Optimization of Non-Conventional Airfoils for Martian Rotorcraft using Direct Numerical Simulations

Lidia Caros*, Oliver Buxton* and Peter Vincent*
Corresponding author: lidia.caros-roca19@imperial.ac.uk

* Imperial College London, London SW7 2AZ, UK.

Abstract: Martian atmospheric conditions present various challenges when designing rotorcraft. Specifically, the thin atmosphere and lower speed of sound compared to Earth requires Martian rotor blades to operate in a low-Reynolds-number (1,000 to 10,000) compressible regime, for which conventional airfoils have not been designed. Airfoils with sharp leading edges and flat surfaces have been shown to perform better than conventional airfoils under these conditions. Previous studies have used evolutionary techniques to optimize non-conventional airfoils. These algorithms usually require many cost function evaluations, and hence, they typically employ Reynolds-Averaged Navier Stokes (RANS) solvers because of their low computational cost. However, RANS solvers have limited predictive capability when the flow becomes unsteady and separated at moderate angles of attack, a particular issue at such low Reynolds number. Enabled by recent advances in solver technology and GPU hardware, the current study overcomes this limitation by undertaking optimization using high-fidelity three-dimensional (3D) Direct Numerical Simulations (DNS), which are able to capture the flow physics via the compressible flow solver in PyFR (www.pyfr.org).

Keywords: Martian Aerodynamics, Optimization, Direct Numerical Simulations, Low-Reynolds-Number, Unsteady Flows.

1 Introduction

In the search for optimal airfoils for Martian atmospheric conditions, several studies have explored optimizing non-conventional airfoils using Genetic Algorithms (GA) [1]. These studies normally use RANS solvers, which limit the optimization to low angles of attack. However, non-conventional airfoils with sharp leading edges achieve high-lift performance at moderate/high angles of attack through early separation of the flow leading to the formation of large and strong vortices which roll up on the suction side of the airfoil, inducing a large area of low pressure [1]. The vortex roll-up can be seen in Figure 1 (a) for a triangular airfoil at $\alpha = 12°$.

Our work overcomes this limitation by using GA based optimizations of non-conventional airfoils under Martian conditions using high-fidelity DNS, able to capture the unsteady flow physics and 3D effects. We will present our optimization results and compare optimum configurations obtained with two-dimensional and three-dimensional DNS cost function evaluations at various angles of attack to assess the need for DNS and 3D flow resolution. The findings will contribute to the design of new rotorblades for next-generation Martian rotorcraft.

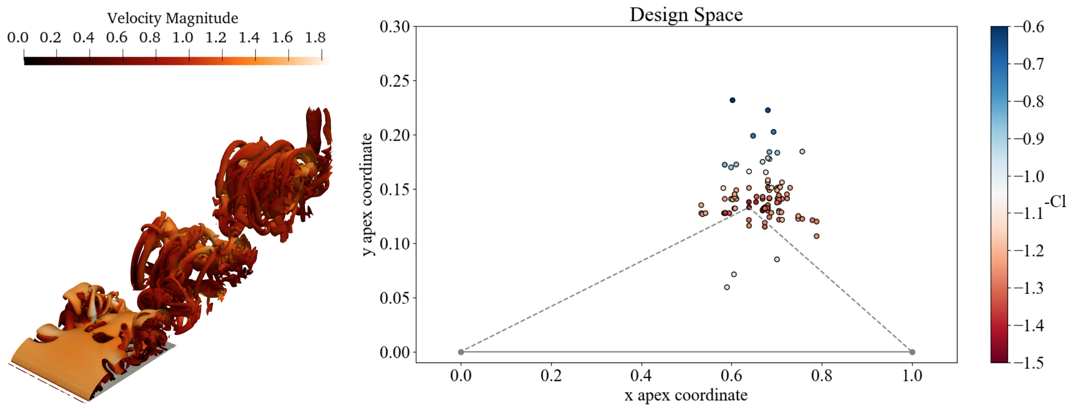
2 Numerical Method

In this work we use pymoo [2] as the optimizer, an open-source Python-based framework for multi-objective optimization. Specifically, we use the Non-dominated Sorting GA (NSGA-II).

We use PyFR [3] to solve the compressible Navier-Stokes equations for the cost function evaluation. PyFR is based on the high-order Flux Reconstruction approach.

3 Results

The optimization is set to maximize lift and minimize drag. Specifically, the multi-objective problem is defined as $minimize\big(f_1(\mathbf{x}), f_2(\mathbf{x})\big)$ with $f_1(\mathbf{x}) = -Cl(\mathbf{x})$ and $f_2(\mathbf{x}) = Cd(\mathbf{x})$, where $\mathbf{x}$ are the design variables. For a triangular airfoil, these are the horizontal x and vertical y coordinates of the apex of the triangle. Figure 1 (b) shows a set of apex locations evaluated by a 3D DNS NSGA-II optimization of a triangular airfoil at $\alpha = 12°$.



(a) (b)

Figure 1: (a) Instantaneous Q-criterion isosurfaces $Q = 1$, coloured by velocity magnitude, from 3D DNS of a particular triangular airfoil at $\alpha = 12°$. (b) Design space evaluated by a triangular airfoil shape optimization. The dots are the evaluated apexes coloured by the -Cl produced by each airfoil. The dashed line shows a representation of the airfoil with maximum Cl.

References

[1] Witold J. F. Koning, Ethan A. Romander, and Wayne Johnson. Optimization of low reynolds number airfoils for martianrotor applications using an evolutionary algorithm. *AIAA SciTech* (2020).

[2] Julian Blank and Kalyan Deb. Pymoo: Multi-objective optimization in python. *IEEE Access*, (2020) PP:1–1.

[3] F. D. Witherden, A. M. Farrington, and P. E. Vincent. PyFR: An open source framework for solving advection-diffusion type problems on streaming architectures using the flux reconstruction approach. *Computer Physics Communications*, (2014) **185(11)**:3028–3040.