Prediction of airfoil aerodynamic coefficients at near-stall angles in critical Reynolds number flow using CFD

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SUMMARY

Flow behaviour around an airfoil is most complex at high angles of attack and critical Reynolds number flow. Challengingly, industrial wind turbine blades are designed to operate at their maximum efficiency at high, near-stall angles of attack and often in flows with near-critical Reynolds numbers of 10^5 to 10^6. In this study, the aerodynamic force coefficients of the widely-studied NACA 0012 airfoil are evaluated under these complex conditions. Existing wind tunnel studies of this airfoil under these conditions are collected and compared. The results from many CFD simulations of various mesh fidelities, dimensionalities, turbulence models, and closure models are then compared to these existing studies, with the aim of identifying preferred modelling techniques. It is found that an effective, efficient model with decent matching to experimental results was generated using a combination of 3D simulation, URANS momentum equations, and the k-ω turbulence closure model.

Keywords: *airfoil, computational fluid dynamics, wind tunnel, wind turbine, stall, critical Reynolds number*

1. INTRODUCTION

Flow behaviour around an airfoil is most complex at high angles of attack associated with stalling – flow separation which causes a reduction in lift as the angle of attack increases – and in critical Reynolds number flow – the transition point between laminar and turbulent flow behaviours for a given cross-sectional shape. This presents a challenge for wind energy researchers, as industrial wind turbine blades are designed to operate at their maximum efficiency at high, near-stall angles of attack and often in flows with a near-critical Reynolds number of 10^5 to 10^6 (defined using the airfoil chord length as the reference length). In this study, the aerodynamic forces on the widely-studied NACA 0012 airfoil, in the form of the drag and lift coefficients of the cross-section, are evaluated under these conditions using CFD simulations and compared to existing wind tunnel research to identify preferred modelling techniques. Section 2 of this paper details the existing data; Section 3 details the CFD simulation setup and optimization; Section 4 compares the results and recommends the most effective modelling technique for these conditions.

2. EXISTING DATA

Existing measurements of the drag and lift coefficient curves of the NACA 0012 airfoil up to large angles of attack performed in near-critical Reynolds number flow in the range of 10^5 to 10^6 were collected. These studies include Jacobs and Sherman (1939), Critzos et al. (1955), Sheldahl and Klimas (1981), Johari and Durgin (1998), and Benyahia et al. (2003). Table 1 summarizes the relevant wind tunnel studies which were collected. The trends from this data were used to synthesize approximate average lift coefficient splines for the airfoil at the different Re values, which are shown in Figure 1. As can be seen, the Reynolds number of the flow strongly controls the onset of stall and therefore the maximum achievable lift coefficient for the airfoil.

3. CFD METHODOLOGY

The feasibility of CFD to model aerodynamic forces on the NACA 0012 airfoil in critical Re flow including at stalling angles of attack was investigated via a robust parametric set of 48 3D CFD simulations.

As it was the most robust available data set, geometric conditions from Sheldahl and Klimas (1981) were replicated in this study; therefore the domain was designed to test an airfoil with a chord length of 0.15 m and a 0.91 m across-width span. Testing was performed at a constant wind speed of 49.3 m/s, achieving a Re flow of $5*10^5$, the middle of the range investigated in this study. A typical semi-circular/rectangular domain was constructed for this study, the general construction of which is shown in Figure 2. A cross-shaped refinement region around airfoil was included as well as a further refinement at the airfoil. Following a mesh validation study, a base mesh size of 0.025 m was adopted, reduced to 0.005 m in the refinement region and 0.002 m at the airfoil boundary, with 30 prism layers ranging from $6*10^{-6}$ to 0.007 m thick. In total, this resulted in a 7.2M cell mesh for these 3D studies. A preliminary 2D study was also performed to evaluate turbulence closure models for RANS simulations, where the k-ω turbulence closure model was found to be the most effective.

Ultimately, 48 3D CFD simulations were performed using the finalized domain: 16 different angles of attack from 0° to 26° each using a RANS, URANS, and a preliminary LES turbulence model. An example flow visualization is presented from these simulations in Figure 3.

