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Optimising airfoils for rotorblades of Martian helicopters with PyFR

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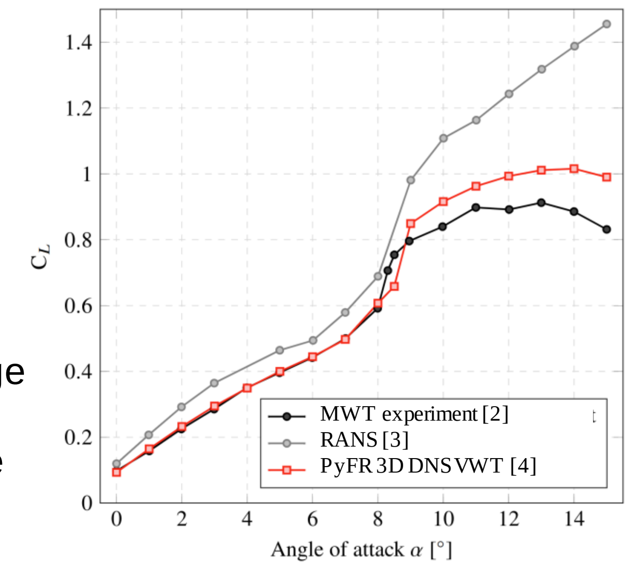
Introduction

Martian atmospheric conditions present various challenges for rotorcraft design.

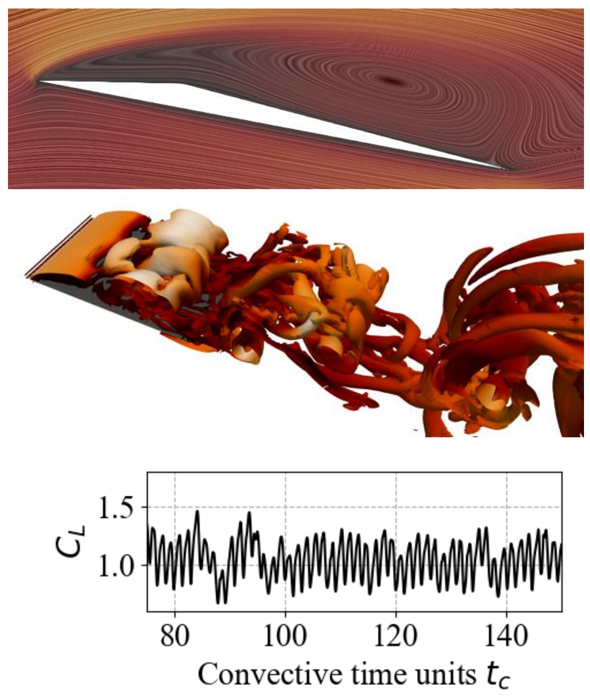
- Martian rotorblades need to be optimised for a **low-Reynolds-number compressible regime**, not typical of conventional airfoils.
- **Sharp leading edged airfoils** have shown to perform better than conventional airfoils but optimal shapes still need to be found.
- Enabled by the capabilities of PyFR [1], a high-order highly scalable CFD solver, this work undertakes **optimisation of unconventional airfoil shapes with 3D Direct Numerical Simulations (DNS)** which can capture the flow physics accurately.
- 3D DNS with PyFR have been compared against experimental data [2] and 2D RANS simulations [3] for a simple sharp leading edge airfoil, a triangular airfoil, at various angles of attack at flow conditions of Re = 3,000 and M = 0.15. **DNS results offer improved accuracy** at moderate to **high angles of attack** when the **flow separates from the leading edge** and the aerodynamic forces on the airfoil are driven by roll-up of vortices on the upper surface that cover the entire wing. [4]

