HIGH-FIDELITY SIMULATIONS OF FLOW TRANSITION ON A WIND TURBINE BLADE

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Summary Numerical simulations of the flow over a section of a wind turbine blade are carried out to study its aerodynamic characteristics and specifically to investigate the effect of transition to turbulence. An airfoil designed to operate at relatively low-Reynolds numbers - NREL S827 - is employed and various flow conditions are considered to assess the sensitivity of the transition onset location. Of particular importance is the variation of the aerodynamic lift as a function of the angle of attack and the presence of strongly non-linear behavior at low angle of attack, well below the maximum lift and stall. Numerical simulations are used to confirm the presence of laminar separation bubbles observed in experimental studies. Statistical analysis of the temporal data extracted from the simulations are used to illustrate the appearance of a breathing mode as the potential trigger of the lift behavior.

INTRODUCTION

The design of large-scale wind turbines poses several challenges in the areas of structural mechanics, energy conversion, aerodynamics, acoustics, etc. The multidisciplinary nature of the problem requires modeling tools that balance the need for single-discipline accuracy and the overall efficiency of the coupled solution procedure. Recently NREL has devoted considerable efforts in the development of simplified single-physics codes that can be assembled into a cost-effective design tool; one example of such tools is EOLO[1] a fast, low-fidelity computational infrastructure for aeroelastic and acoustic analysis of wind turbines, which accounts for realistic environmental conditions. EOLO has been used both for performance analysis under uncertainty and for robust optimization. An important component of this tool is the aerodynamics module, which predicts the aerodynamic forces acting on the blade. The relatively low-Reynolds numbers in which the wind turbine operates results in transitional flow over the blade sections, and therefore, leads to complex, non-linear behavior that low-fidelity tools might not be able to capture accurately.
High-fidelity predictions of the transitional and turbulent flows over airfoils has a long history [2]. These simulations require large computational resources and typically cannot be used within the design phase of wind turbine. On the other hand, the insights they afford lead to an increased understanding of the limitations of low-fidelity tools and therefore provide confidence in the predictions obtained using EOLO-like tools. The study of laminar bubbles and their unsteady dynamics has received considerable attention through the development of dedicated experiments [3] and detailed simulations [4] but relatively few studies have attempted to study thick airfoils such as the one employed in high-power wind turbines. Some details of the airfoil used in the present study and corresponding aerodynamic characteristics are reported in the next section. Results obtained from the high-fidelity simulations are reported in the following section.

THE S827 AIRFOIL

In 1992 the National Renewable Energy Laboratory (NREL) designed a family of airfoils for extra-large blades for turbines rated at 400-1000 kW. The s827 configuration was designed specifically for rotors with large swept area by constraining the maximum lift at the rotor tip and the zero-lift pitching moment[6]. The corresponding airfoil section has a thickness/chord ratio of 21% and is characterized by transitional boundary layers and the presence of separation bubbles. The NREL s827 airfoil was tested in the NASA Langley Low-Turbulence Pressure Tunnel in a range of Reynolds ($Re = 1 \times 10^6$ to $Re = 49 \times 10^6$ per meter) and Mach numbers ($M = 0.05$ to $M = 0.47$). The turbulence level in the test section was generally below 0.05 percent for unit Reynolds numbers up to $Re = 13 \times 10^6$ per meter at Mach numbers up to $M = 0.15$. A laminar bucket (low drag over a range of flow angles) is present and extends up to 5 degrees angle of attack as illustrated in Fig. 1; as the angle of attack continues to increase, the lift curve also shows a crisis at 5 deg.