4. RESULTS

Comparisons of the measured drag and lift coefficients for the NACA 0012 airfoil at $Re = 10^5$ for angles of attack up to 26° are presented in Figure 4. These values are compared to the synthesized values from the existing wind tunnel tests presented in Figure 1. It is found that while there is room for further mesh refinement, the URANS simulation generally captures the wind tunnel trends the best, predicting smooth coefficient curves which predict the stall and post-stall angles of attack with high accuracy. The preliminary LES simulation is seen to require further development; the meshing requirements, particularly at the airfoil boundary, are more stringent for this more comprehensive modelling technique.

It is worth noting that due to the complexity of the flow in these conditions, there is mixed agreement between even the experimental data collected for this study. While the general increasing lift → stall → recovery trend is captured by most, at equivalent Reynolds numbers the observed onset and severity of stall is inconsistent, likely a result of different turbulence levels and model roughnesses. Therefore, URANS CFD simulations with the k-ω turbulence closure model offer a reasonable estimation of the near-stall Reynolds number behaviour and can be reasonably adopted for more complex airfoil simulations including wind turbine blades.

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Table 1: Summary of wind tunnel studies of the NACA 0012 airfoil in Re flows of 10^5 to 10^6

Source	Re ($\times 10^5$)	Wind speeds (m/s)	Angles of attack (°)	Chord length (m)	Span length (m)
Jacobs and Sherman (1939)	3.3, 6.6	38.5, 76.9	-3 to 30	0.13	0.76
Critzos et al. (1955)	5	49.3	0 to 180	0.15	0.91
Sheldahl and Klimas (1981)	1.6, 3.6, 7.0, 10.0	34.0, 48.6, 68.0	0 to 180	0.15	0.91
Johari and Durgin (1998)	1	15	-4 to 10	0.11	0.46
Benyahia et al. (2003)	1	5	0 to 18	0.30	0.50