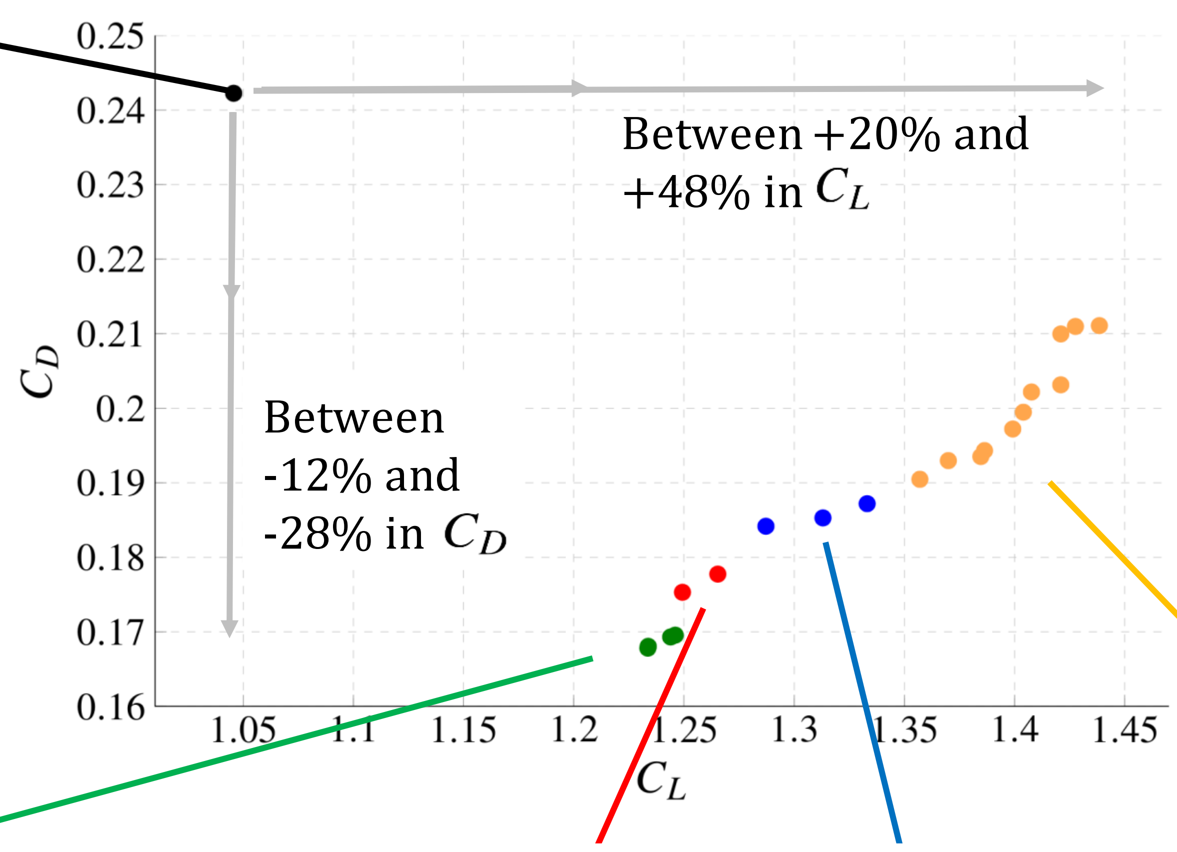


Optimisation of a triangular airfoil

- Genetic Algorithms are used in this work to find the optimal triangular airfoil shapes for a rotorcraft blade under the flow conditions **Re = 3,000 and M = 0.15**, and a fixed angle of attack, **α = 12°**. Specifically, a **NSGA-II multi-objective optimisation of triangular airfoils is performed targeting maximum lift and minimum drag**.

