DNS of NACA65 compressor blades at $Re = 135000$ with spectral/hp element methods

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Motivation

Current RANS-based methods have inherent limitations in modeling transitional and turbulent flows in turbomachinery applications. The recent advances in high-performance computing capabilities support the development of high-fidelity methods to offer better resolved simulations that can shed light on the flow physics and, eventually, lead to better design techniques.

Computational methodology

The software framework Nektar++ is employed to solve the Navier-Stokes equations [1].

- Unstructured high-order 2D mesh generated with NekMesh.
- Spectral element discretisation in the x-y plane, and Fourier expansion in the spanwise z- direction.
- Spectral Vanishing Viscosity [2] relied upon to stabilise the simulation.

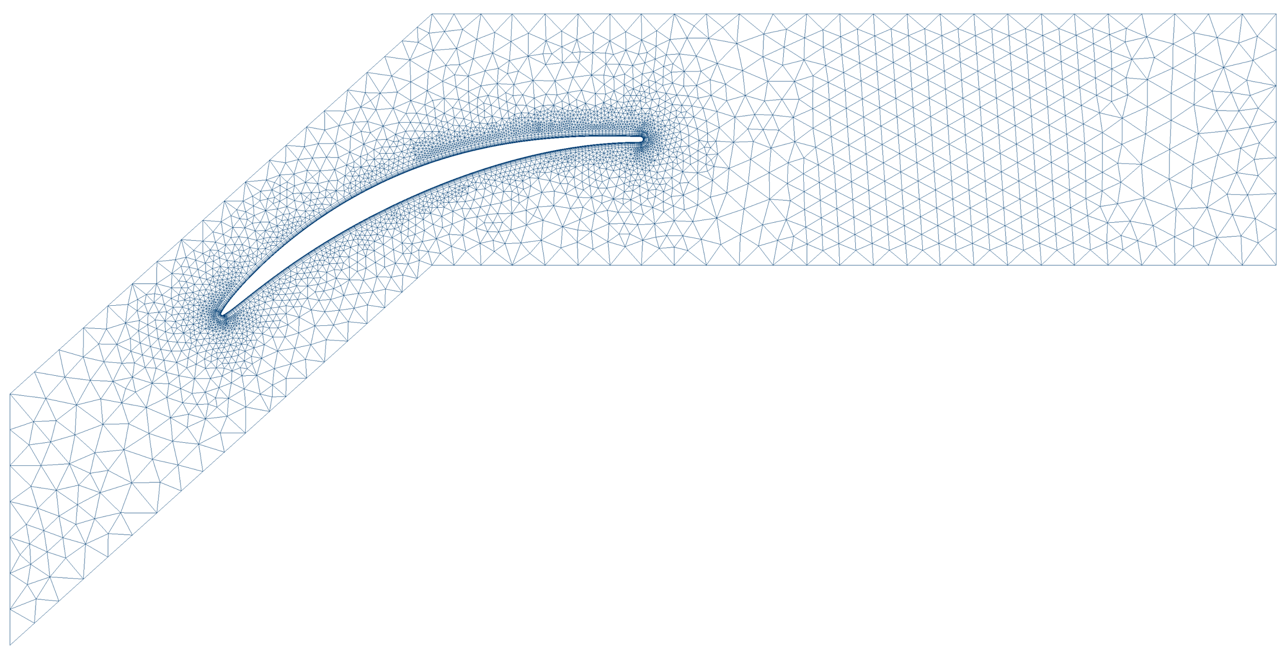

Figure 1: High-order mesh of the NACA65 profile, comprised of 2719 quadrilateral elements in the O-mesh and 6145 triangular elements in the unstructured mesh.

2D results

- Convergence study by p-refinement shows increasing accuracy in pressure distributions
- Comparison against existing numerical data set [3] shows that separation on the suction surface is well captured by the current setup. The recent introduction of a new kernel for SVV, matching the dispersion and diffusion property of DG schemes, also shows good agreement with previous numerical results.

