High Order Direct Numerical Simulation of a 30P30N Three-Element High Lift Airfoil

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Abstract

The purpose of a multi-element airfoil is to significantly increase lift while controlling the stall limit. Though the airflow around a multi-element airfoil at high Reynolds number (O (10^6)) is well understood from experimental and Reynolds-Averaged Navier-Stokes (RANS) and hybrid turbulence model numerical investigations, this is not the case for low Reynolds number flows (O (10^3)). In this paper, we numerically investigate this airflow over a three-element high lift 30P30N airfoil to study the complex physics in the slat cove region. The targeted Reynolds numbers based on the stowed chord length are 5000 and 8320. The two-dimensional Direct Numerical Simulation (DNS) is carried out using an open source solver NEK5000 [1] that is based on a high order spectral element method for the incompressible Navier-Stokes equations. For validation of results, comparison with experimental particle image velocimetry results of Wang et al [2],[3] will be performed.

Introduction

The flow over the 30P30N multi-element airfoil has been studied both experimentally and numerically at high Reynolds numbers (O ($10^6 - 10^7$)) quantifying good aerodynamic performance [4]. However, for small size aerial vehicles, investigation of high-lift devices flow at low Reynolds numbers is still to be explored. Wang et al. [2] have studied this complex low Reynolds number flow. They have observed Görtler vortices for this configuration at angles of attack of $\alpha = 2°$-$12°$, which was quite different from the high-Reynolds number case. They also found that the Görtler vortices travel in the spanwise direction and secondary counter-rotating vortices are induced beneath the main Görtler vortices. Later, Wang et al. [3] found two types of slat wake interactions with the shear layer above the main airfoil that have significantly different effects on the main airfoil boundary layer. They also mentioned a critical interval of Reynolds number ($1.27 \times 10^4 < Re_c < 1.38 \times 10^4$). Below 1.27×10^4, Görtler vortices dominate the flow in the slat wake region. Above 1.38×10^4, both spanwise and streamwise vortices exist in the slat wake. The current work focuses on the investigation of the flow physics in the slat cove region for Re = 5000 and 8320 with $\alpha = 0°$. The results presented here are preliminary, showing instantaneous contours for velocity and vorticity; the oral presentation will include time-averaged contours that will be compared with the experimental results of Wang et al [2], [3].

Methodology

The two-dimensional DNS was performed using the open source code NEK5000 [1] for the incompressible Navier-Stokes equation which is based on the higher order Spectral Element

