Aerodynamic Optimisation of Aerofoils for Martian Rotorcraft

ERCOFTAC, 10th October 2024

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PROF. PETER VINCENT

PROF. OLIVER BUXTON

Outline

- Introduction
- Optimisation setup
- Optimisation results
- Effects of free-stream eddies
- Summary and future work

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Introduction - Motivation

Ingenuity achieved **first powered flight on another planet (Mars)** on 2021

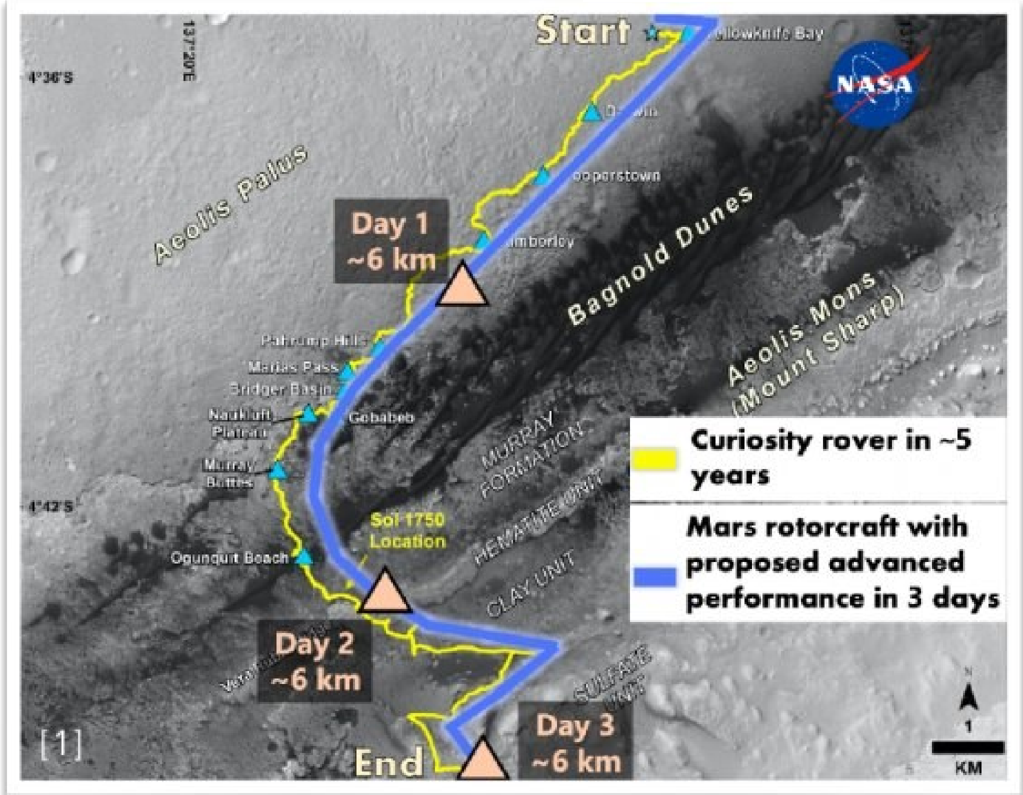
Technology demonstrator – 5 planned flights
Flew from April 2021 to January 2024
72 flights - Covered 17 km

https://mars.nasa.gov/technology/helicopter

Introduction - Motivation

Next-generation Martian helicopter for science and discovery

Increased payload – science equipment
Increased range – exploration beyond rovers



[1]

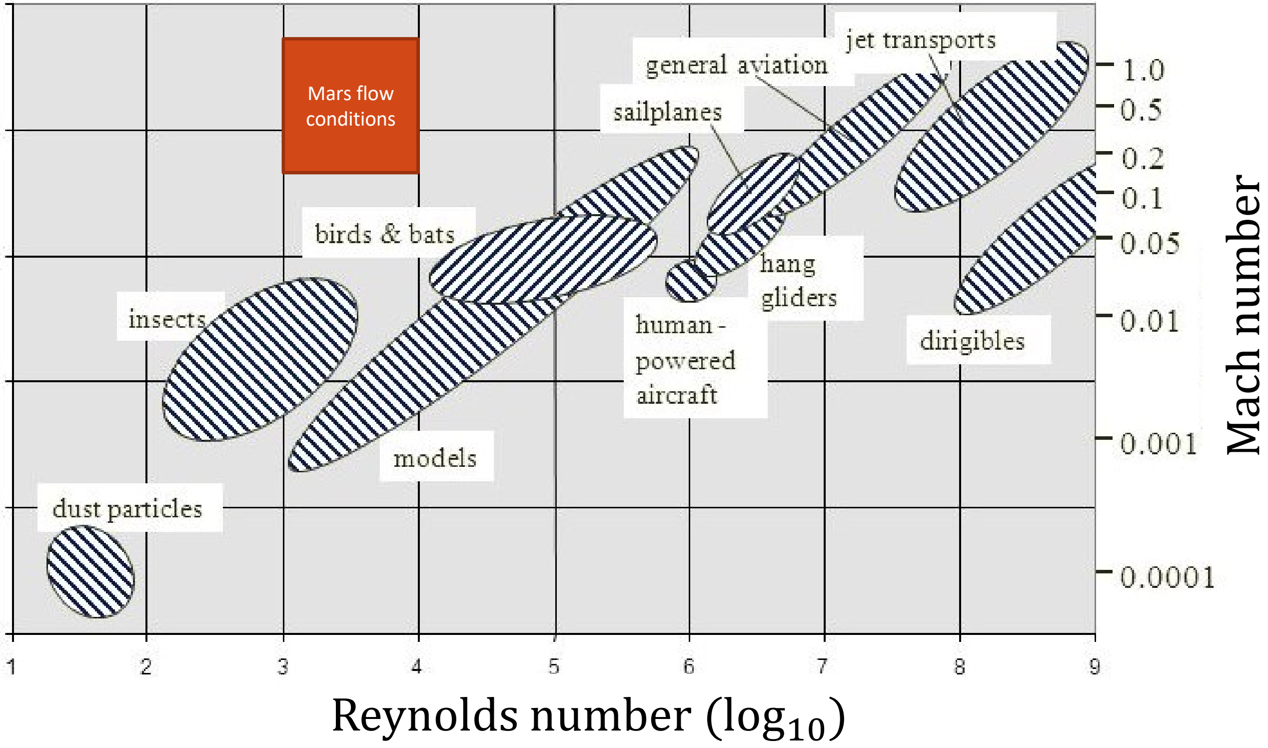
Introduction - Martian atmospheric conditions

Designing airfoils for Martian Rotorcraft is challenging due to the flow conditions on Mars of very low density and low speed of sound:

Low Reynolds Number $(10^3 - 10^4)$

Compressible Mach Number $(0.7 - 0.9)$

- Years of research have optimised airfoils for all flow conditions on Earth
- Martian rotorcraft airfoils is a reasonably unexplored field



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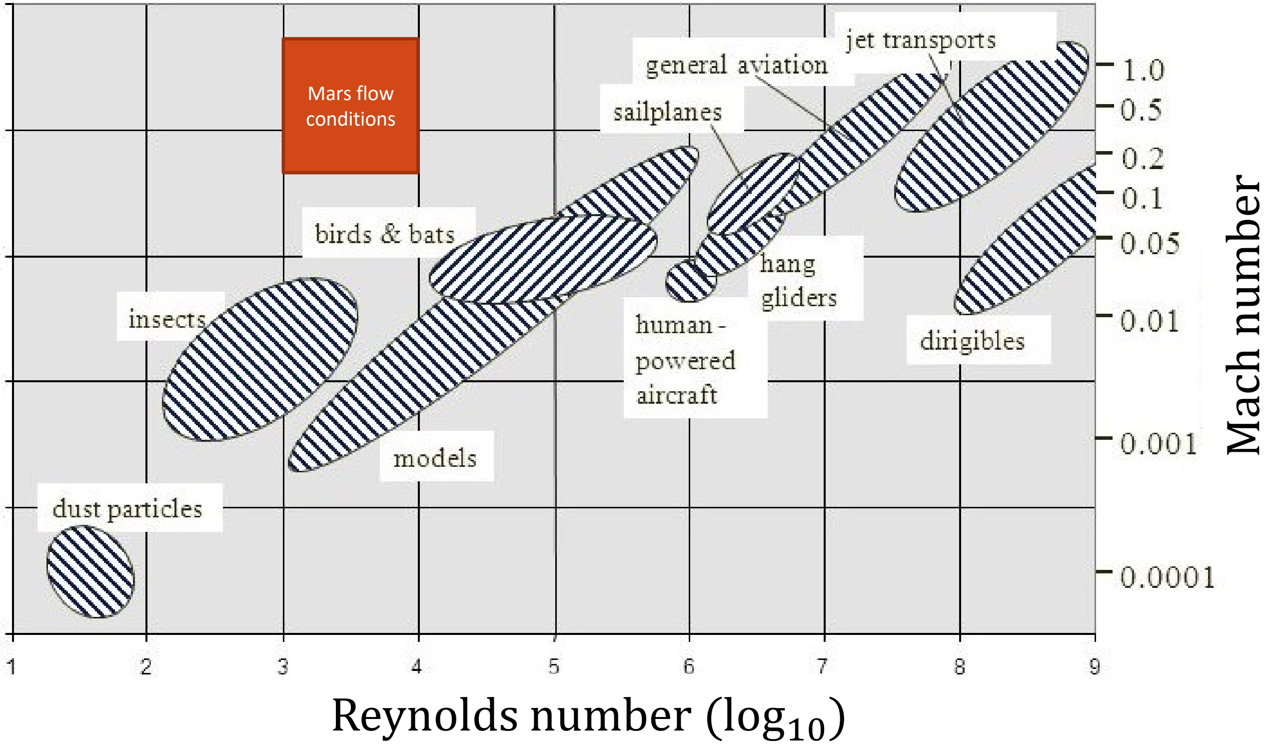
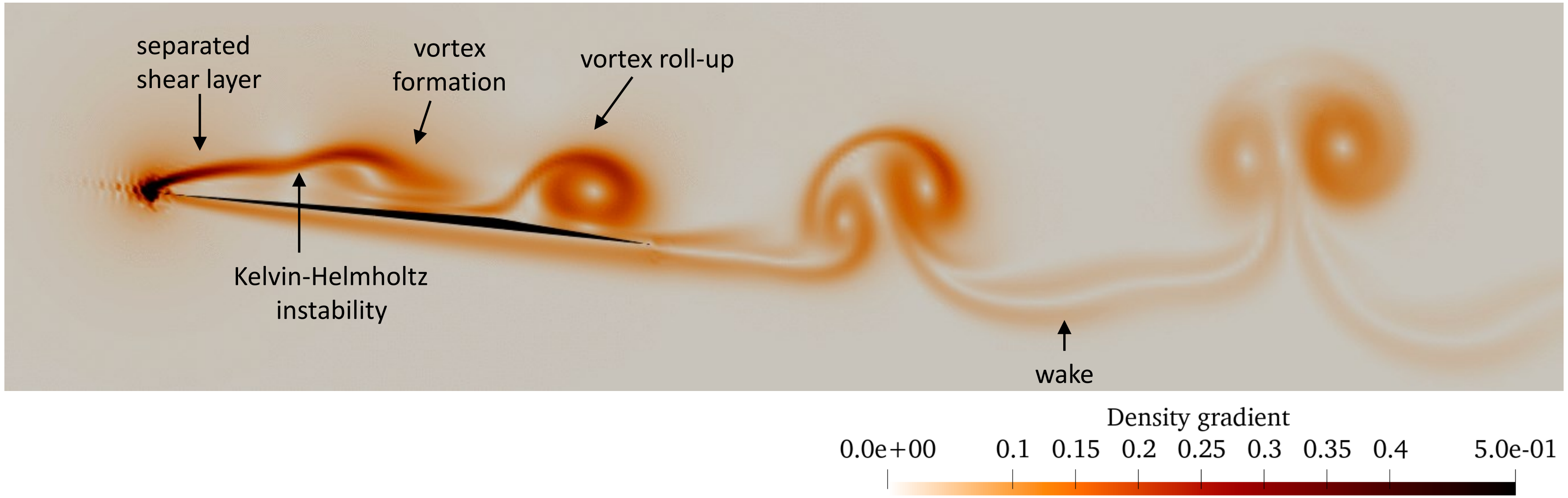


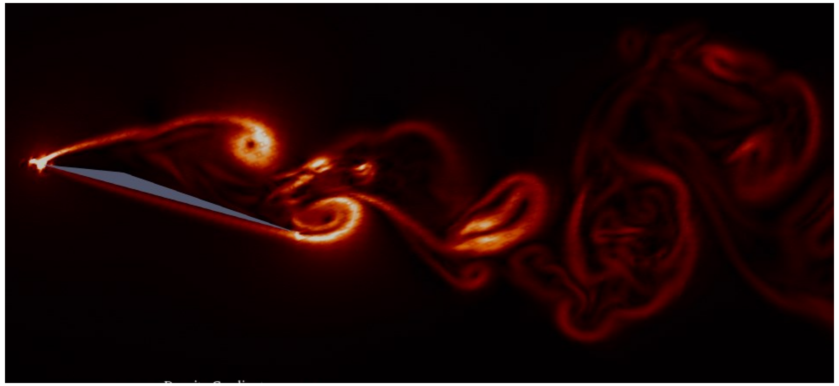
Introduction - Sharp-leading-edge airfoils

- Separated flow from the sharp leading edge
- Separated shear layer ondulates
- Formation of large coherent vortices (roll-up)
- Flow unsteadiness



Introduction - Optimisation of sharp-leading-edge airfoils

Unsteady and transitional flow - DNS



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J. Blank and K. Deb, **pymoo**: Multi-Objective Optimisation in Python, in IEEE Access, vol. 8, pp. 89497-89509, 2020, 10.1109/ACCESS.2020.2990567

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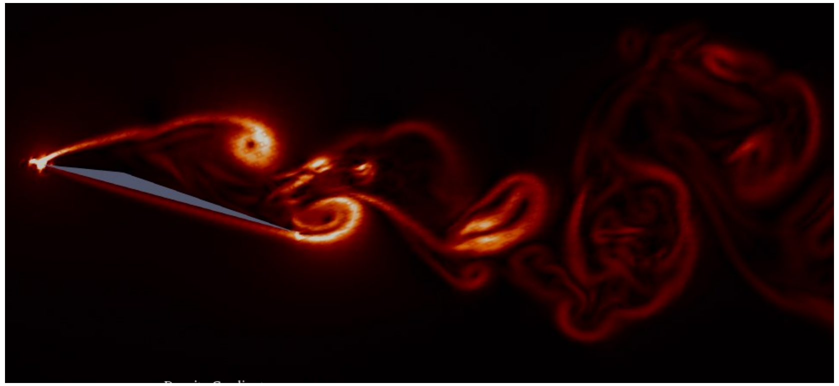

Direct Numerical Simulations

- High order accurate
- Unstructured meshes
- High parallel performance
- GPU-enabled

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pymoo

Genetic Algorithms

- No gradient information needed
- Avoid local optima
- Easy to parallelize

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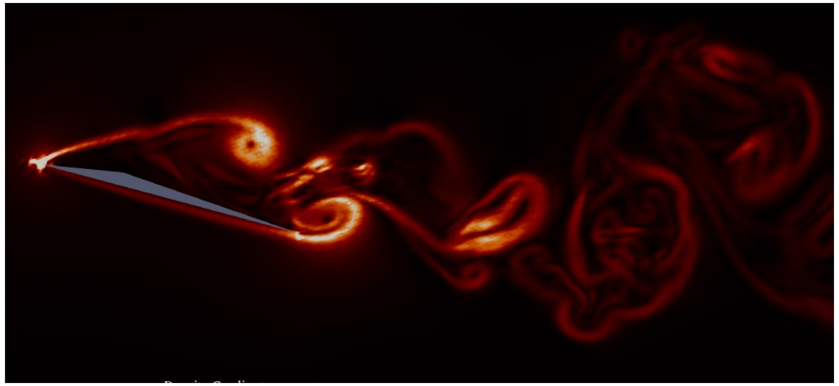

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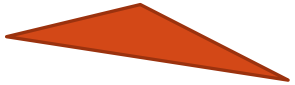
Triangular airfoil



