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Towards Scale-Resolved Simulation of Airfoil Stall at High Reynolds Numbers Using the Lattice Boltzmann Method

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Identifying the stall behaviour of airfoils is crucial for many engineering applications, including the design of aircraft lifting surfaces, wind and hydrokinetic turbines, helicopter rotors and turbomachinery blades. To do so numerically, however, remains a challenging task. Whilst Reynolds-Averaged Navier-Stokes (RANS) methods may provide reasonably accurate gross flow characteristics [5], turbulence models exhibit deficiencies when applied to massively separated flows [6], and they are of limited use for exploring viscous flow mechanisms in detail [8]. Scale-resolved methods enable a higher fidelity analysis than RANS, and thus a deeper understanding of the underlying flow mechanisms. Good matches with experimental data for the dynamic stall of a NACA-0012 wing at Reynolds numbers to the order of 10^5 have recently been achieved by Kim et al. [3], Ouro et al. [7], and Visbal et al. [8], using Navier-Stokes based methods.

The Lattice Boltzmann Method (LBM) is an emerging alternative to Navier-Stokes based methods, with promising accuracy and scalability. Recent advancements [1] have greatly improved stability in the higher Reynolds regime ($O(10^5)$). To the authors' knowledge, no analysis of stall at these conditions using LBM has yet been presented. The aim of this study is to apply an advanced LBM to analyse the static stall of a blade with a sharp leading edge. This geometry is considered an important stepping stone to axial compressor blades, the detailed analysis of which is the long-term goal of this work. An in-house LBM code based on the open-source code OpenLB [4], and extended to include localised grid refinement [9], is used. Firstly, force coefficients and chordwise pressure coefficient distributions obtained from the LBM simulations are compared against reference experimental and numerical data. Next, we proceed to investigate the detailed flow mechanisms preceding stall, by both qualitative and quantitative means. The ability to do so thoroughly is the important advantage of scale-resolved methods compared to methods of lower fidelity such as RANS.

A preliminary result of static stall analysis is presented in Fig. 1, in which contours of unsteady velocity magnitude and spanwise vorticity at the mid-span of the blade are shown. As expected, the boundary layer remains attached at zero angle of attack, with a clear von Karman vortex sheet emanating from the trailing edge. At 8^o angle of attack we observe a laminar separation directly at the leading edge, followed by a small separation bubble and a turbulent reattachment to the upper surface. This agrees with the expected development of a 'thin-airfoil stall', as described in literature [2, 6]. At 16^o the region of separated flow covers the entire chord, indicating a full stall. The remaining simulations at intermediate angles of attack that are underway will enable us to explore in more detail the progression of the stall, such as the expected rearward expansion of the separation bubble, followed by total separation of the upper surface flow.

This study demonstrates the suitability of the Lattice Boltzmann Method for efficient scale-resolved modelling of aerofoil stall at Reynolds numbers to the order of 10^5, and serves as a significant intermediate step to static stall investigation of axial compressor blades. Future work will also involve investigation of the dynamic stall of these blades, as the LBM includes the capability for large-scale unsteady geometric deformations.

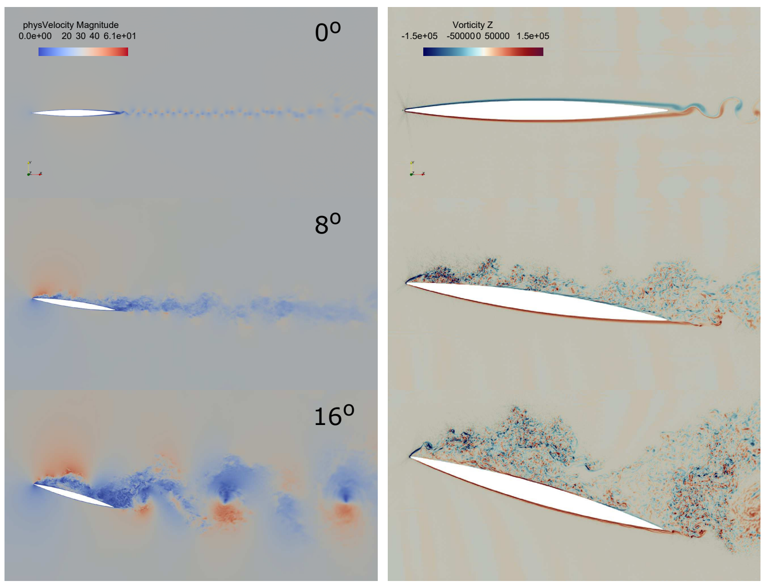

Figure 1: Velocity magnitude (left) and spanwise vorticity (right) contours at blade mid-span.

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