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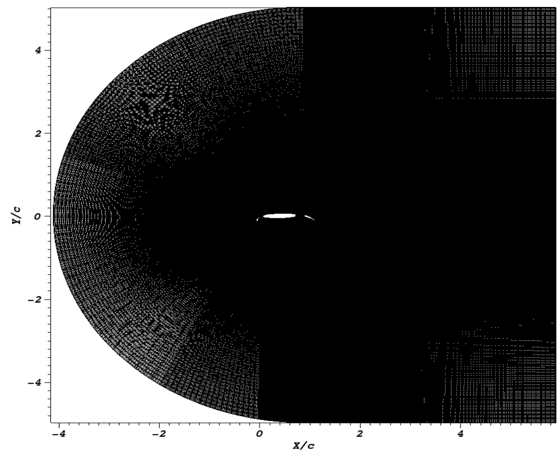
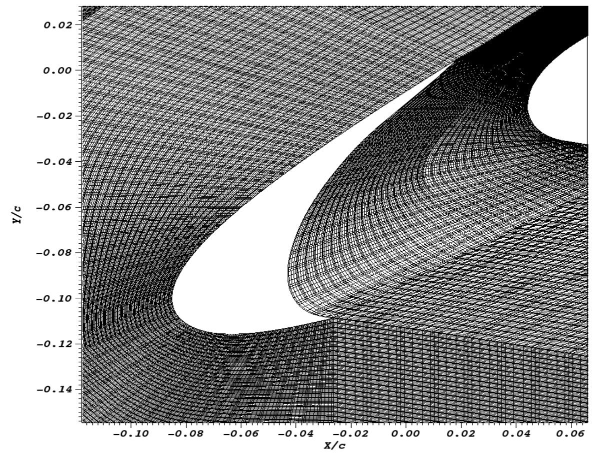
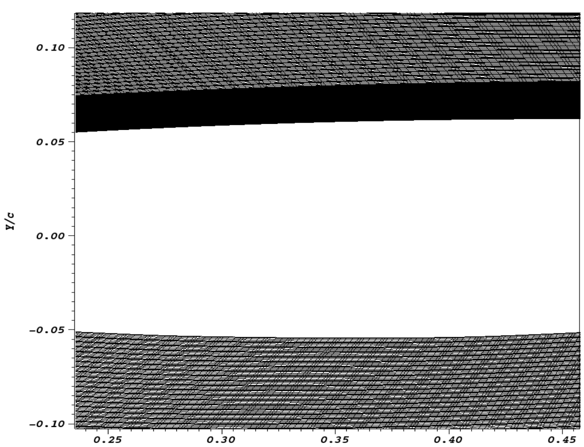
Method (SEM) [5] to study the flow over a 30P30N three-element high lift airfoil. The geometry and mesh were generated using the open source software GMSH [6]. A multi-block approach was used to generate the mesh inside a C-type domain that has 49 blocks, shown in the figure 1. After generating the mesh in GMSH, the gmsh2nek [7] converter was used to export the mesh in NEK5000-suitable format. Also, checkMesh, the built-in mesh quality checker in OpenFoam [8], was used to check the mesh quality, wherein different parameters were considered such as orthogonality, skewness, and aspect ratio.



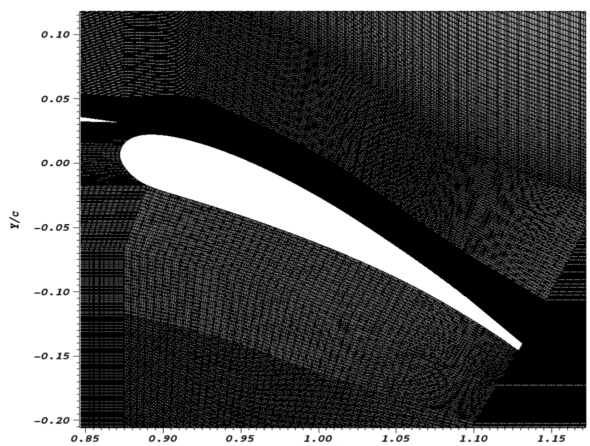
(a) Full Domain



(b) Slat



(c) Main



(d) Flap

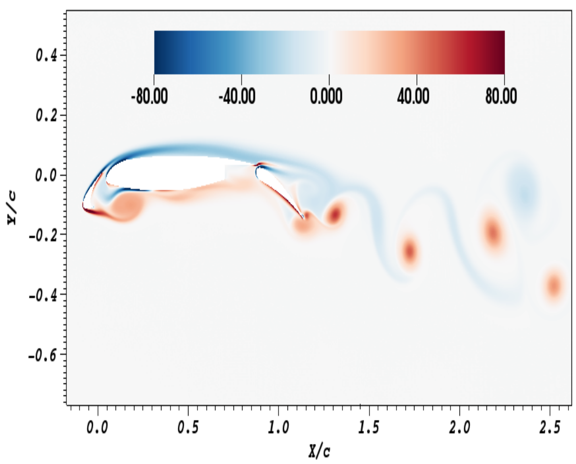
Figure 1: Multi-block spectral element mesh of a 30P30N three-element high lift airfoil

The solution was approximated by tensor products of Legendre polynomial Lagrangian interpolants on each of the 179,159 spectral elements. The degree of Legendre polynomial was set to N = 5 for both velocity and pressure resulting in a total of 4,478,975 points. The farfield boundary was set at five times the stowed chord length of the airfoil in all directions (including the outflow boundary as measured from the trailing edge of the main element).