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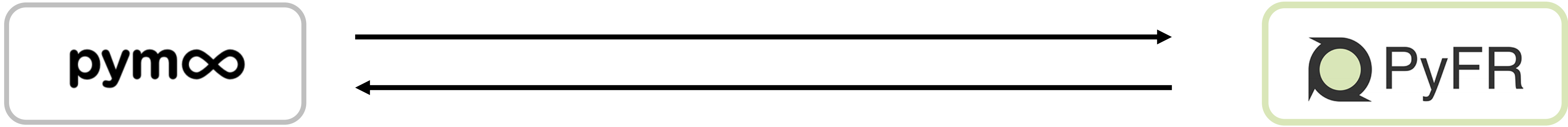
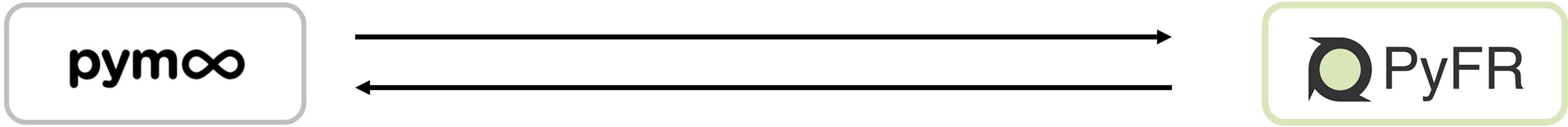


Design variables

Apex coordinates of a triangular airfoil at angle of attack of **α = 12°**

Re = 3,000 and **M = 0.15**

Optimisation setup



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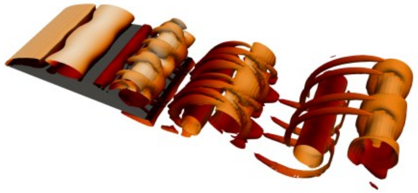
Evaluation

3D DNS with span 0.6c



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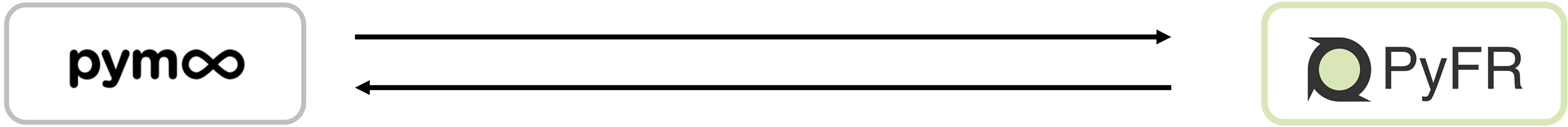

Objective functions

CL and CD

Multi-objective optimisation

↓

Multiple optimum solutions

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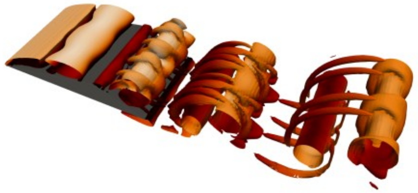

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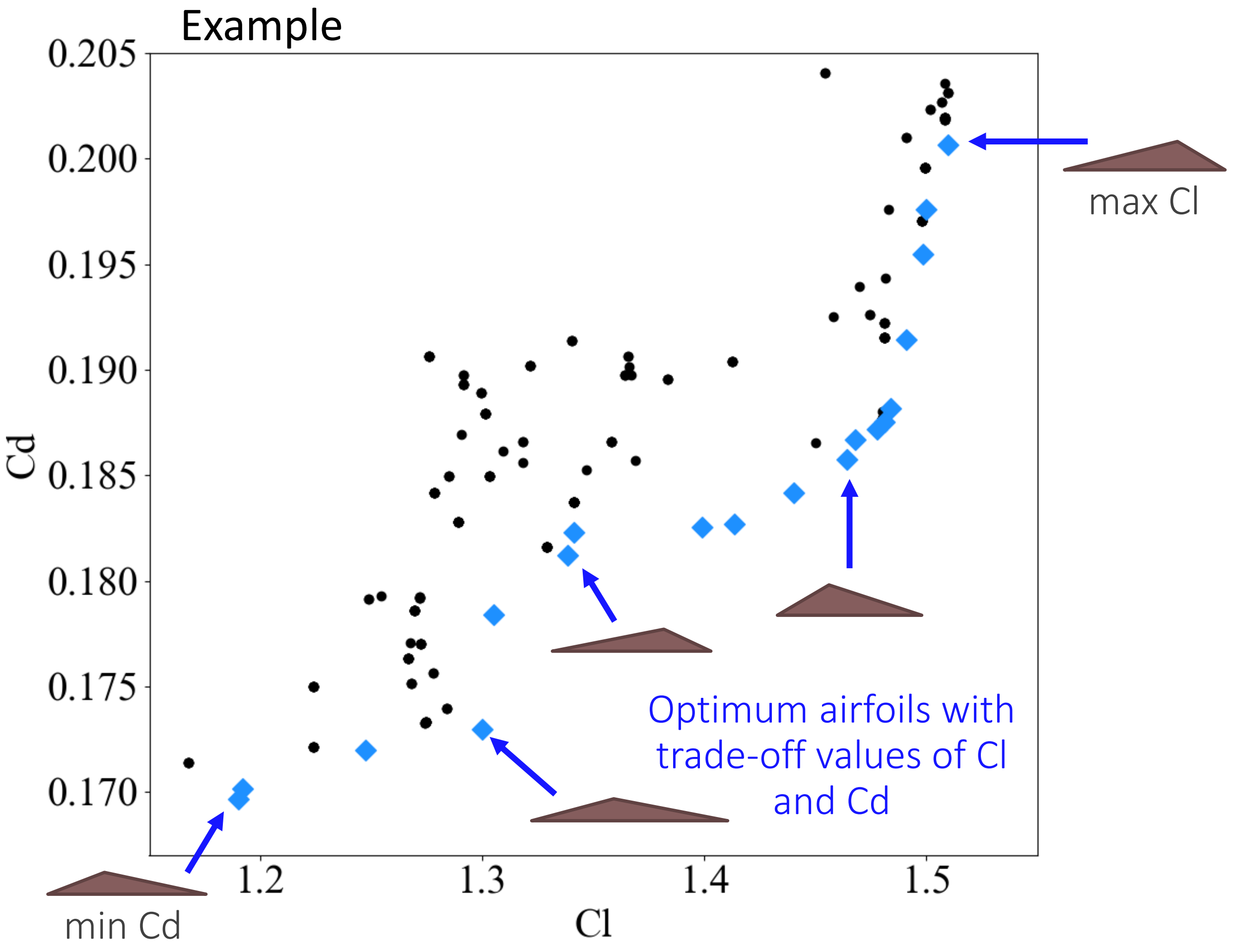
Multiple optimum solutions



Optimum airfoils with trade-off values of Cl and Cd

Optimisation setup

pymoo

Objective functions

CL and CD

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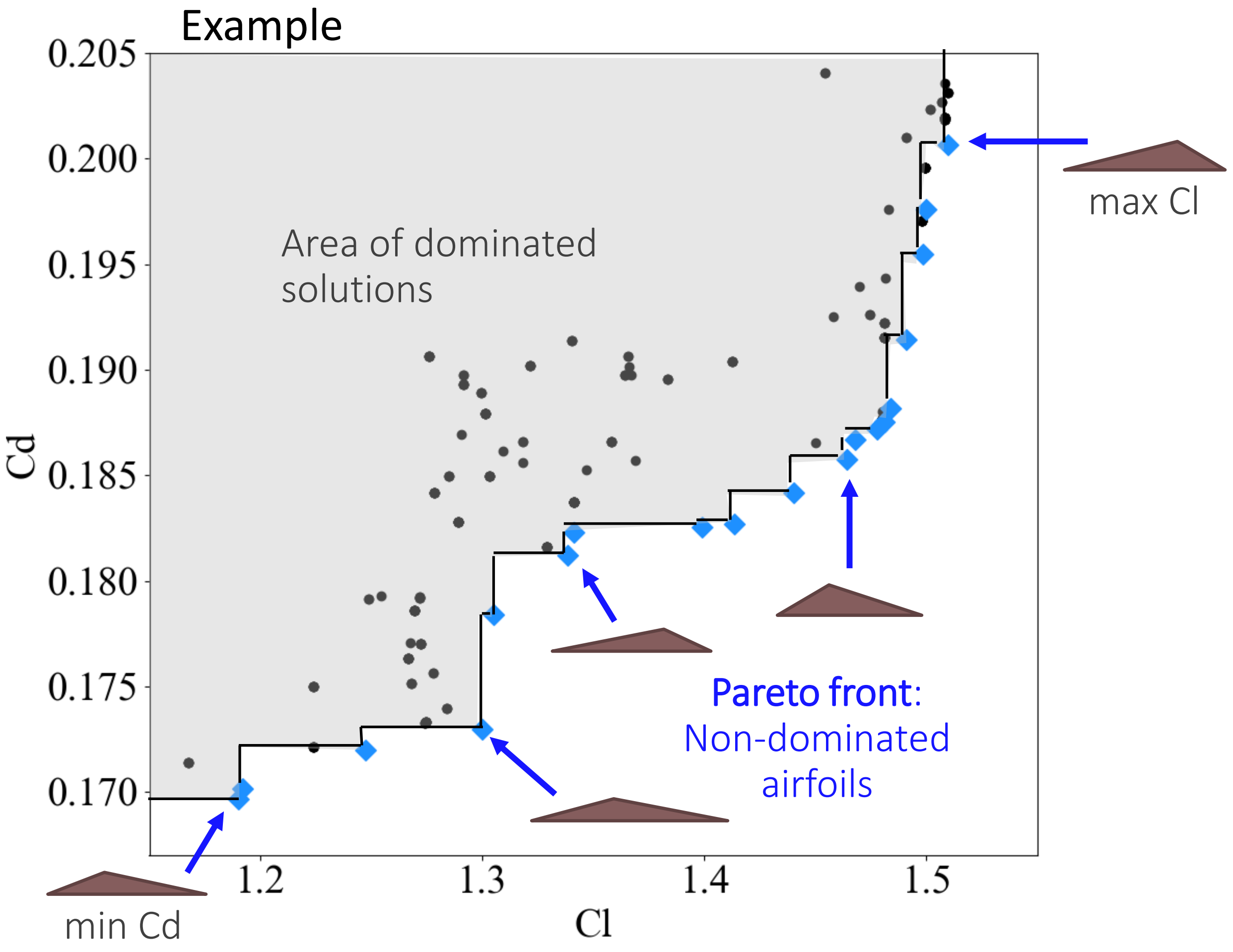
↓

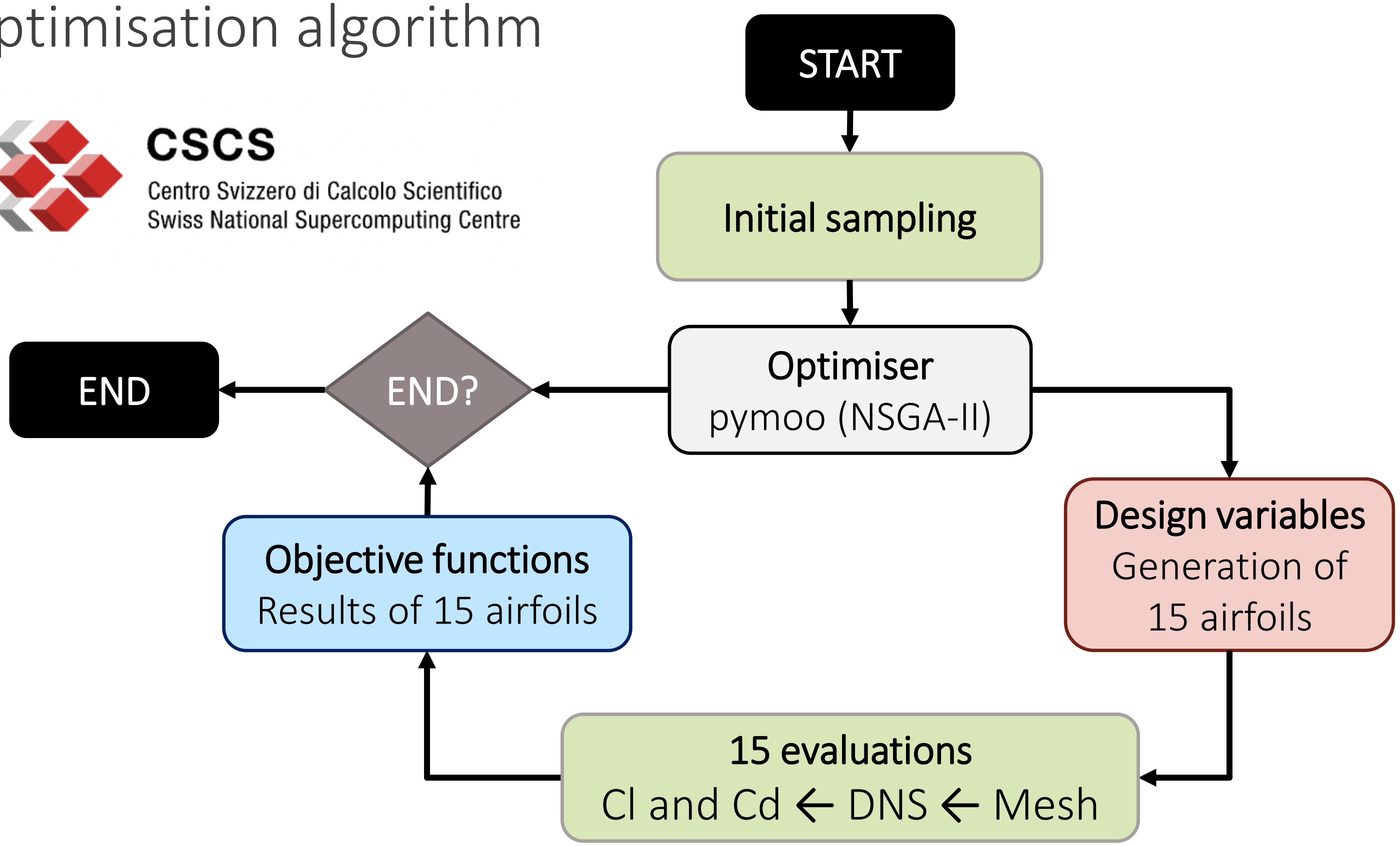
Multiple optimum solutions



Optimisation setup

Optimisation algorithm

CSCS
Centro Svizzero di Calcolo Scientifico
Swiss National Supercomputing Centre



START

Initial sampling

Optimiser
pymoo (NSGA-II)

Design variables
Generation of 15 airfoils

15 evaluations
Cl and Cd ← DNS ← Mesh

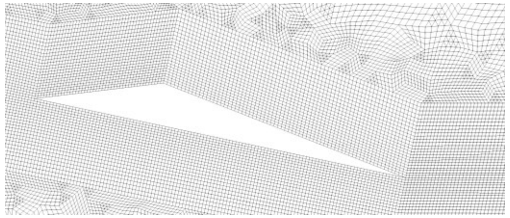
Objective functions
Results of 15 airfoils

END?