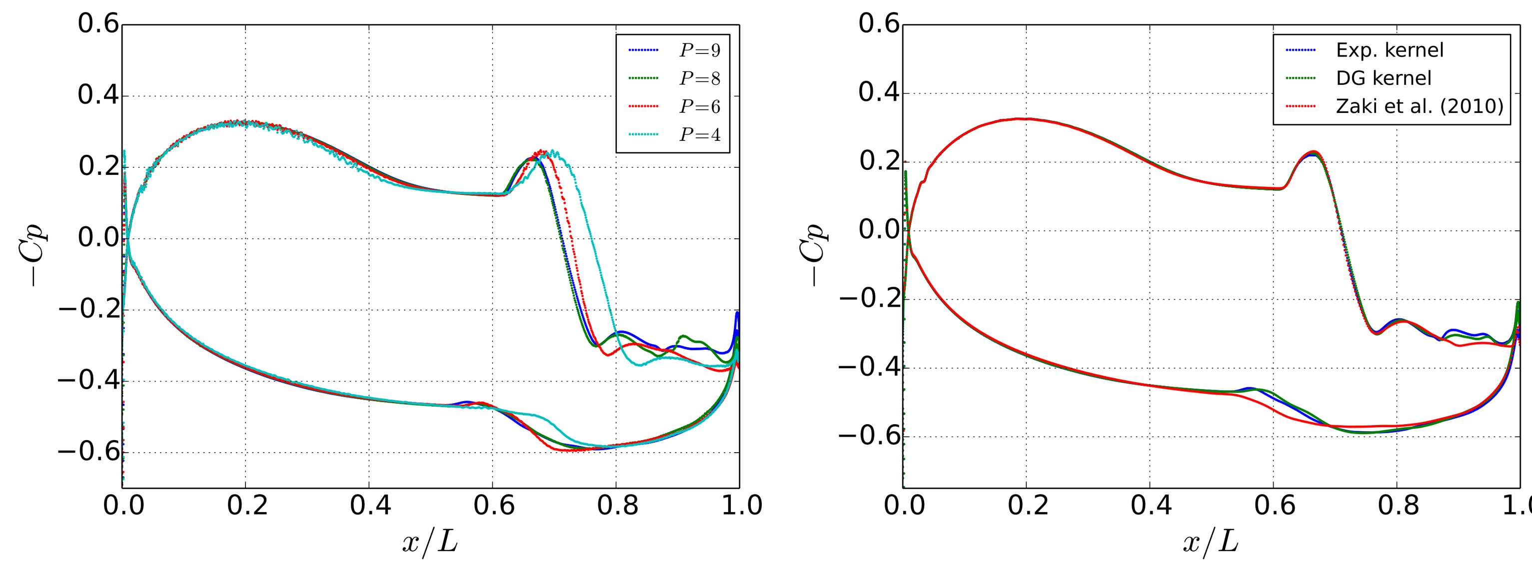

Figure 2: Pressure distributions. Left: P-refinement effect. Right: Comparison between exponential kernel (cutoff $M = 0.75$, diffusion coefficient $\epsilon_{SVV} = 1$), DG kernel and previous results from [3].

2-5D results

Velocity and vorticity fields are shown as computed with 7-th order expansions, a spanwise width of $L_z = 0.2$ and 128 Fourier planes in the z-direction. It can be appreciated that the flow separates and undergoes transition to turbulence on both the pressure and suction side.