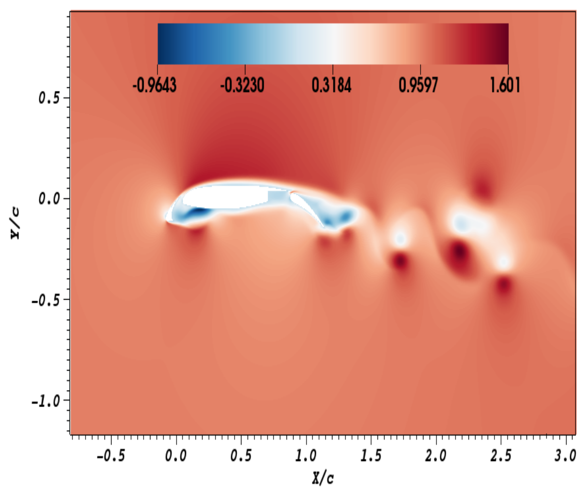
The boundary conditions imposed on the domain are free stream velocity on the top, bottom and ahead of the airfoil; outlet (atmospheric pressure outlet) behind the airfoil, and no-slip wall on the airfoil surfaces.

Preliminary Results

A successful multi-block grid has been constructed for the spectral element simulation of a 30P30N multi-element high lift airfoil for Reynolds number of 5000 and 8320 at zero-degree angle of attack. Figure 2 shows the vorticity and X-velocity contours for Re = 5000, $\alpha = 0°$ at time t = 3.15. Figures 3 and 4 represent the closeup view of instantaneous vorticity contours near slat for Re = 5000 and 8320 respectively, at $\alpha = 0°$. A distinct roll up is observed near the slat trailing edge for both cases that is in a good agreement with the experimental data of Wang et al [2]. Interaction of the shear layer coming from the upper surface of the slat with the boundary layer on the upper surface of main element is shown in Figures 3b and 4b. Moreover, these figures show the existence of two separated shear layers on the upper surface of main element. As expected, the higher Reynolds number flows produce sharper shear layers but shed vortices can end up larger for higher Reynolds number cases (such as the large vortex under the main airfoil seen in Figure 4b). The quantities associated with length are normalized by the stowed chord length, c, velocities are normalized by the free stream velocity U_∞, and time is normalized by $\rho c^2/Re\mu$.