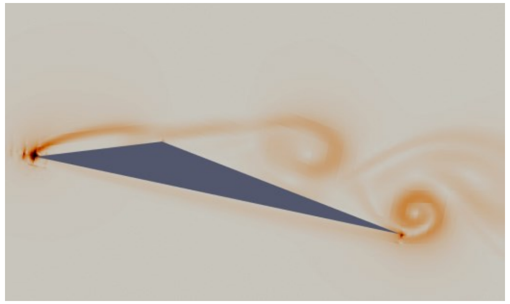
END

Evaluation

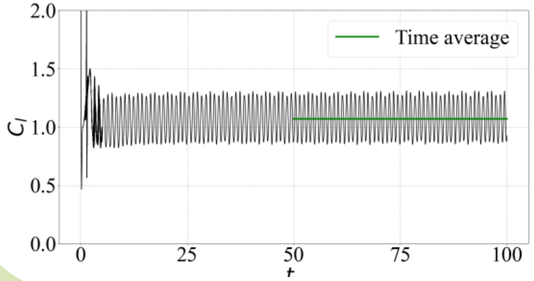
Mesh adaptation with Gmsh



3D DNS with PyFR



Aerodynamic forces



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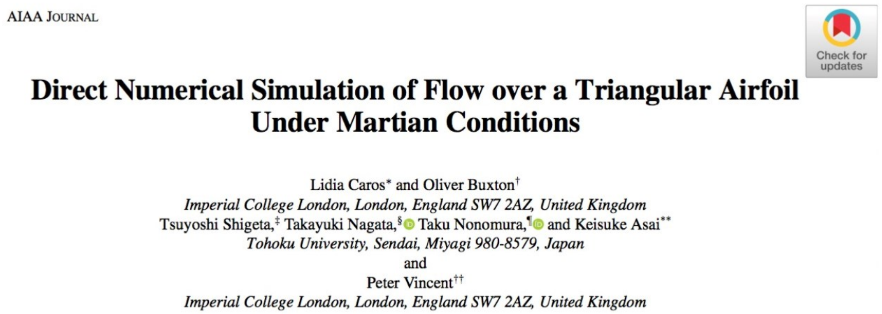
Validation

Paper: L. Caros et al. AIAA Journal 2022 10.2514/1.J061454



AIAA Journal

Direct Numerical Simulation of Flow over a Triangular Airfoil Under Martian Conditions

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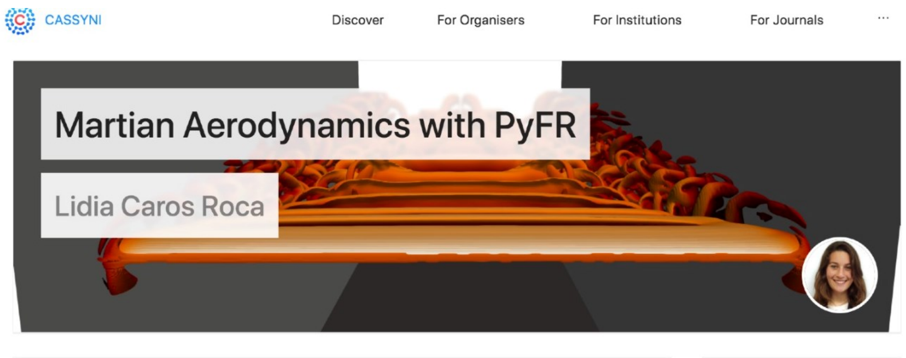
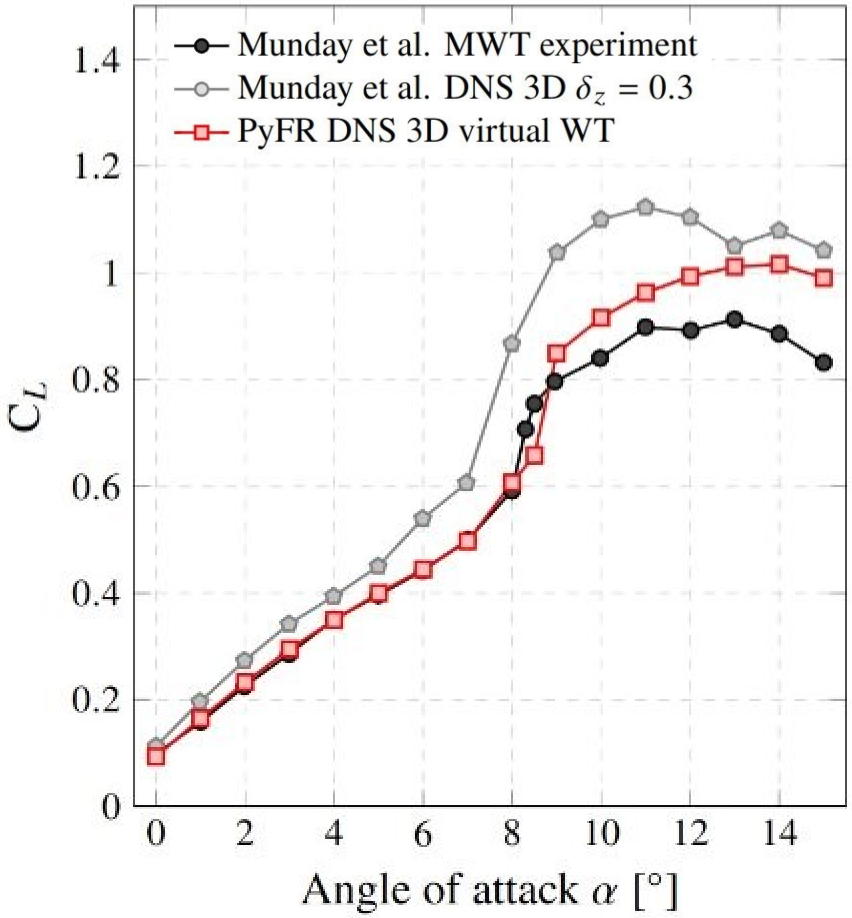
Imperial College London, London, England SW7 2AZ, United Kingdom
Tsuyoshi Shigeta,[‡] Takayuki Nagata,[§] Taku Nonomura,[¶] and Keisuke Asai[**]
Tohoku University, Sendai, Miyagi 980-8579, Japan
and
Peter Vincent[††]
Imperial College London, London, England SW7 2AZ, United Kingdom

Seminar: L. Caros. Cassyni 2021 10.52843/47ly7q



Martian Aerodynamics with PyFR

Lidia Caros Roca



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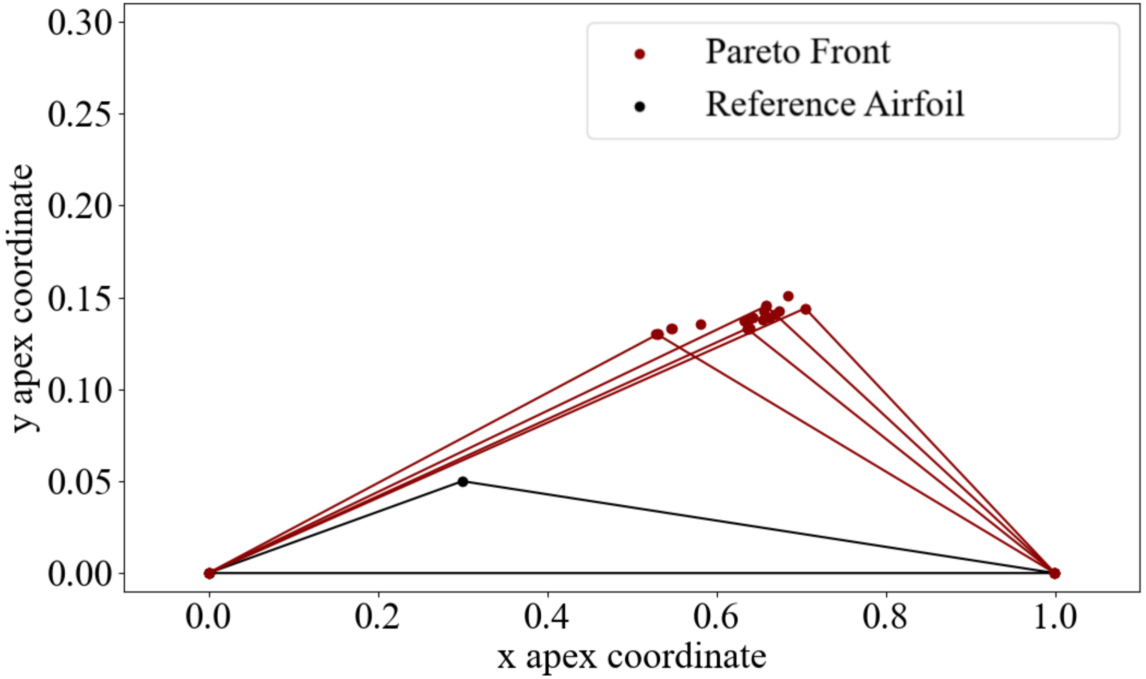

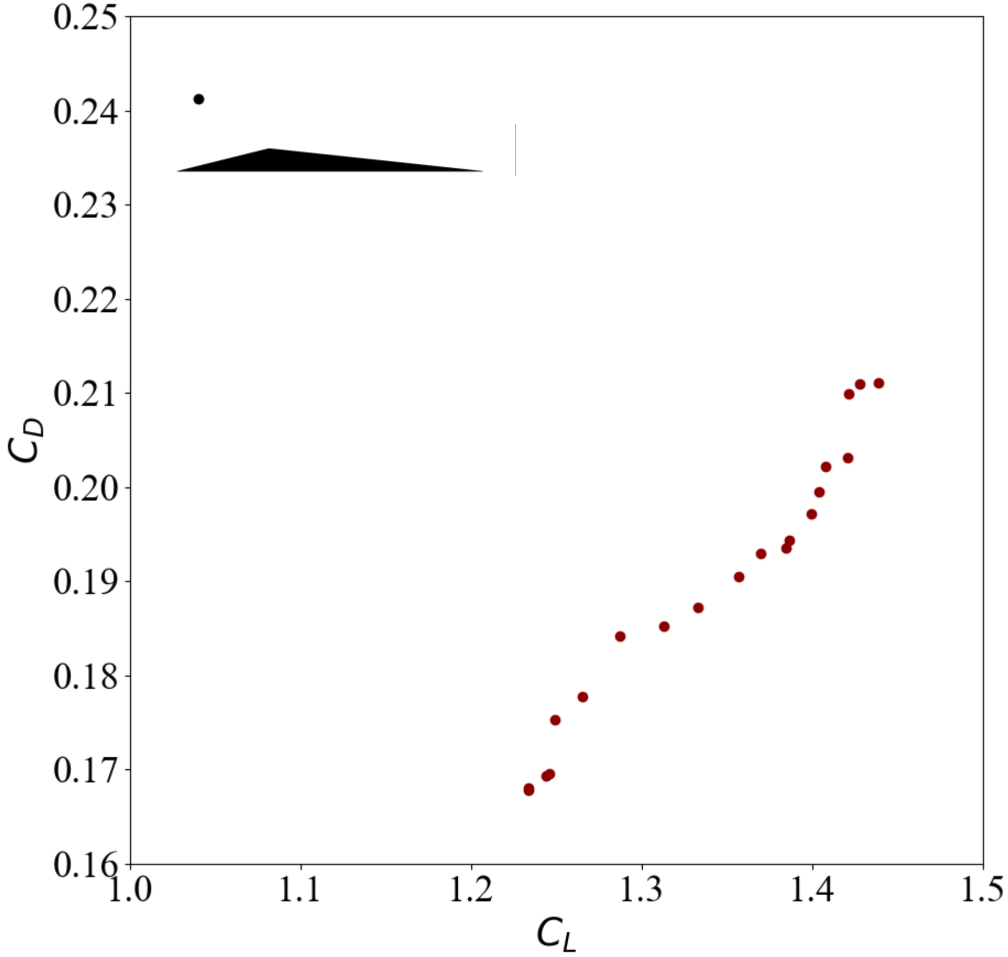

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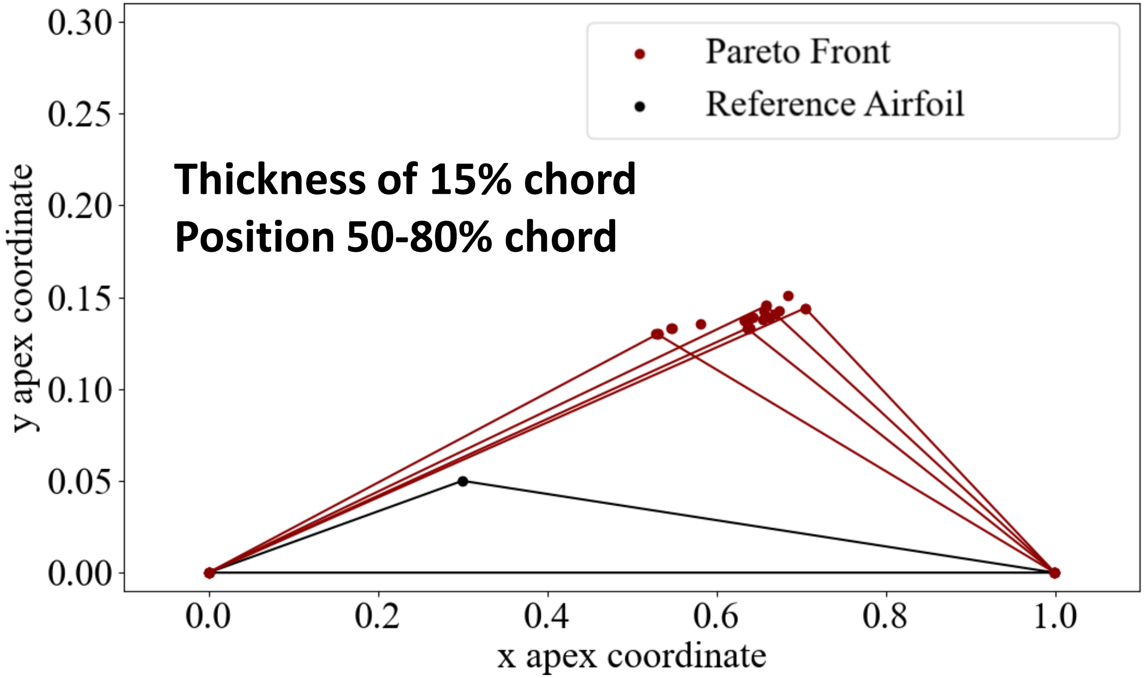
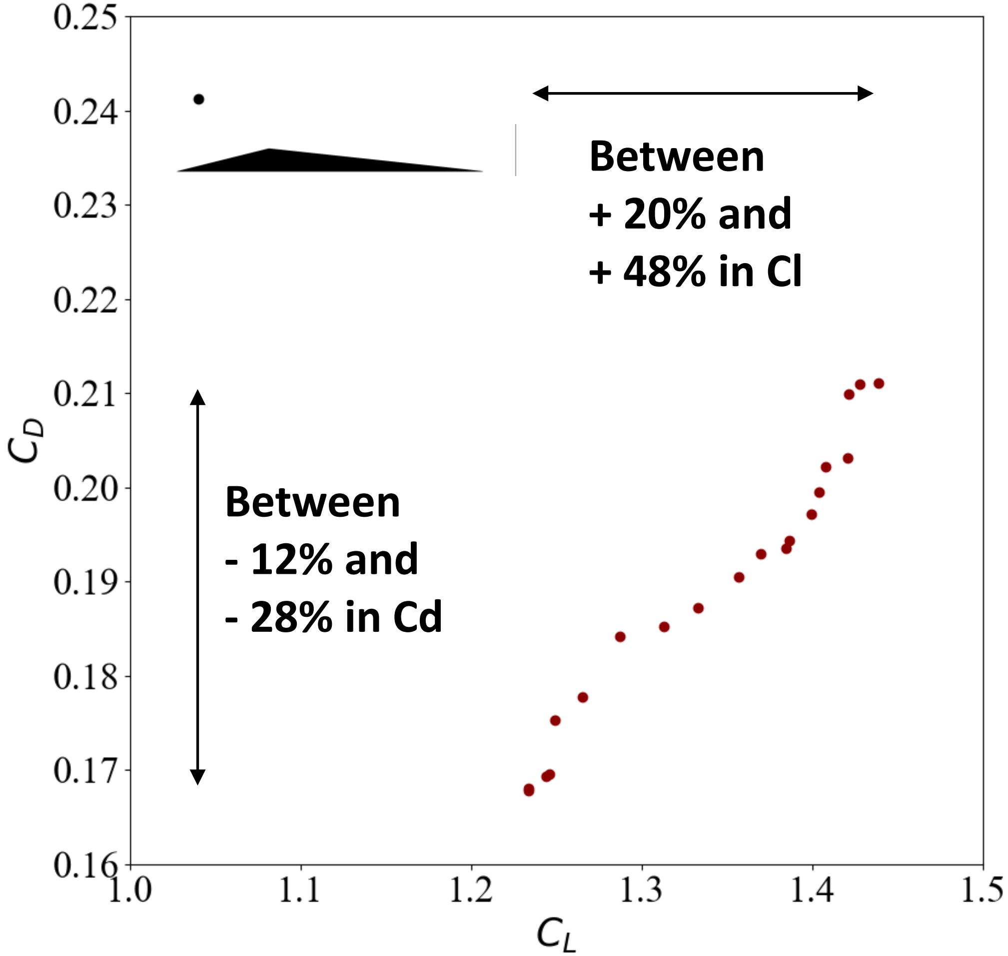


Thickness of 15% chord
Position 50-80% chord

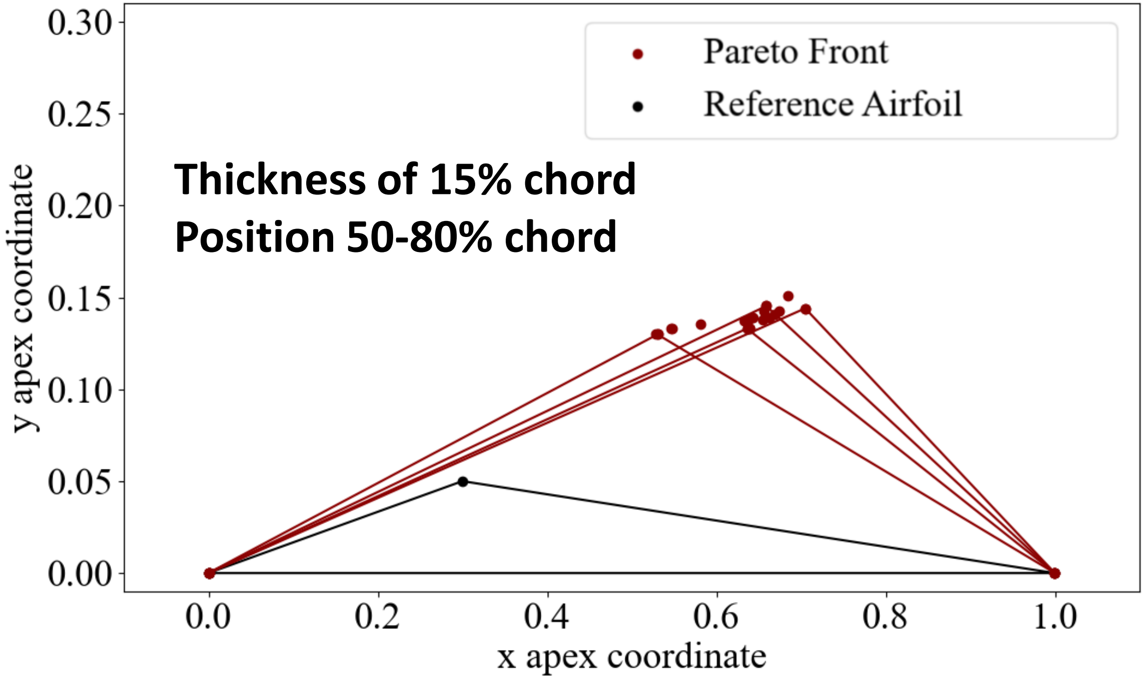


Between
+ 20% and
+ 48% in Cl

Between
- 12% and
- 28% in Cd

Optimisation Results

All exploit vortex roll-up. First suction surface almost parallel to the flow.