HIGH FIDELITY SIMULATIONS

We perform large eddy simulations using a parallel, structured grid solver for compressible fluids based on high-order compact finite difference discretization operators, that has been already used to study transition on high-speed flat plates [5]. The computations are carried out on two different grids consisting of 8M and 64M elements. The computational domain in the airfoil cross-section extends to 20 chords away from the surface while the spanwise extent of the domain is 10% of the chord.
The numerical simulations provides insights on the complexity of the flow; between $1 \times 10^6 < Re < 4 \times 10^6$ and zero angle of attack, short laminar separation bubbles are present on the upper and lower surfaces - approximatively at 70% chord and 50% chord respectively, see Fig. 2. As the angle of attack is increased, the bubble on the upper surface moves slightly backward, whereas the bubble on the lower surface moves forward. At an angle of attack of about 5 degrees the

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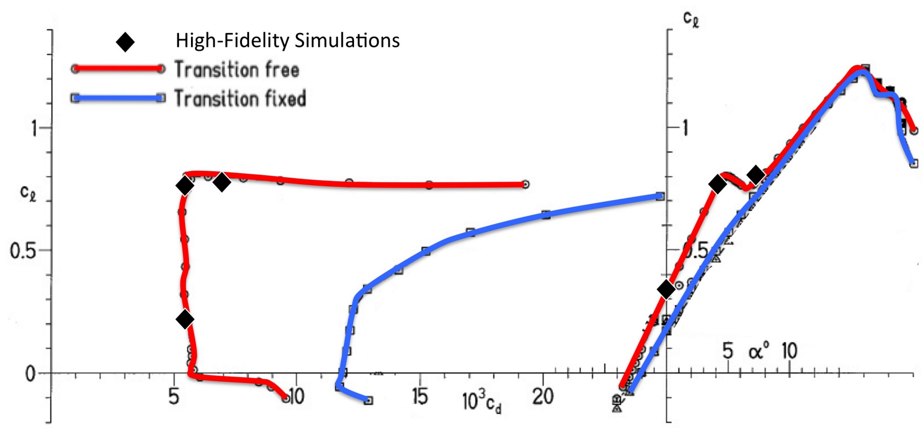

Figure 1. The aerodynamic forces measured over the NREL s827 airfoil at $Re = 3 \times 10^6$ and $M = 0.1$, from Somers[6]. Left: drag vs. lift; Right: lift vs. angle of attack. The blue and red line represent experiments carried out with a tripped and naturally transitioning boundary layer, respectively. The present simulations are carried out under natural transition conditions.

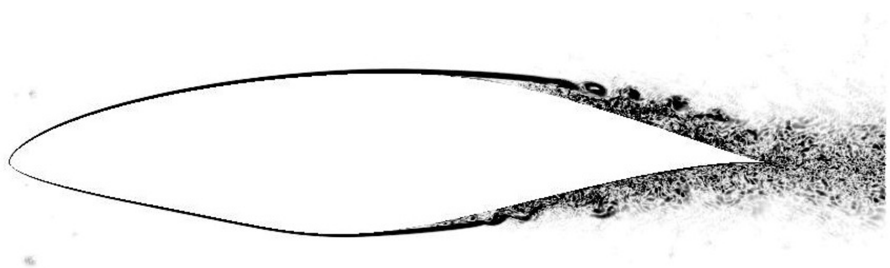

Figure 2. Instantaneous vorticity contours from large eddy simulations at $Re = 3 \times 10^6$, $M = 0.1$ and $\alpha = 0$.

bubble on the upper surface has almost disappeared. As the angle of attack is increased further, transition moves rapidly forward and turbulent, trailing-edge separation occurs on the upper surface. The separation point moves forward with increasing angle of attack until it reaches about 70% chord.

Initial analysis of the time-dependent velocity distributions within and downstream of the separation bubbles reveals the presence of a low-frequency breathing mode corresponding to shear layer instability (see Fig. 2). The bubble unsteadiness rather than a dramatic and sudden burst appear to be responsible for the non-conventional behavior of the aerodynamic forces.

CONCLUSIONS

High-fidelity simulations of the flow over the NREL s287 airfoil are carried out to study the strongly non-linear behavior of the aerodynamic forces at low incidence. The computations reproduce well the measured surface pressure in the angle of attack range $\alpha \in [0 : 8]$ degrees, and, in turn, capture the boundary of the laminar bucket in the lift/drag curve. On-going analysis of the unsteady behavior of the laminar separation bubbles appears to shed light on the mechanism for the rapid changes in lift.

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