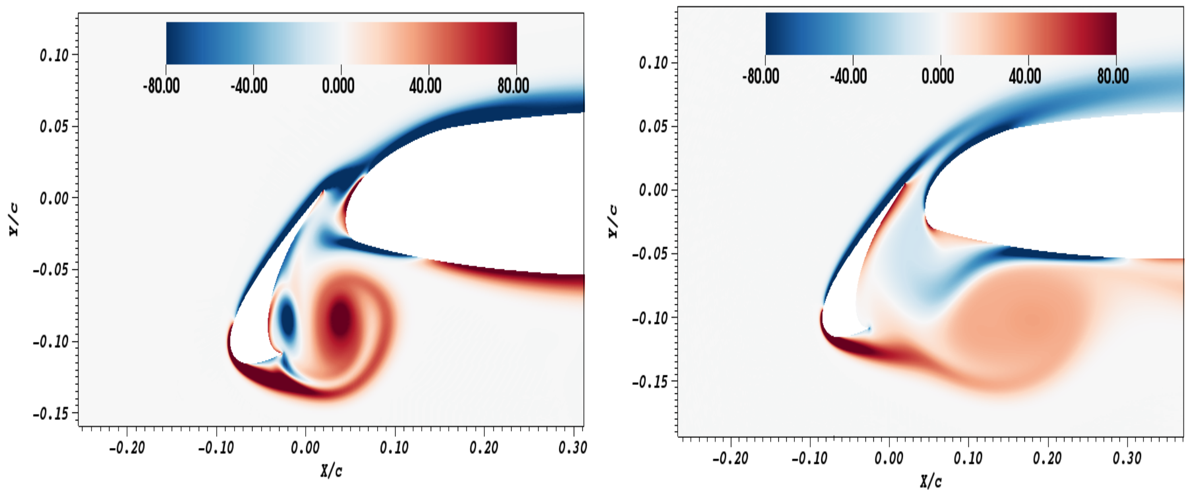


(a) Vorticity at time t = 3.15



(b) X-velocity at time t = 3.15

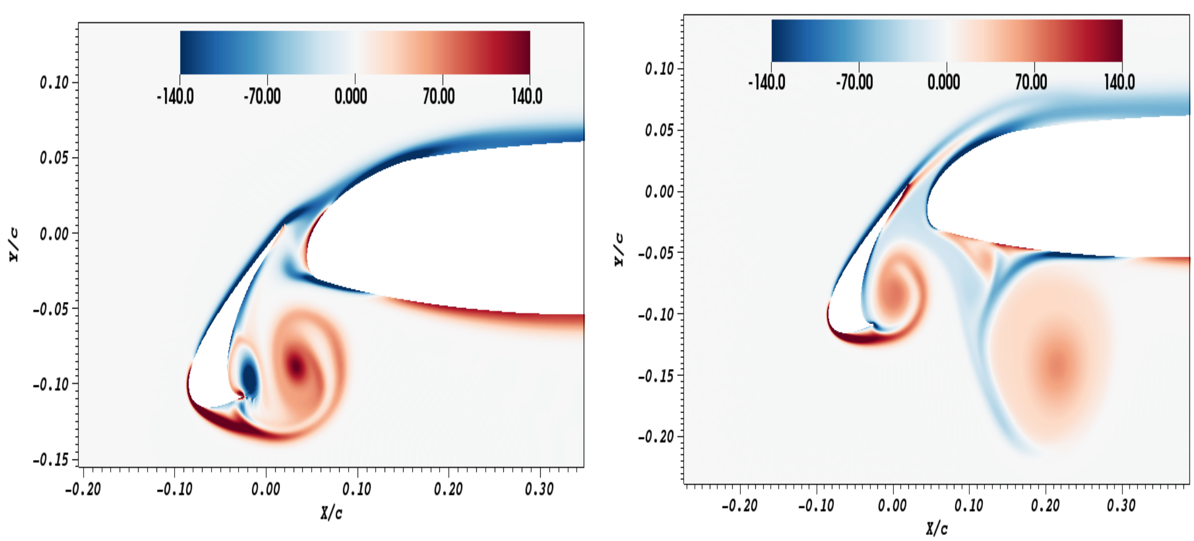
Figure 2: Instantaneous vorticity and X-velocity contours for Re = 5000 at $\alpha = 0°$



(a) Time t = 0.29

(b) Time t = 3.15

Figure 3: Instantaneous vorticity contours for Re = 5000 at $\alpha = 0°$



(a) Time t = 0.28

(b) Time t = 1.22

Figure 4: Instantaneous vorticity contours for Re = 8320 at $\alpha = 0°$

Conclusion

A suitable grid has been developed for the high order spectral element direct numerical simulation of Re = 5000 and 8320 flows over a 30P30N three-element high lift airfoil. Instantaneous vorticity and velocity contours have been presented that resemble the experimental results of Wang et al [2], [3] at the same Reynolds numbers. Work is progressing towards the extraction of time-averaged plots of vorticity and velocity that will be compared with

Wang et al's [2],[3] experimental results in the conference presentation. Interactions of the slat-generated shear layers and shed vortices with the aerodynamic performance of the main airfoil will be investigated. These calculations represent a significant advance for high order methods in capturing complex flows generated by complex aerodynamic geometries.

References

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