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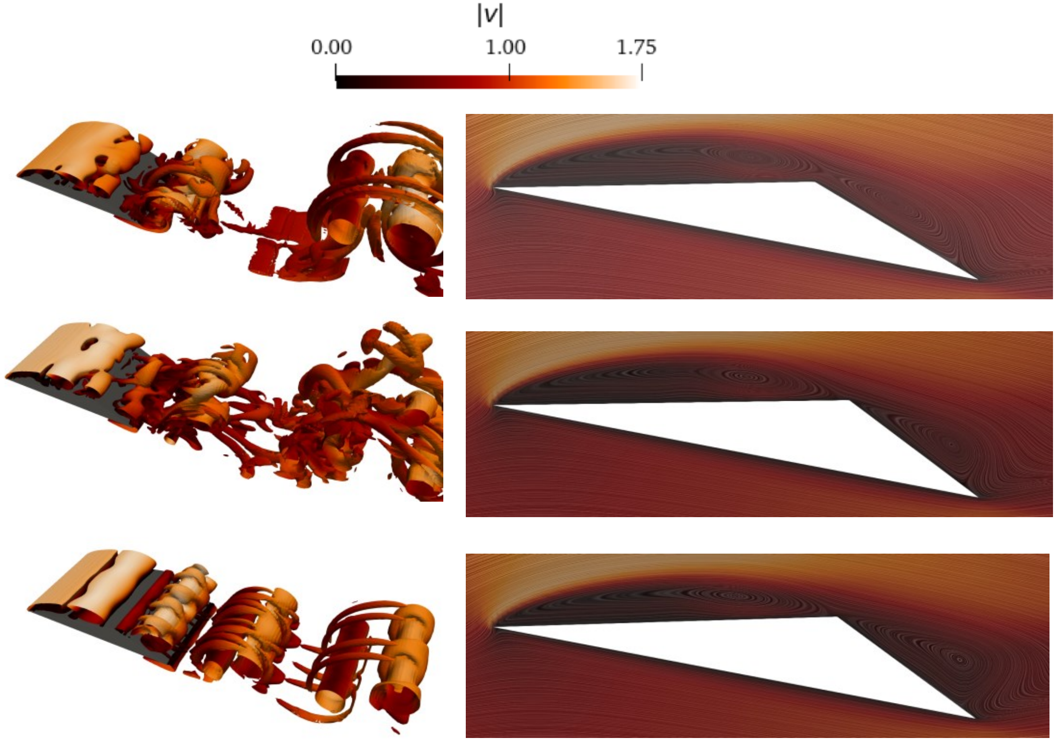

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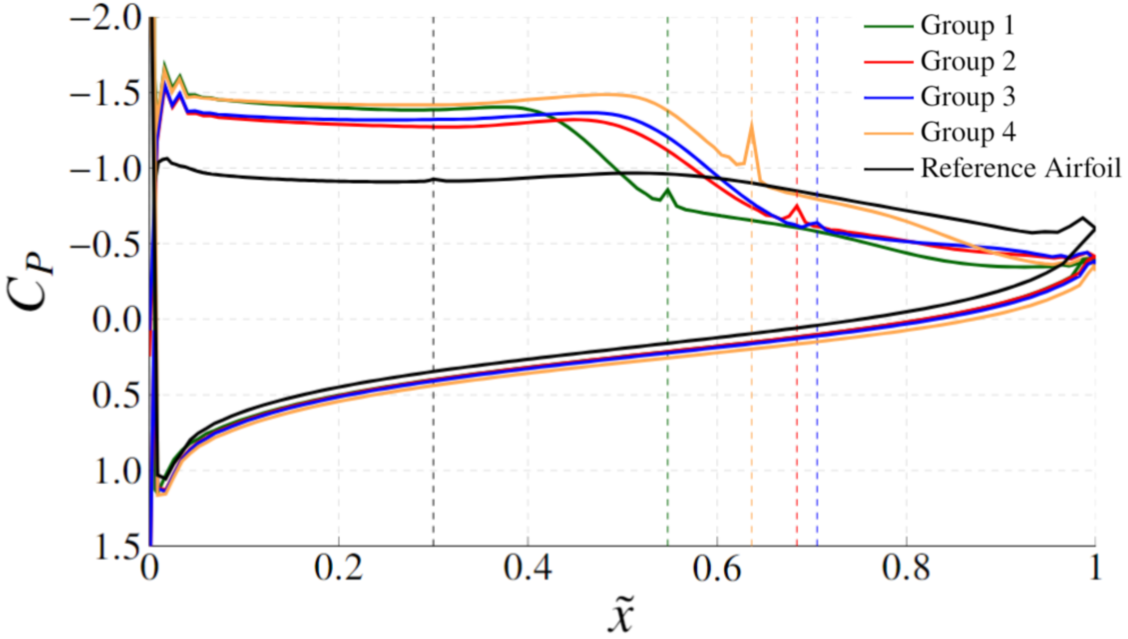
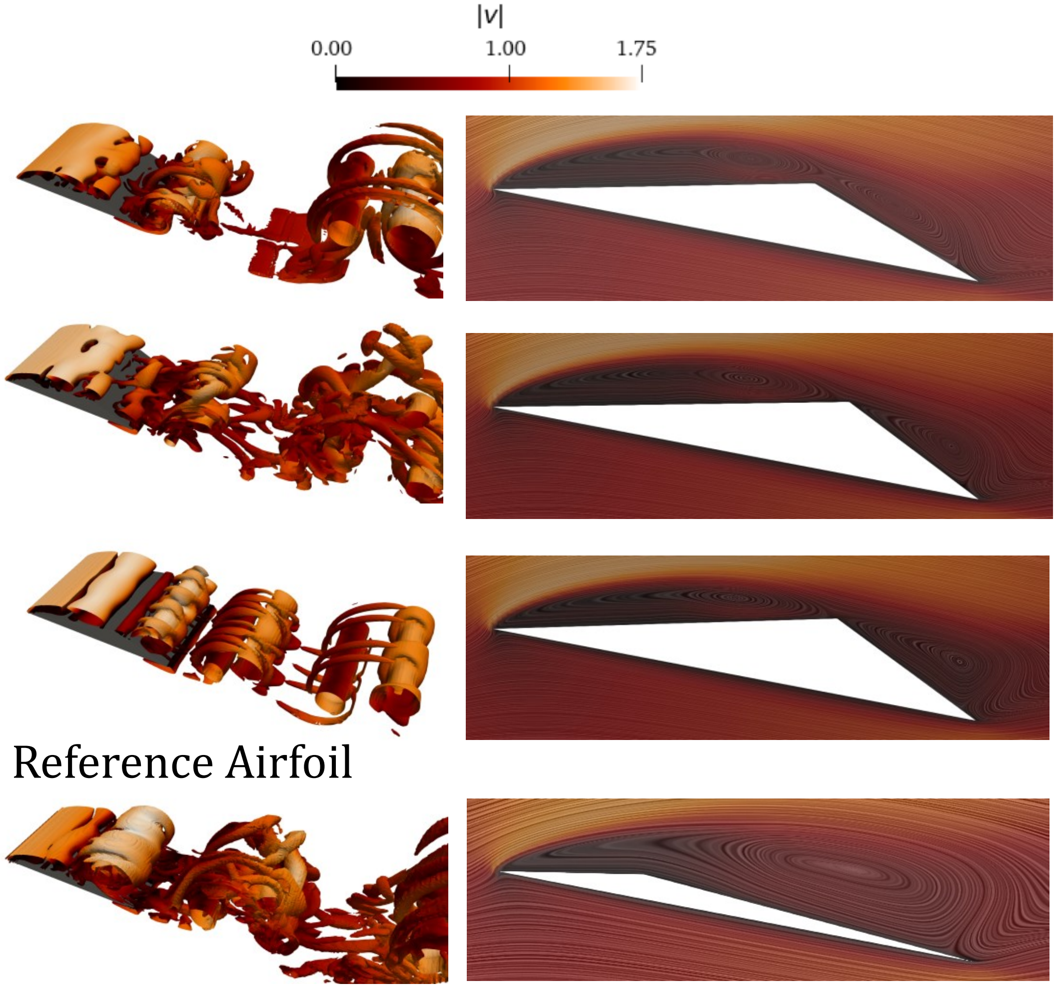
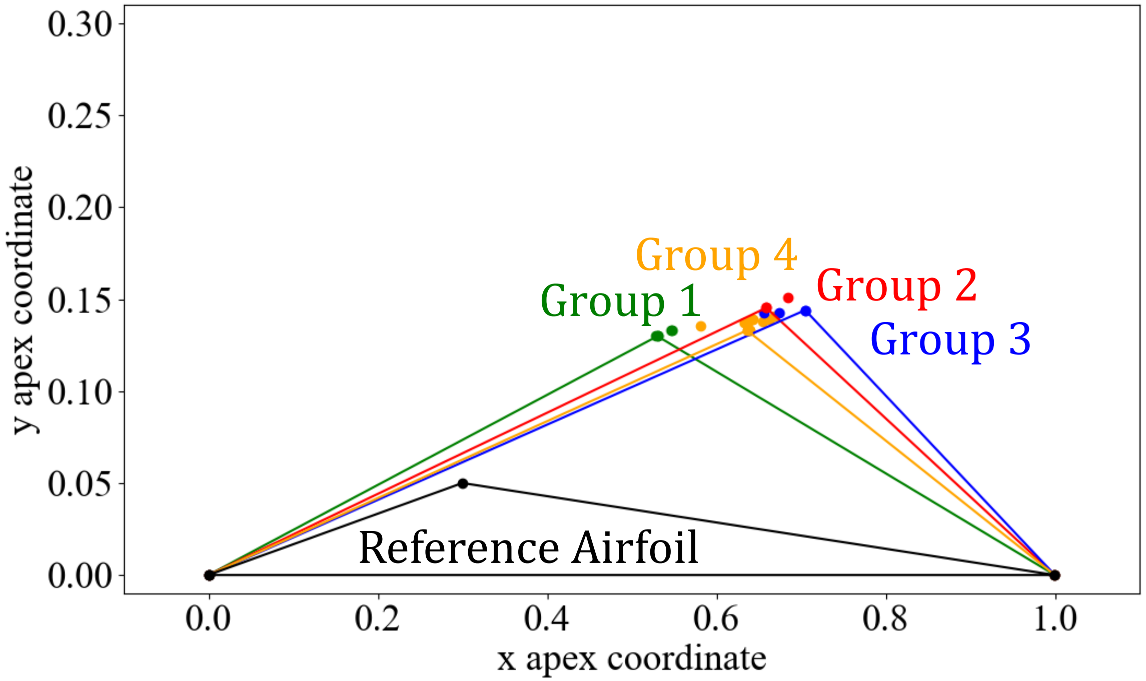
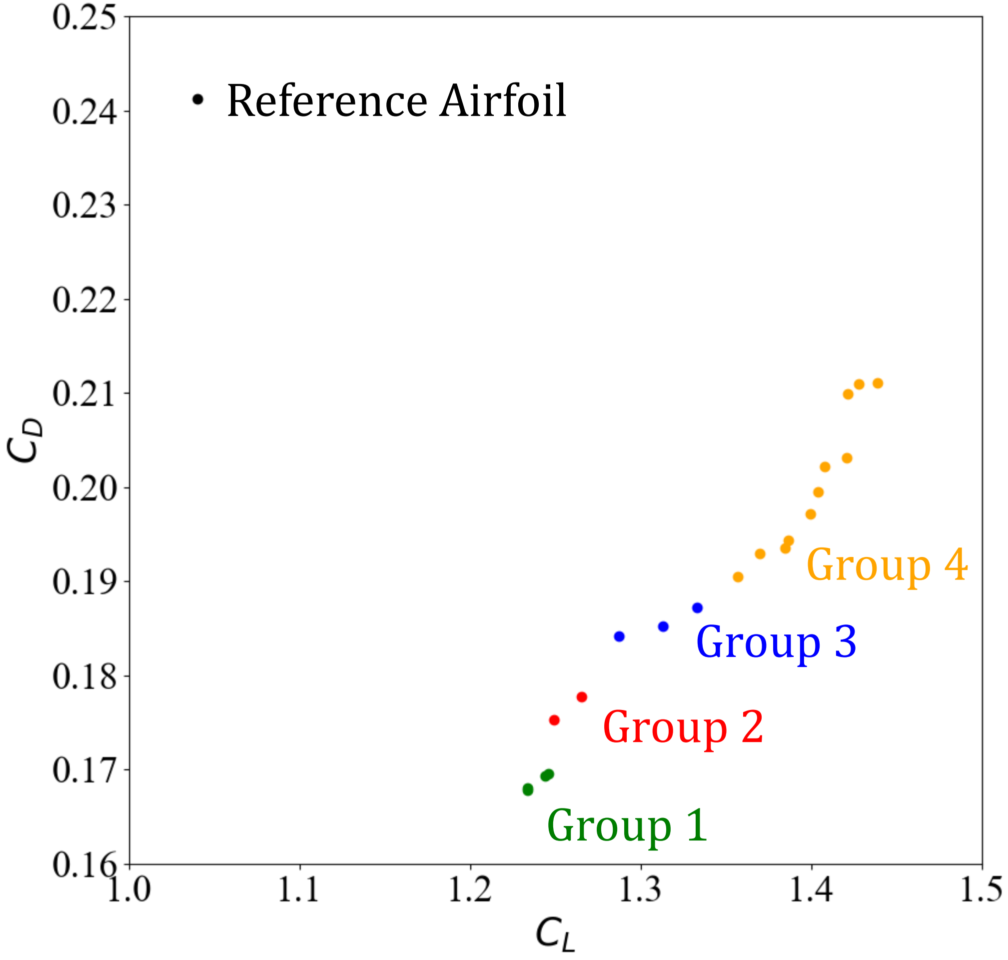