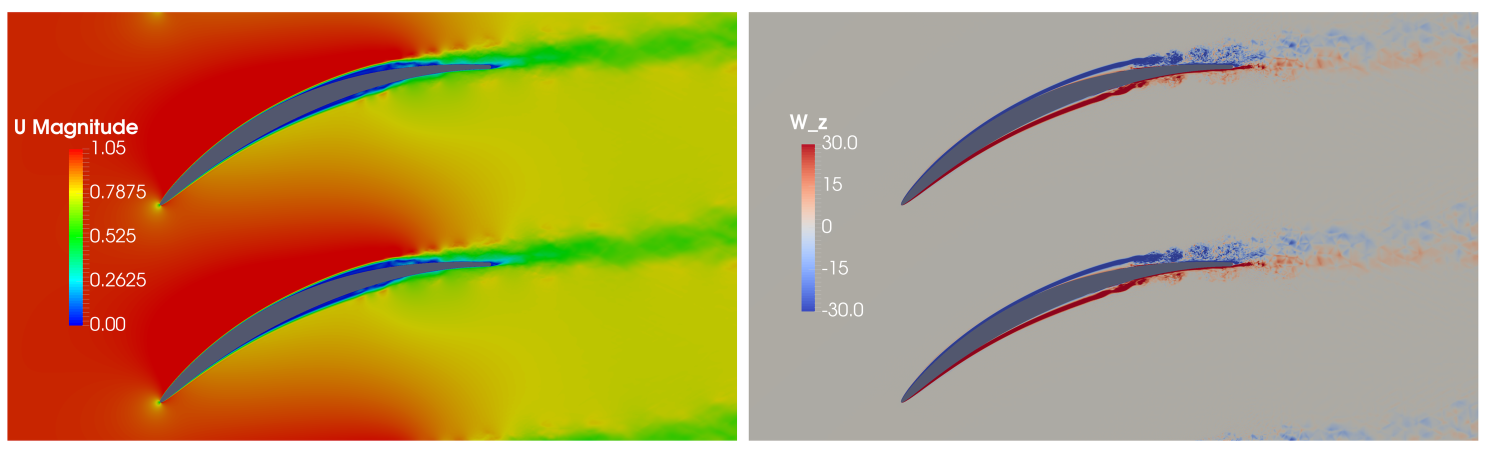

Figure 3: 2D mean mode (plane zero in Fourier space) of the 2.5D simulation. Left: instantaneous velocity magnitude field. Right: instantaneous spanwise vorticity field.

Boundary layers extraction

Boundary layer edge detection is based on a pseudo-velocity defined as [4]:

$$\mathbf{u}^*(\mathbf{s}, n) := \int_0^n (\boldsymbol{\omega} \times \hat{\mathbf{n}}) \mathrm{d}n'$$

The boundary layer edge is computed as being the first wall-normal location simultaneously satisfying the two conditions:

$$\|\bar{\boldsymbol{\omega}}\| \, n < \epsilon_1 \|\bar{\mathbf{u}}^*\| \,, \qquad \left\| \frac{\partial \bar{\boldsymbol{\omega}}}{\partial n} \right\| n^2 < \epsilon_2 \|\bar{\mathbf{u}}^*\|$$

with $\epsilon_1 = 0.01$ and $\epsilon_2 = 0.1$. The overbar denotes temporal and cross-flow averaging. This framework further provides with a way of calculating boundary layer parameters such as displacement thickness, momentum thickness and shape factor.

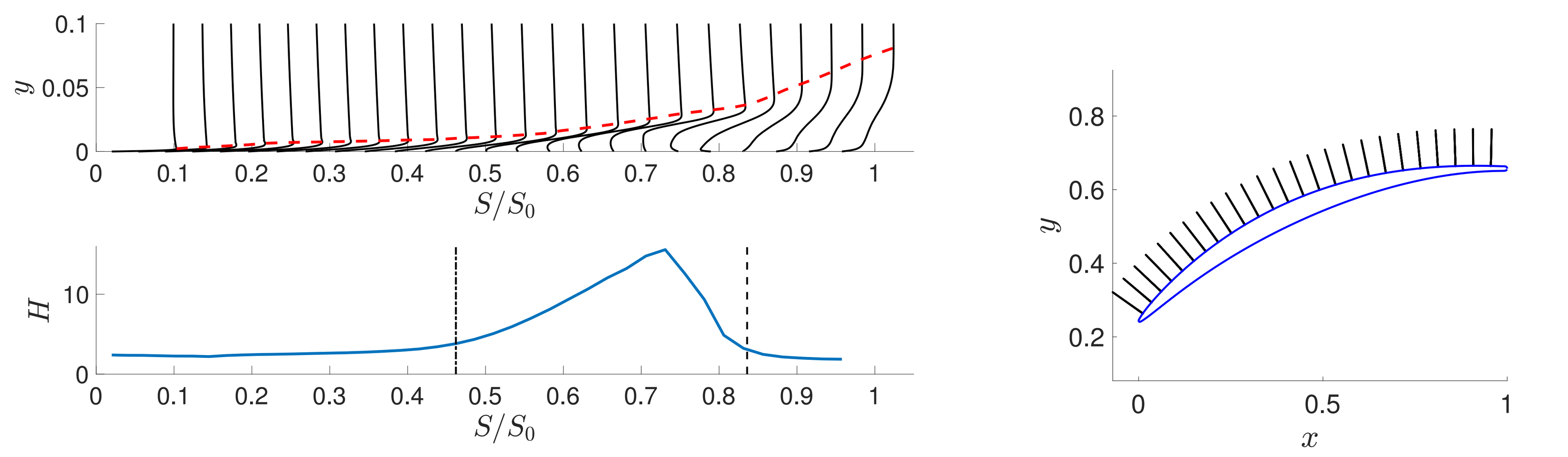

Figure 4: Top-left: boundary layer profiles extracted along the blade. The red dashed line indicates BL thickness. Bottom-left: shape factor profile. Right: corresponding locations of the boundary layer profiles.

Q iso-surfaces

Q iso-surfaces extracted from the suction surface of the blade reveal the presence of full-span Kevin-Helmholtz roll-ups near the trailing edge. As these coherent structures convect downstream, they develop spanwise waviness before breaking down to turbulence.

