that is similar to the baseline case in addition to the dominant peaks at the high frequency domain.

5. Conclusions and Outlook
Computational fluid dynamics analyses have been carried out for a very thick wind turbine airfoil (40% relative thickness) employing active separation control devices by means of continuous suction and blowing approaches. Fully resolved two-dimensional URANS and three-dimensional DDES approaches were employed to simulate the turbulent flow over the airfoil. In the first part of the studies, the impacts of mass flow rate combination for the suction and blowing devices were examined. The results demonstrated that the aerodynamic performances of the thick airfoil could be improved by applying the underlying active flow control systems. The maximum effect on the airfoil efficiency was generated by applying suction and blowing mass flow rates of $C_{\mu,s} = 0.00373$ and $C_{\mu,b} = 0.00746$, respectively. Then, this specific combination was tested for the airfoil operating at a large range of the angle of attack within $-10^\circ \leq \alpha \leq 40^\circ$. It was observed for the baseline case that 2D URANS simulations were too optimistic while 3D DDES could deliver an excellent agreement with the available experiment in the post stall region at $\alpha = 20^\circ$. For the case employing the AFC devices, the overall aerodynamic performances
were improved significantly for a wide range of $\alpha$. Flow separation was suppressed and the stall angle was delayed up to around $28^\circ$. The load fluctuations were shifted to a higher frequency range. However, the amplitudes were not necessarily smaller than the baseline case depending on the angle of attack. Further studies are required to improve the proposed systems, not only for the aerodynamic loads improvement but also for reducing the load fluctuations that can generate unwanted fatigue loads on the structures. Furthermore, the assessment of the flow field fluctuations is of interest as this may influence the behaviour of the wake flow in the root area of a wind turbine rotor. The present studies are limited to a thick airfoil, further examinations of the devices on the real wind turbine blade considering the neighbouring section effects shall be taken into account for future investigations.

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