Optimisation Results

Identified four groups based on flow characteristics





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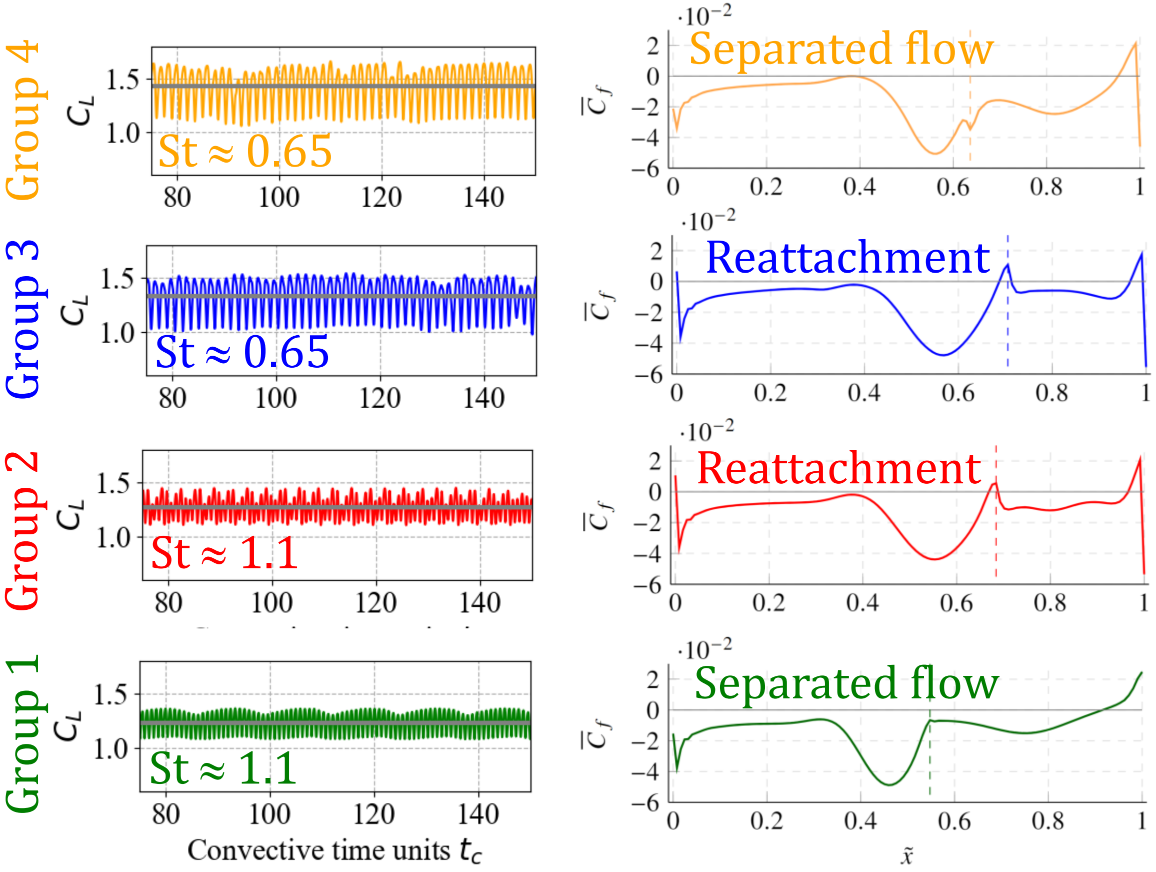
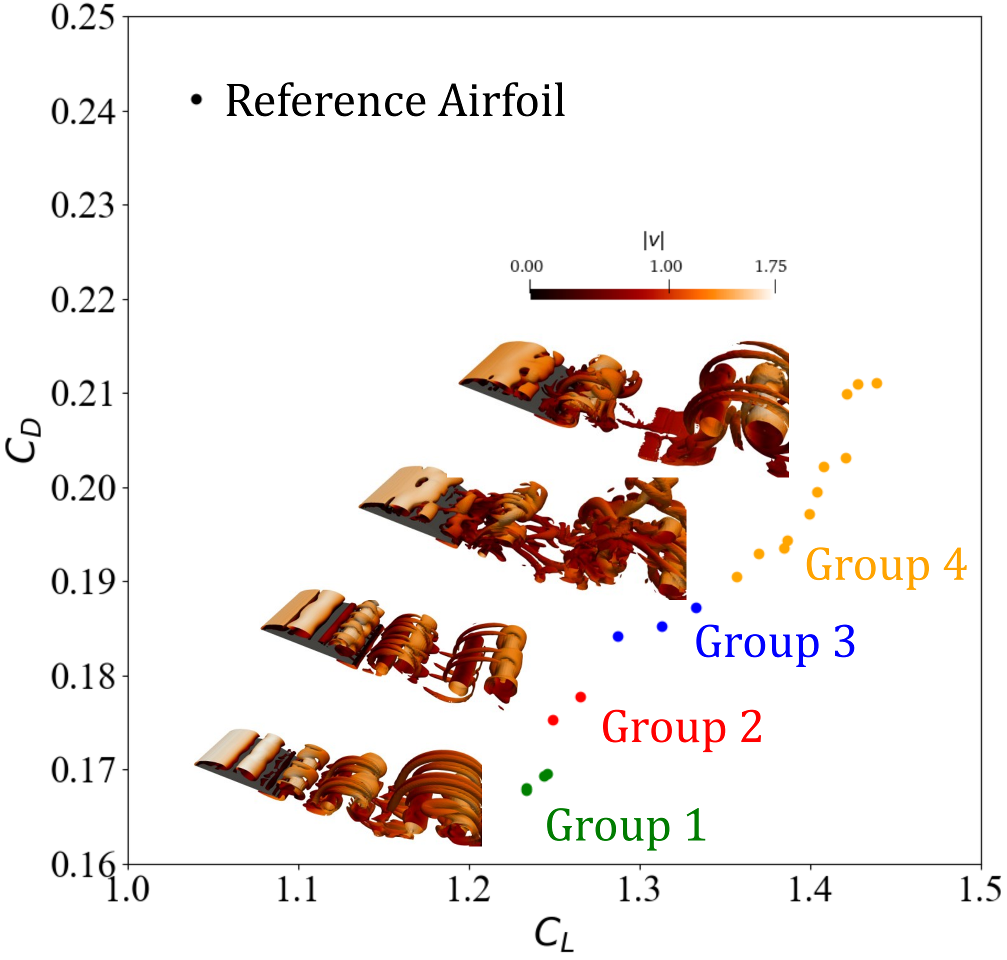
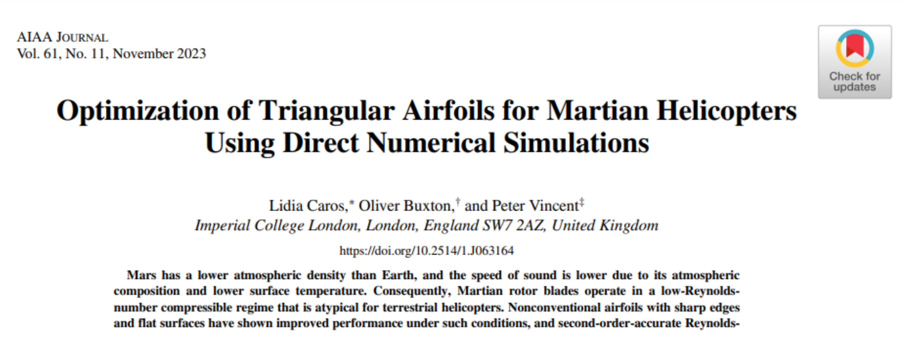




Optimisation Results

Paper: L. Caros et al. AIAA Journal 2023 10.2514/1.J063164



AIAA Journal
Vol. 61, No. 11, November 2023

Optimization of Triangular Airfoils for Martian Helicopters Using Direct Numerical Simulations

Lidia Caros,* Oliver Buxton,† and Peter Vincent‡
Imperial College London, London, England SW7 2AZ, United Kingdom

https://doi.org/10.2514/1.J063164

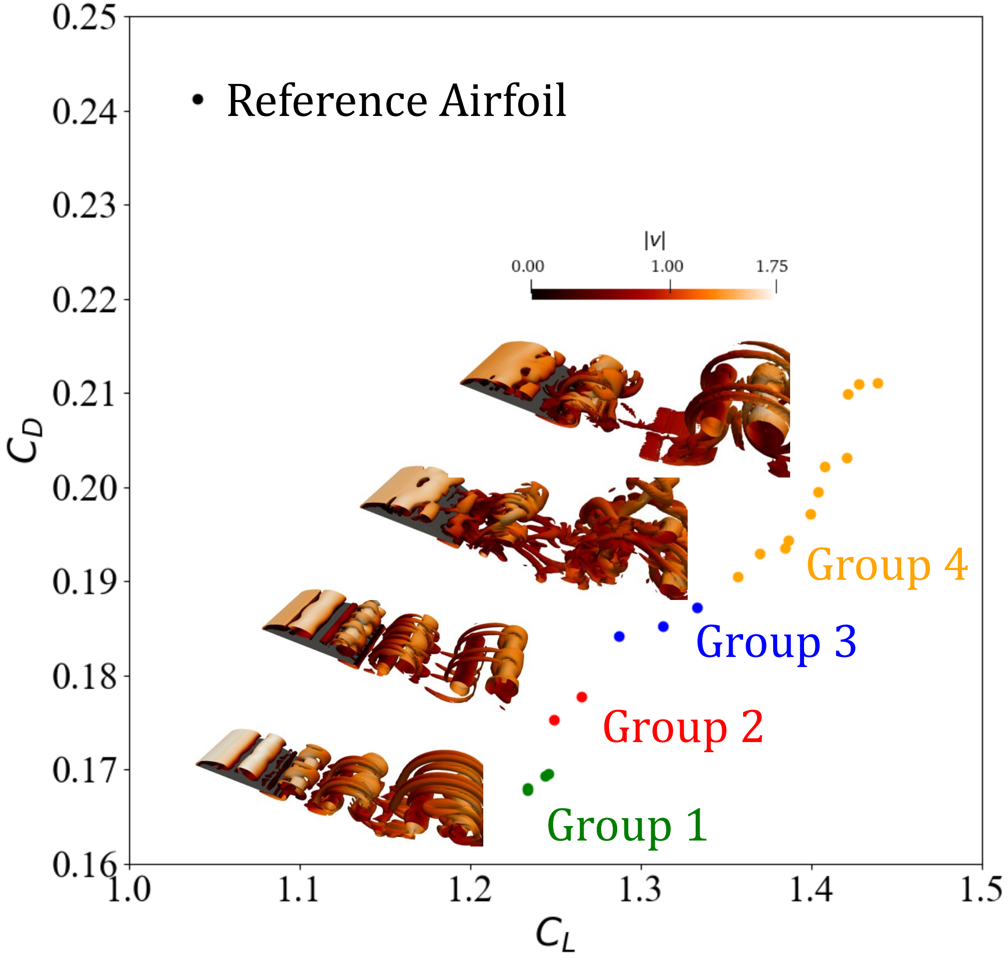
Mars has a lower atmospheric density than Earth, and the speed of sound is lower due to its atmospheric composition and lower surface temperature. Consequently, Martian rotor blades operate in a low-Reynolds-number compressible regime that is atypical for terrestrial helicopters. Nonconventional airfoils with sharp edges and flat surfaces have shown improved performance under such conditions, and second-order-accurate Reynolds-

Seminar: L. Caros. Cassyni 2023 10.52843/cassyni.6r5ry1

DNS-based optimisation of airfoils for Martian helicopters using PyFR

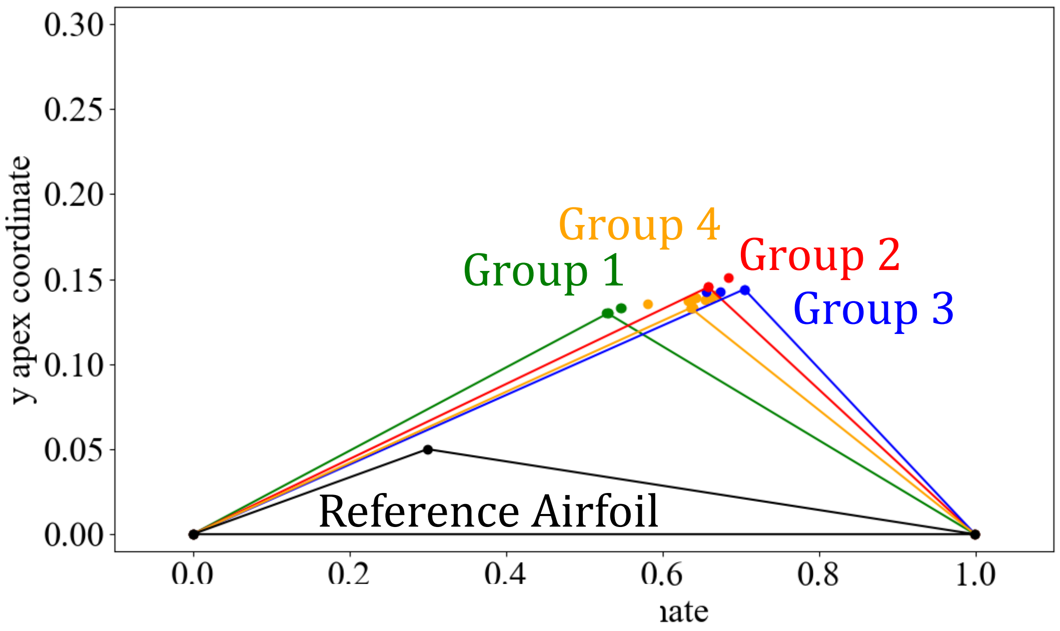
Lidia Caros Roca

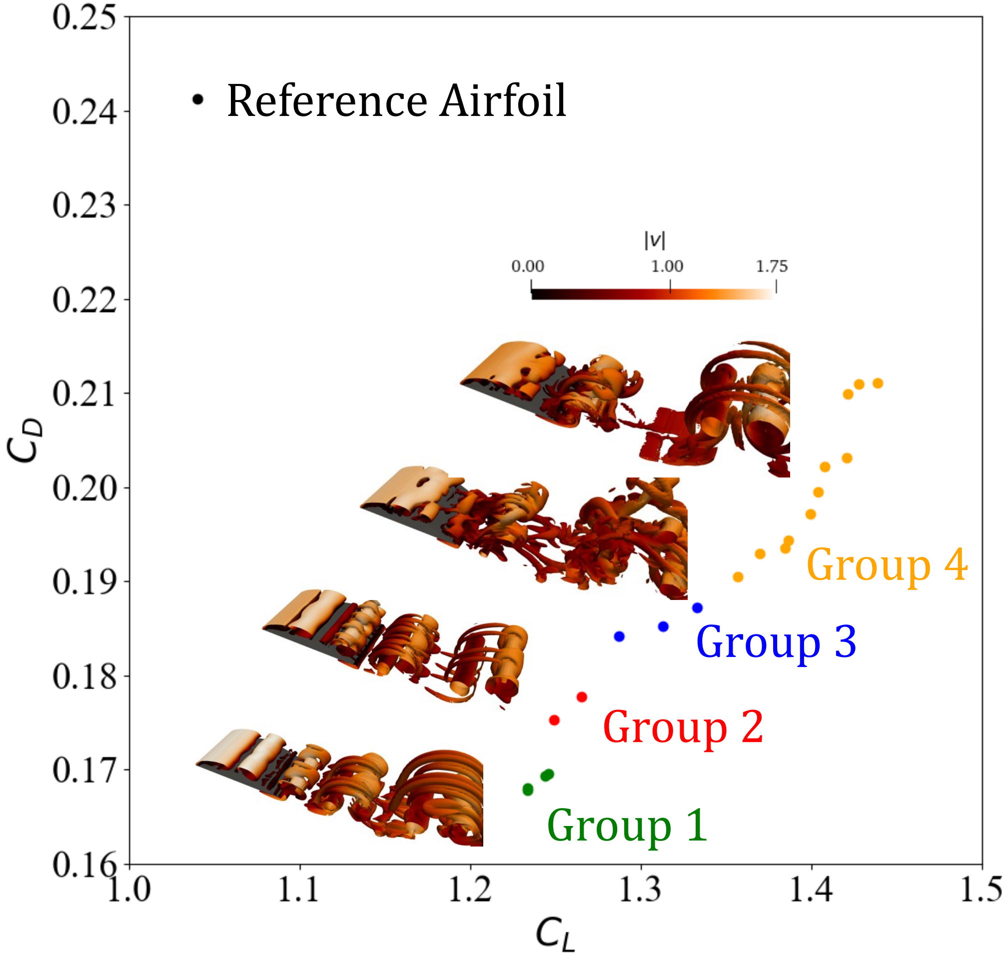
PyFR Seminar Series
PyFR (Imperial College London and Texas A&M University)



Optimisation Results

How sensitive will these airfoils be to perturbations in the flow?