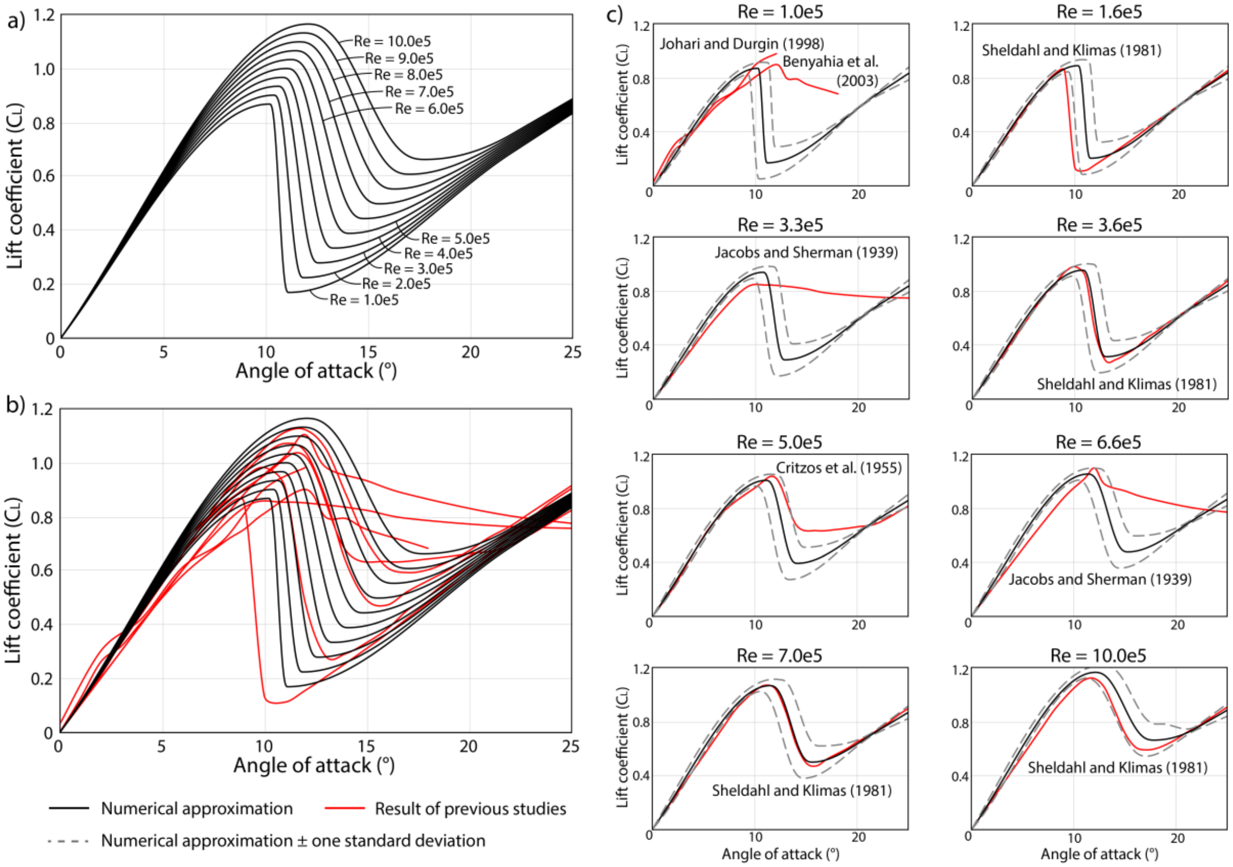

Figure 1: Collected and averaged NACA 0012 lift coefficient curves at Re flows of 10^5 to 10^6

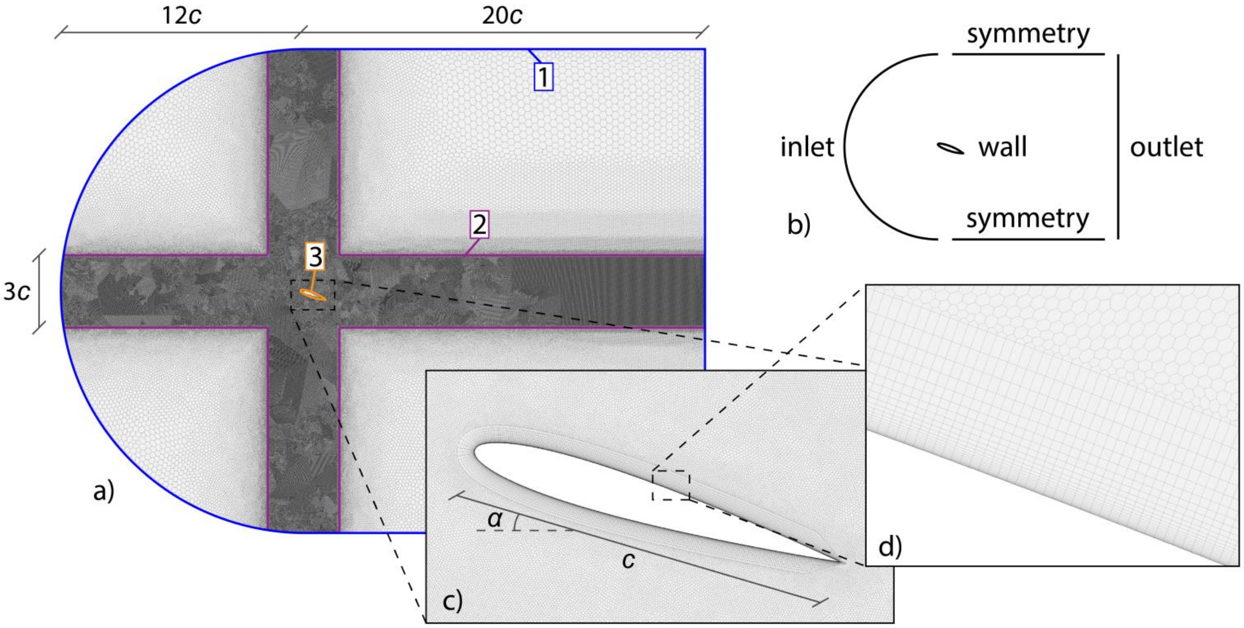

Figure 2: General testing domain and mesh as a function of the chord length *c* (0.15 m in this study)