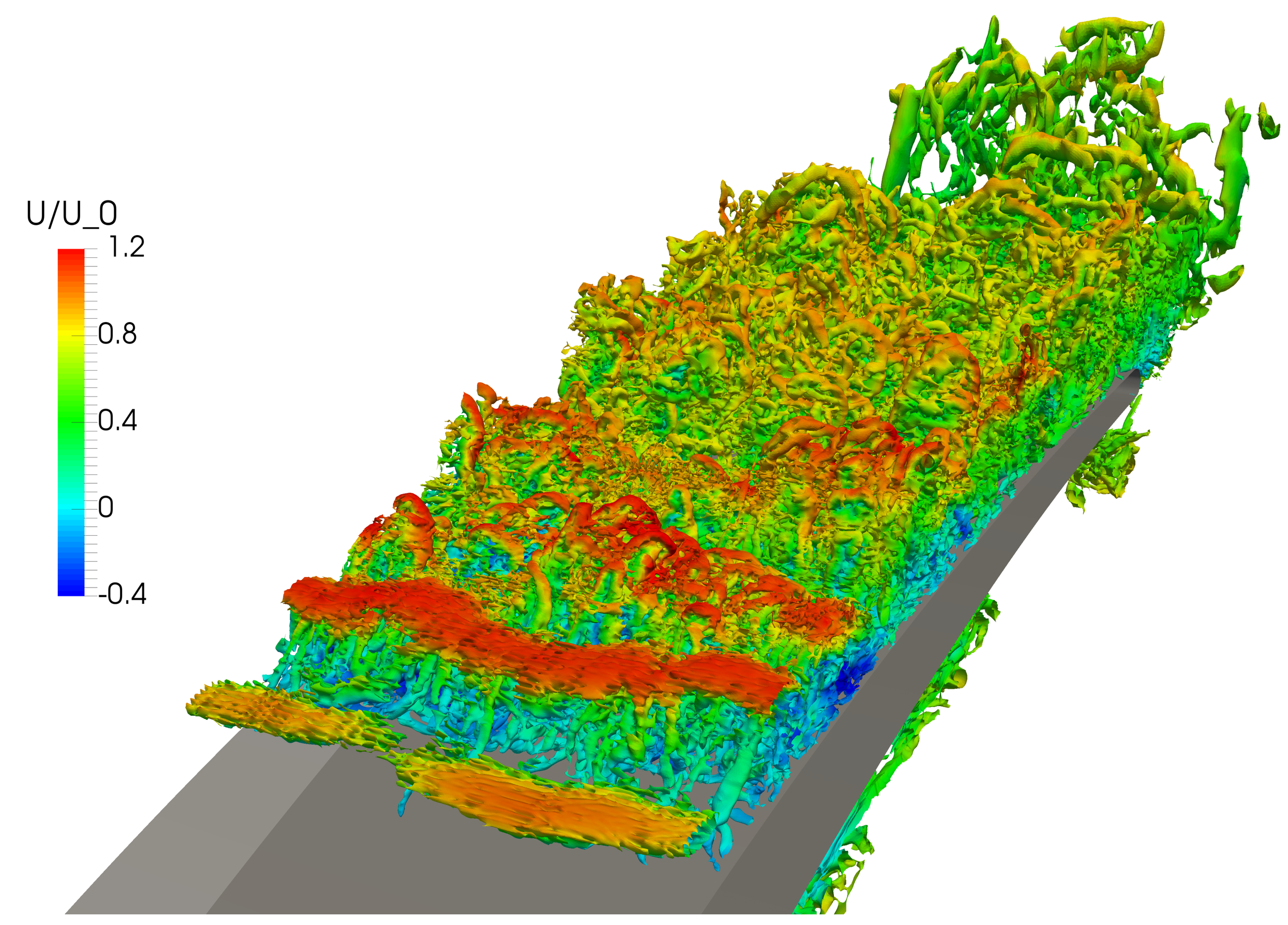

Figure 5: Q iso-surfaces ($Q = 500$) contoured by streamwise velocity.

Summary and future outlook

We have carried out a series of direct numerical simulations of a NACA65 compressor blade, ensuring mesh convergence and assessing the validity of a boundary layer parameters calculation methodology. The high spanwise resolution of the Fourier expansion allows to capture well the three-dimensional features of the flow, visualised through Q iso-surfaces.
The tools here presented provide the grounding for the development of a more systematic and structured refinement study strategy, followed by the introduction of background turbulence and wake passing effects.

References

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