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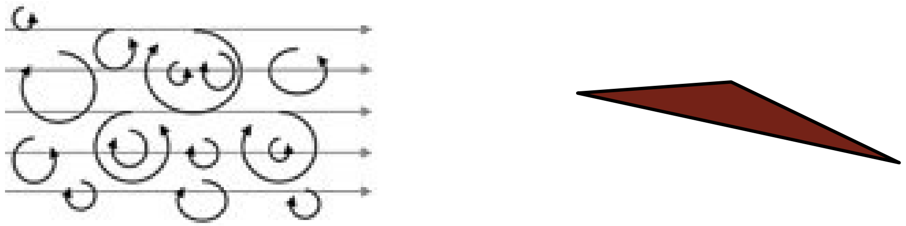
Effects of free-stream eddies on optimised airfoils

Injection of eddies with the Synthetic Eddy Method implemented in PyFR

- Target turbulence intensities
  TI=1% and TI=0.5%

- Target integral lengthscales
  ls=0.1c and ls=0.05c



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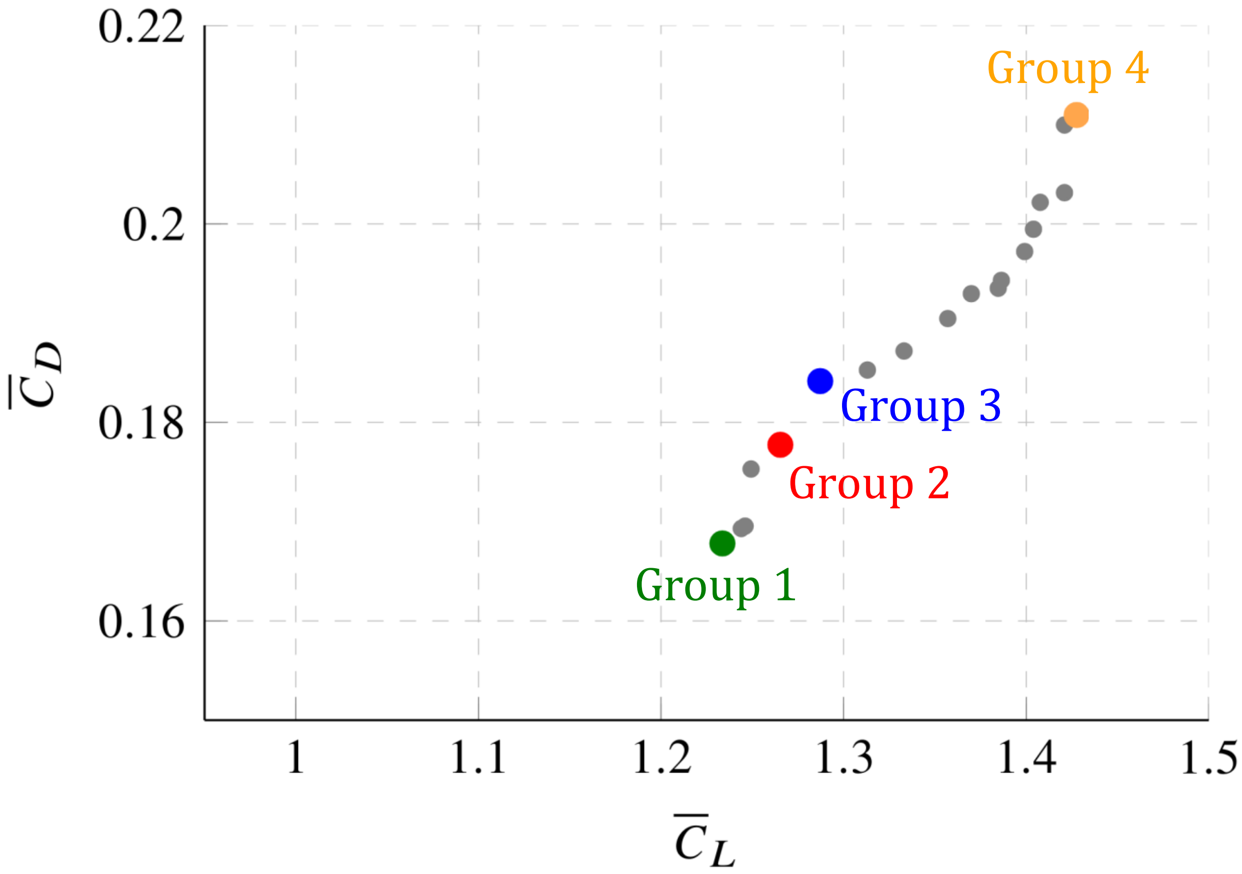

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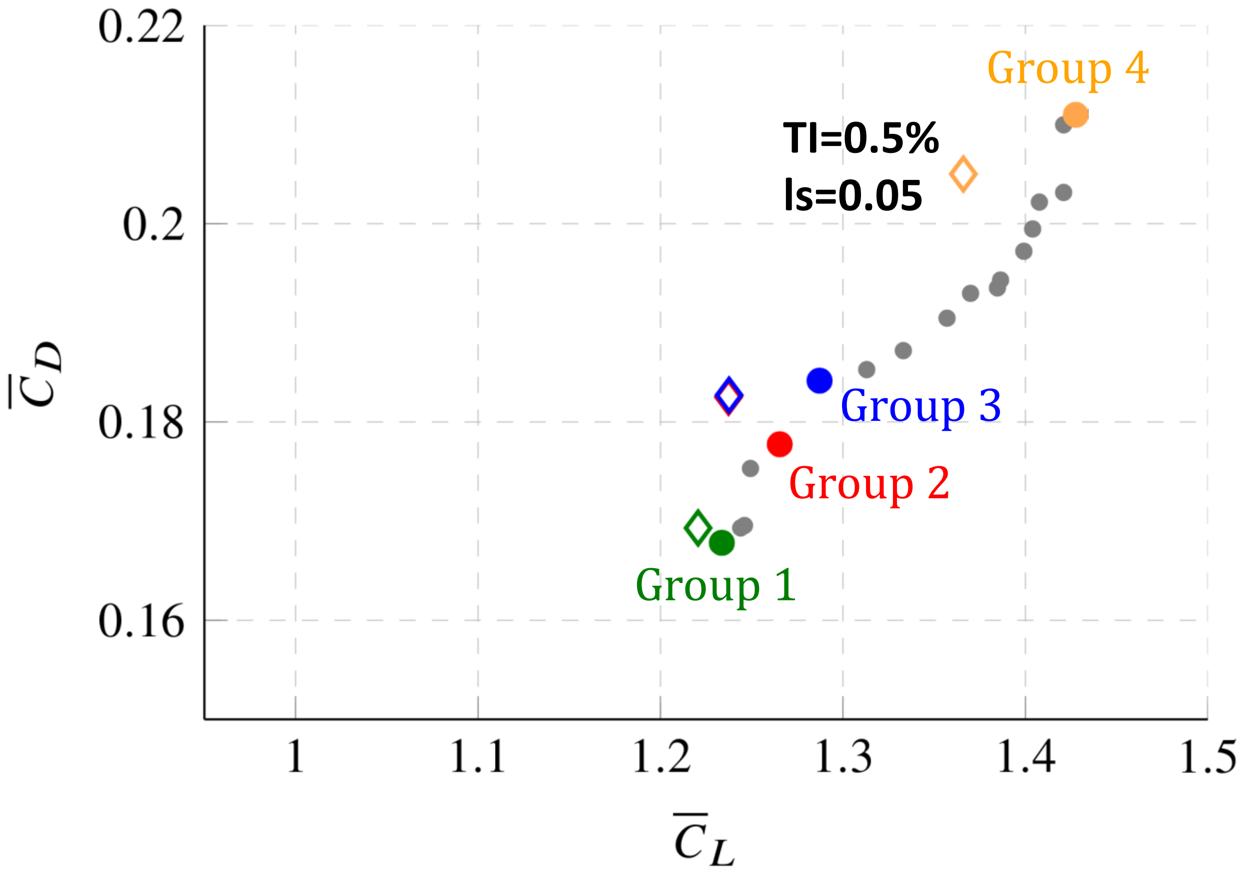

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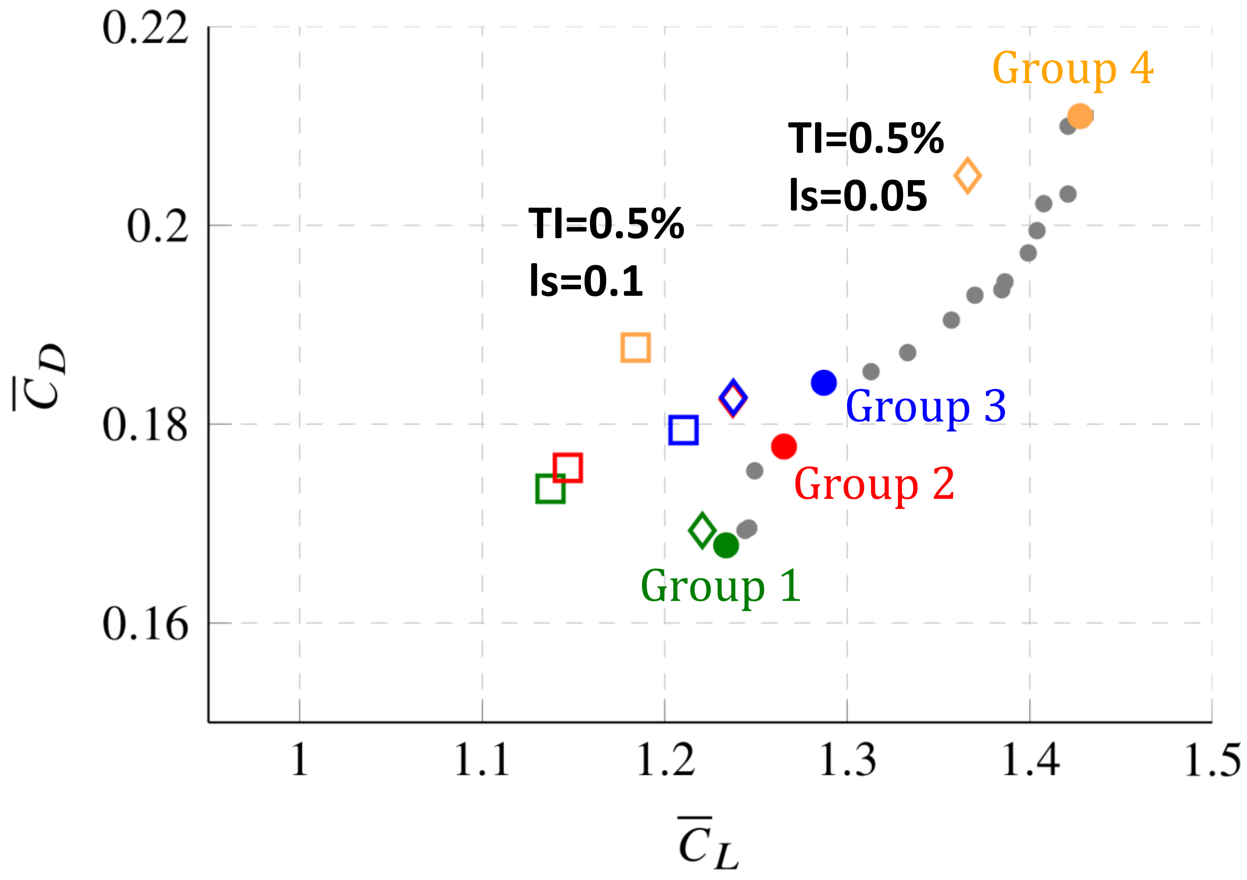

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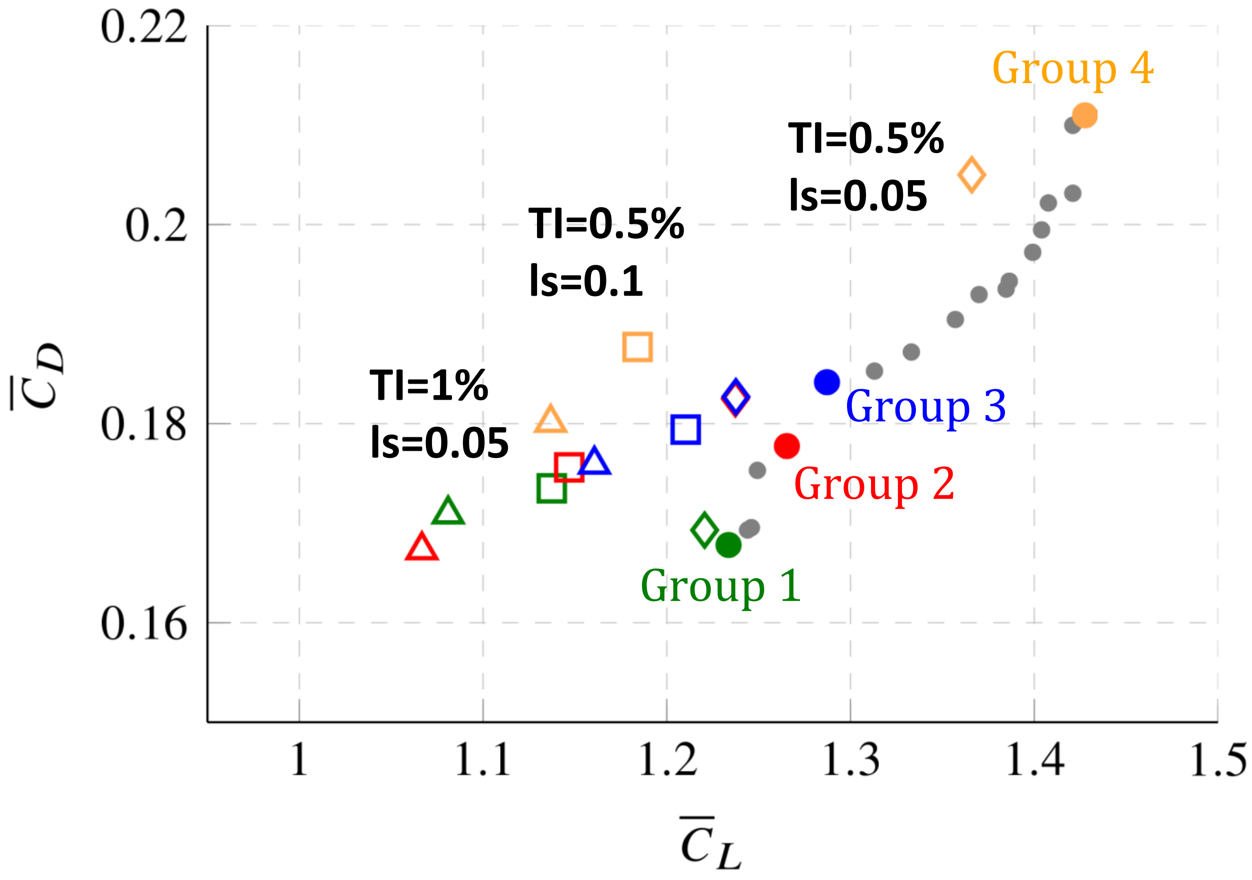