Reference Airfoil

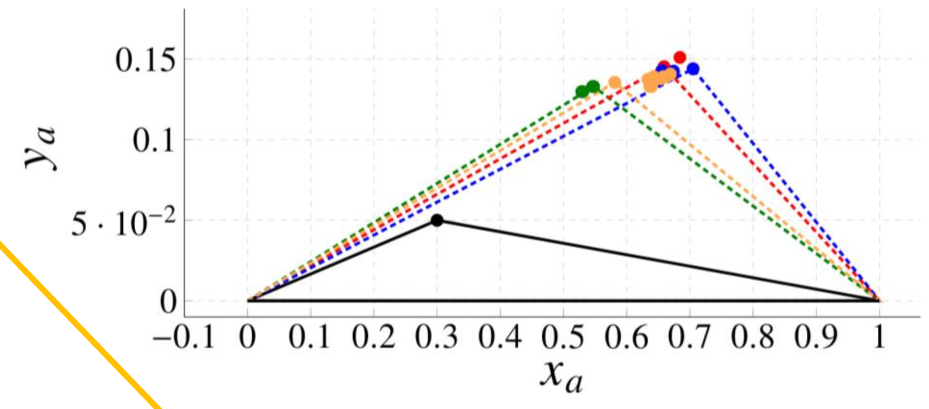


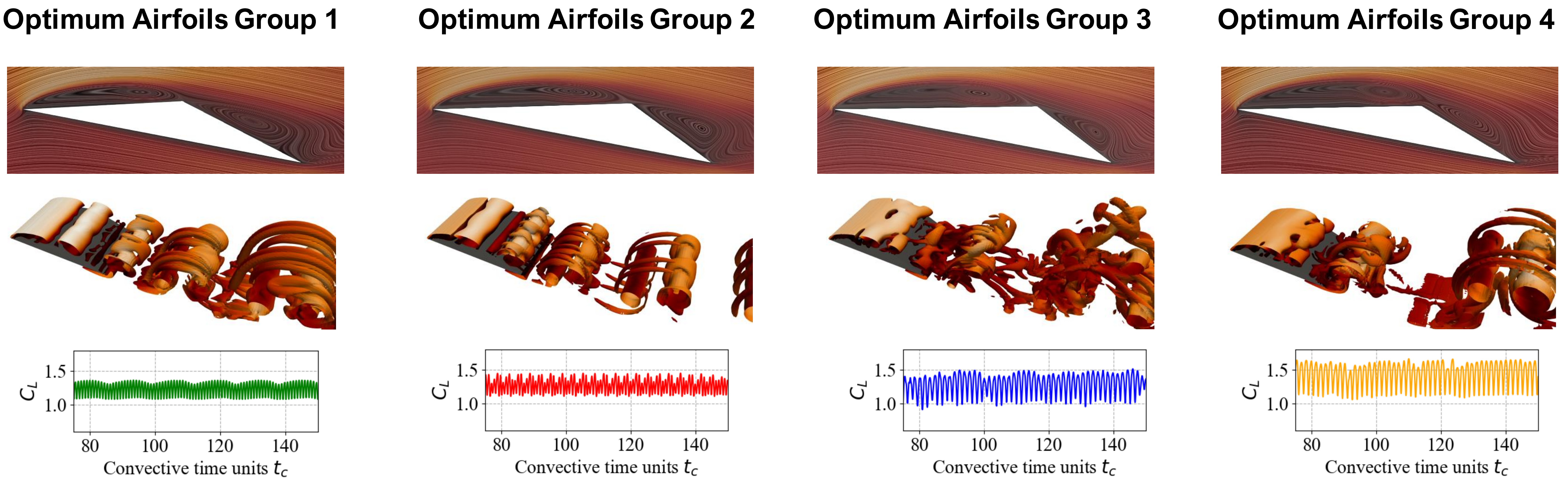


Results

The optimisation produces airfoils such that:

- The **flow separates from the leading edge** exploiting the vortex roll-up as a lifting mechanism.
- **Retain a strong vortex** close to the upstream portion of the suction surface (low pressure area).
- **Avoid excessive inclination of the downstream** portion of the suction surface (high pressure drag).





Deployment and cost

- The optimisation was performed on **Piz Daint**. The optimiser, Pymoo, and the meshing software, Gmsh, were invoked on the login node (Intel Xeon E5-2650 v3 2.30GHz CPU) via Bash scripts, and PyFR was invoked on the compute nodes (Tesla P100-16GB GPUs). Each of the 3D DNS took approximately **23 hours** to run on **36 Tesla P100-16GB GPUs.** 15 3D DNS were run for each generation of the GA optimisation, which ran for a total of 15 generations with a **total cost of ~200,000 GPUhs**.
- A precursor two-dimensional (2D) DNS optimization is run prior to the 3D DNS optimisation. The result of the precursor 2D DNS optimization is then taken as the initial population for the 3D DNS optimization to **accelerate convergence and reduce the overall cost** (2D DNS ~100x cheaper that 3D DNS).

PyFR
EPSRC Engineering and Physical Sciences Research Council
ZONTA INTERNATIONAL
cirrus Powered by epcc
CSCS Centro Svizzero di Calcolo Scientifico Swiss National Supercomputing Centre

References

[1] Witherden, F. D., Farrington, A. M., and Vincent, P. E., "PyFR: An open source framework for solving advection-diffusion type problems on streaming architectures using the flux reconstruction approach," Computer Physics Communications, Vol. 185, No. 11, 2014, pp. 3028–3040.
[2] Munday, P., Taira, K., Suwa, T., Numata, D., and Asai. Non-Linear Lift on a Triangular Airfoil in Low-Reynolds-Number Compressible Flow. Journal of Aircraft, Vol. 52, No. 3, May 2015.
[3] Witold J. F. Koning, Ethan A. Romander, and Wayne Johnson. Optimization of low Reynolds number airfoils for Martian rotor applications using an evolutionary algorithm. AIAA Science and Technology Forum and Exposition (AIAA SciTech), 2020.
[4] L. Caros, O.R.H. Buxton, T. Shigeta, T. Nagata, T. Nonomura, K. Asai, and P.E. Vincent. Direct numerical simulation of flow over a triangular airfoil under Martian conditions. AIAA Journal, March 2022.