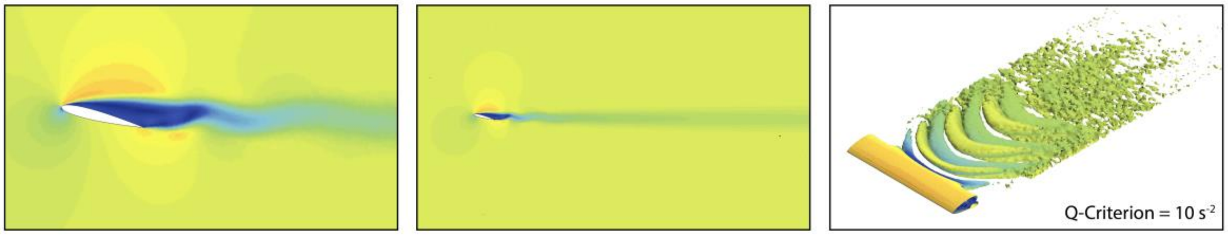

Figure 3: Post-stall flow visualization of the URANS simulation of the NACA 0012 airfoil at 14° AoA, Re=5*10^5

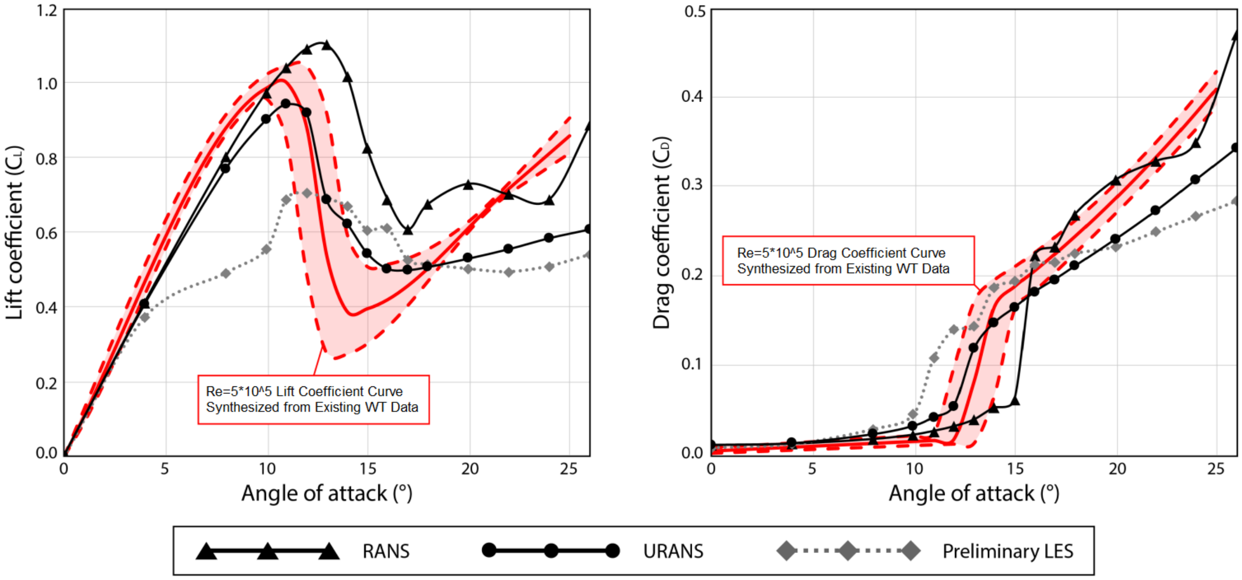

Figure 4: Comparison of drag and lift coefficient curves for the NACA 0012 airfoil at Re = 10^5