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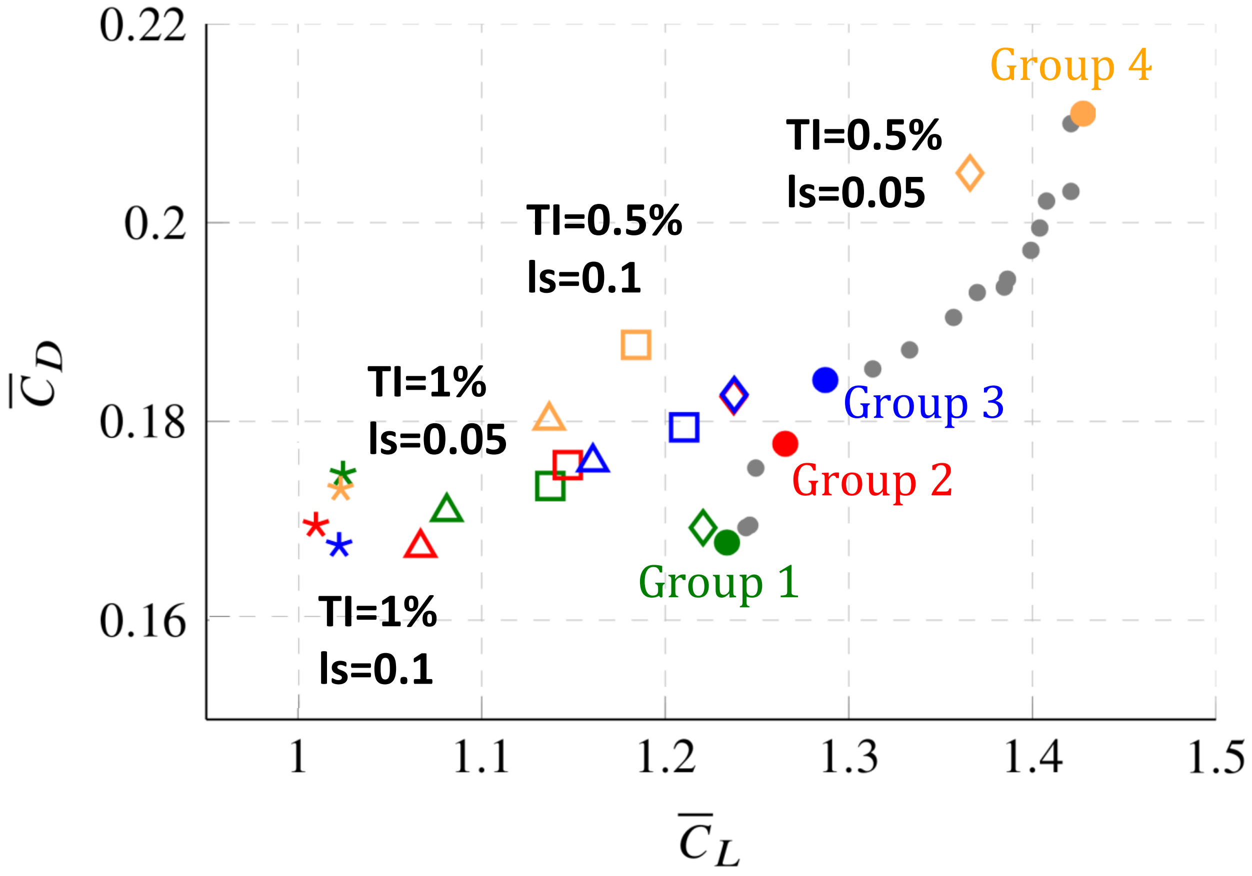

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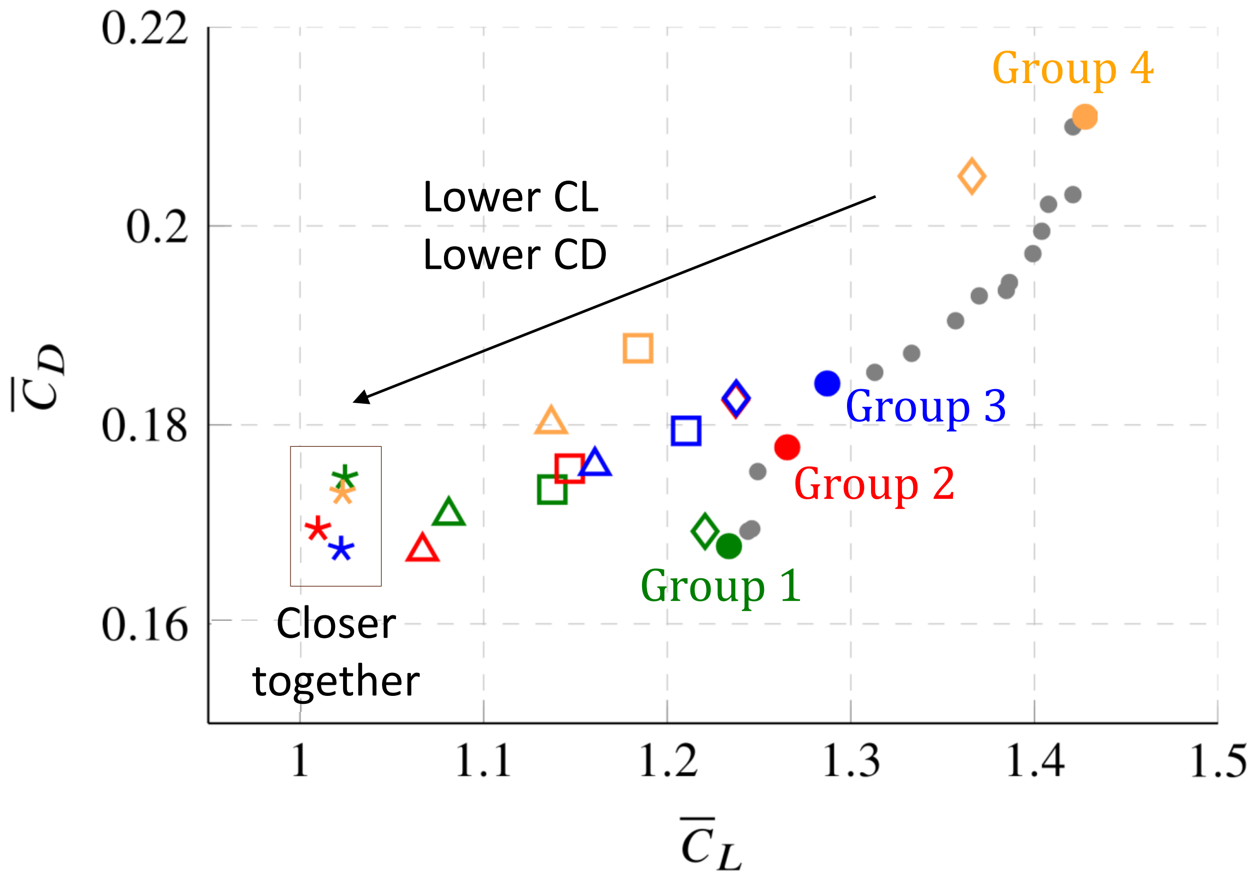
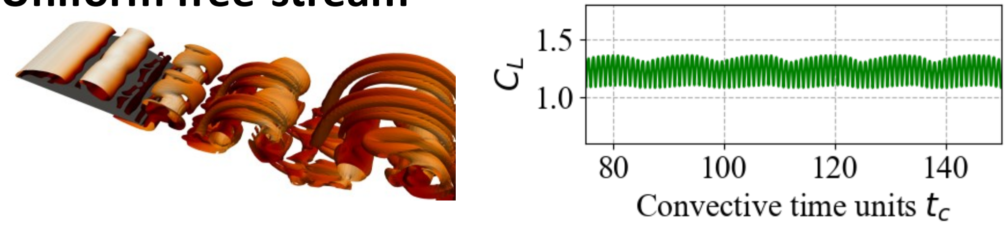


Effects of free-stream eddies on optimised airfoils

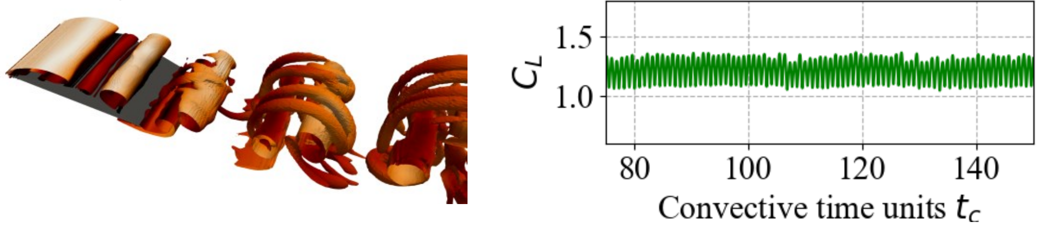
- Free-stream eddies tend **break** the **periodicity** of the flow due to the breakdown of the **coherent vortices**
- The **higher** the **TI** and **ls**, the **stronger** the effect

Group 1

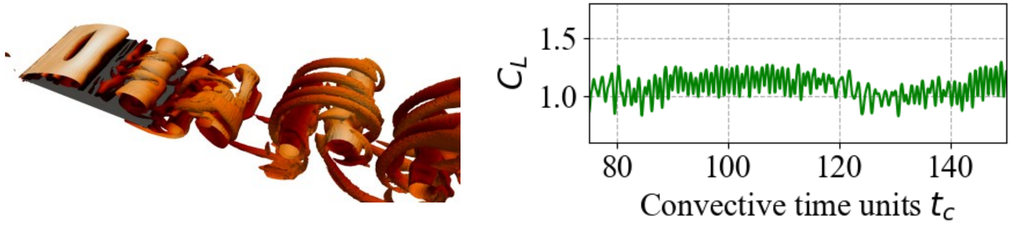
Uniform free-stream



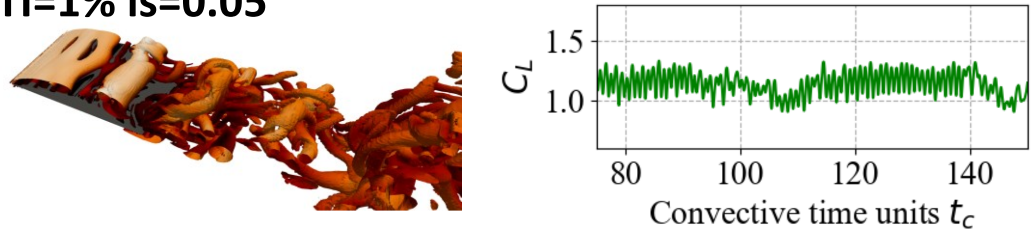
TI=0.5% ls=0.05



TI=0.5% ls=0.1



TI=1% ls=0.05



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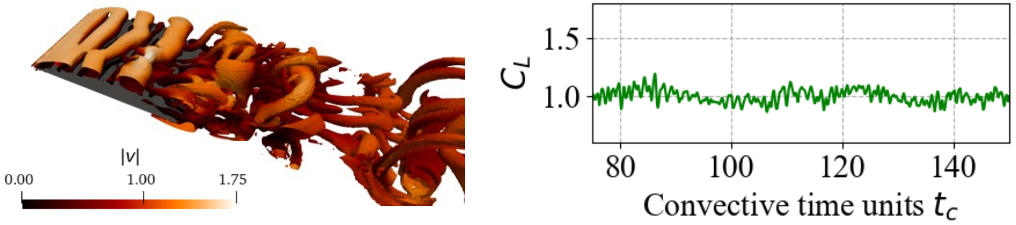
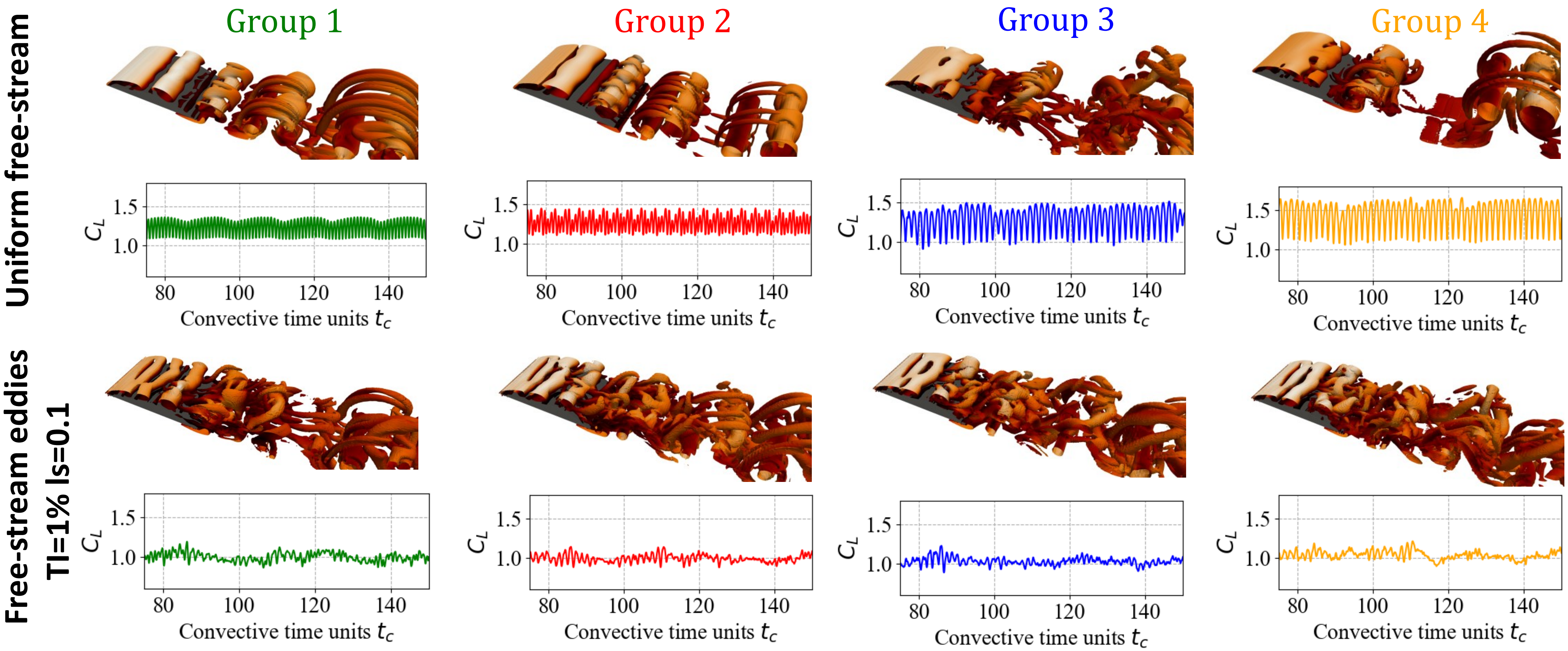
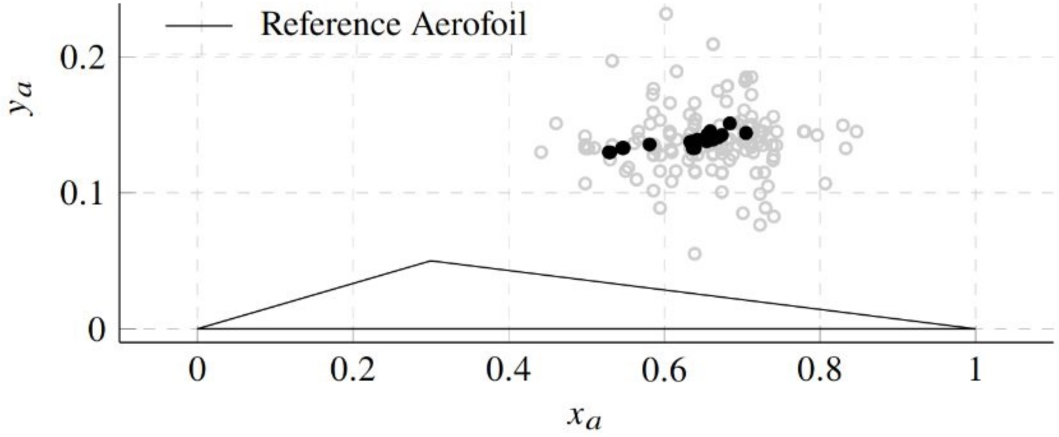


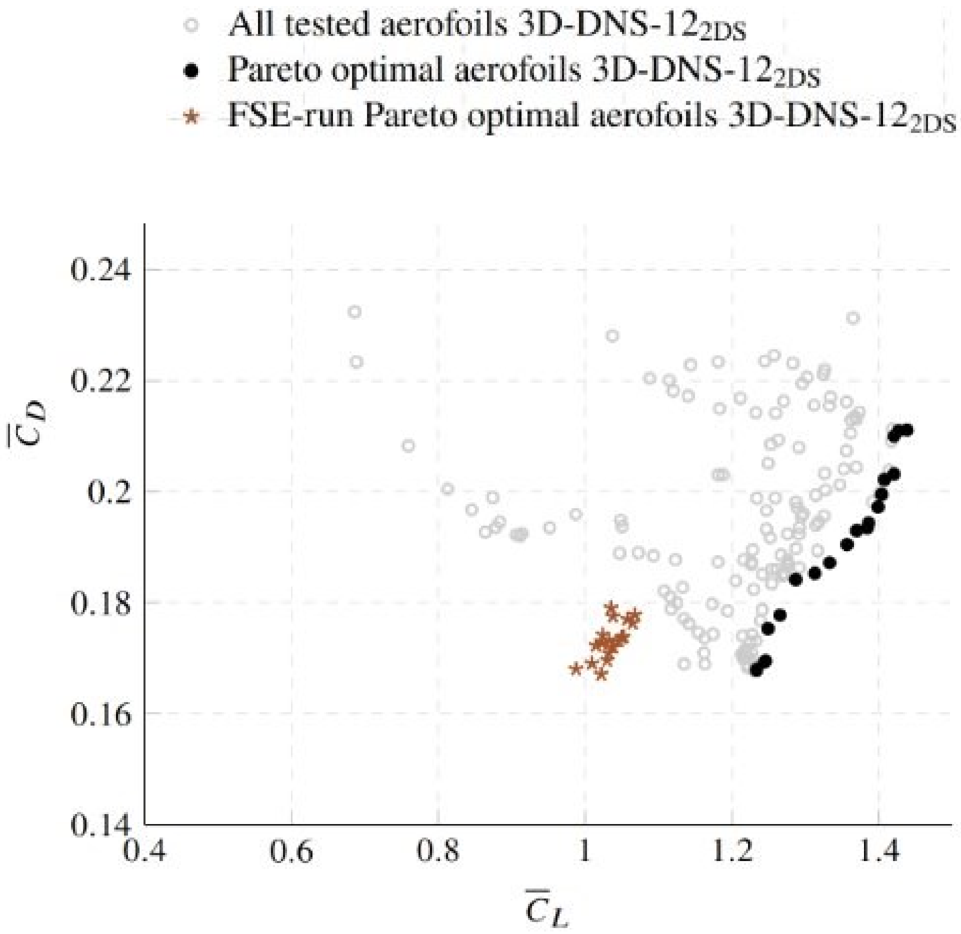
Effects of free-stream eddies on optimised airfoils



Optimisation with free-stream eddies

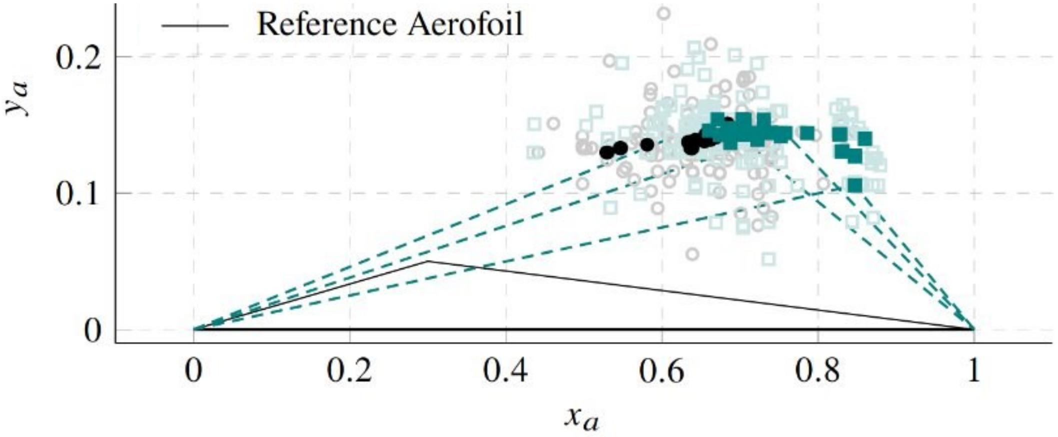
How would optimum airfoils look like if we optimised them with free-stream eddies?

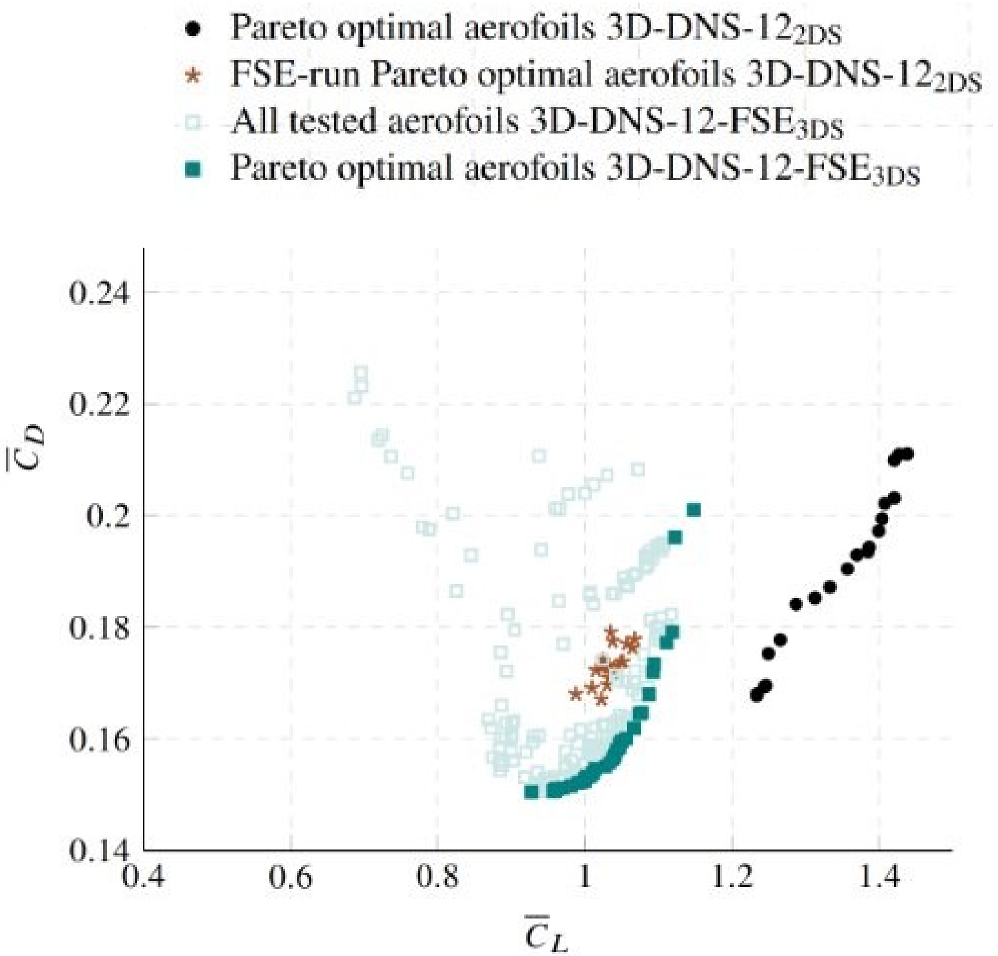




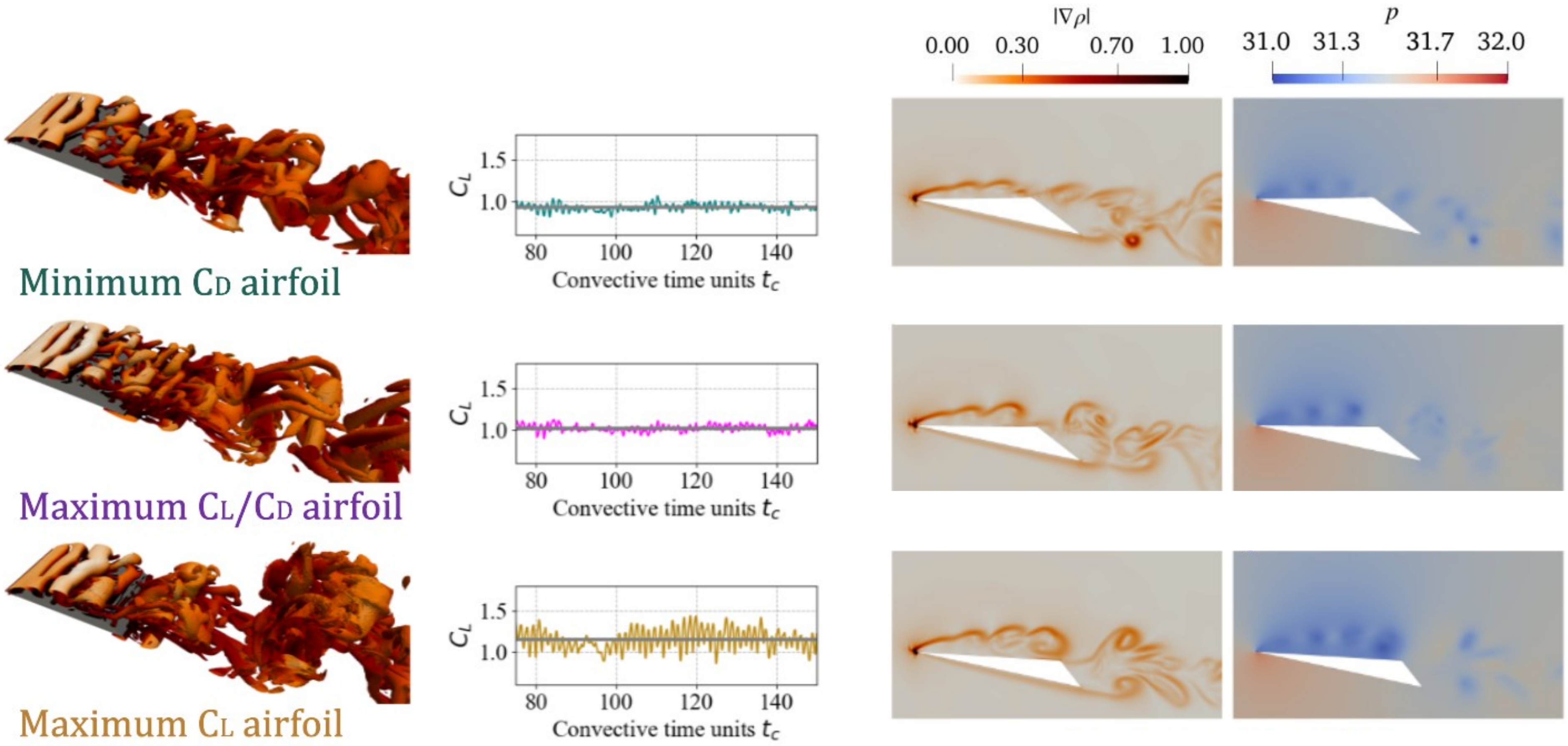
Optimisation with free-stream eddies

- Optimum airfoils under free-stream eddies show apexes towards the trailing edge.



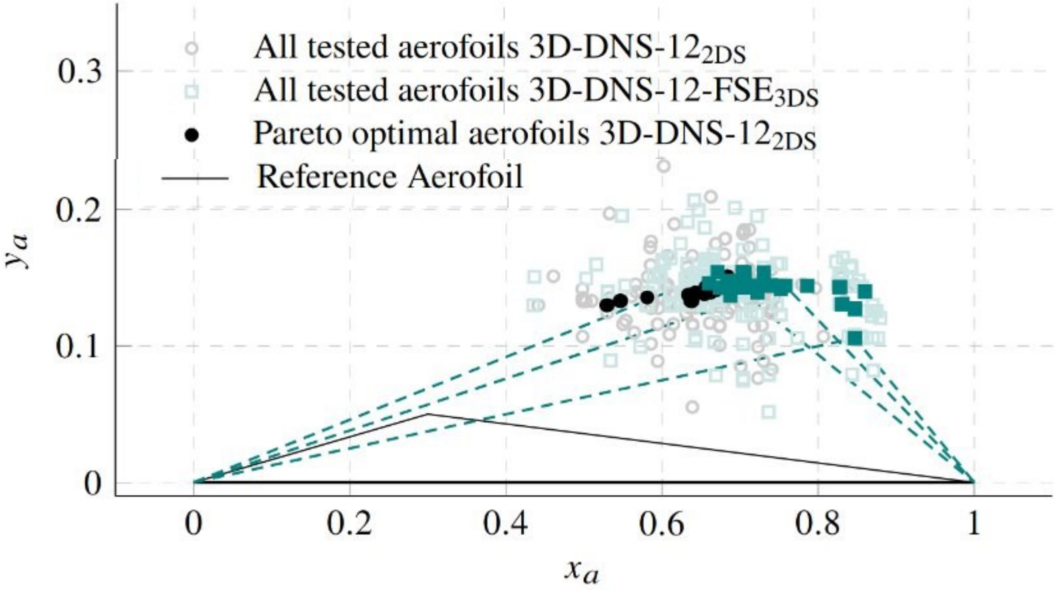


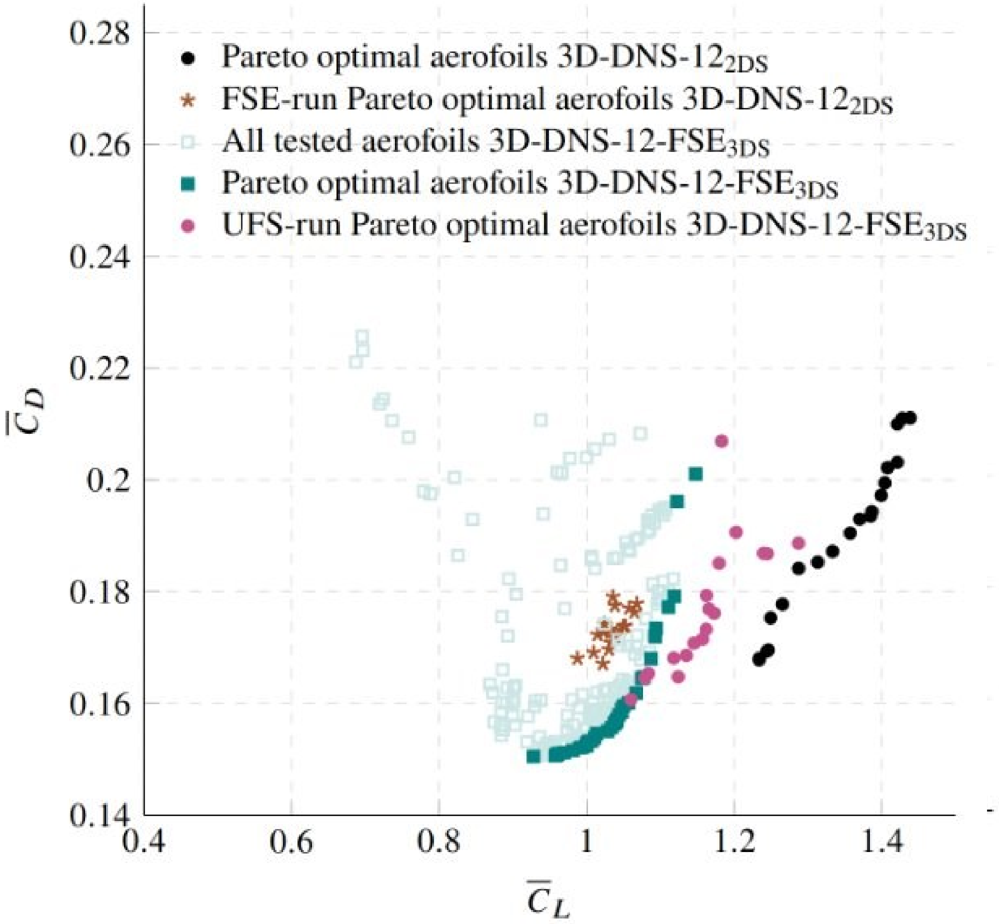
Optimisation with free-stream eddies



Optimisation with free-stream eddies

- Pareto Front from optimisation with free-stream eddies run under **uniform free-stream conditions**
- **Multi-point** optimisation





Outline

- Introduction
- Optimisation setup
- Optimisation results
- Effects of free-stream eddies on optimised airfoils
- Summary and Next Steps

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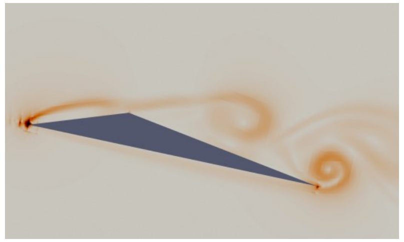
Summary

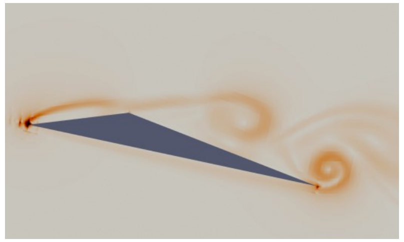


- **Martian conditions -** low Reynolds number, high Mach number - **not typical on Earth**
  - Airfoils with **sharp leading edges** offer good performance – unexplored field

- **Optimisation** using high order accurate **DNS** with PyFR
  - Improved efficiency by **exploiting** the separation of the flow and **vortex roll-up**.

- **Effects of free-stream eddies**
  - Free-stream eddies **break** the **coherent structures** and **regularise performance** of different airfoils.
  - Optimised airfoils extend area to maximise the suction of vortex roll-up.

Summary



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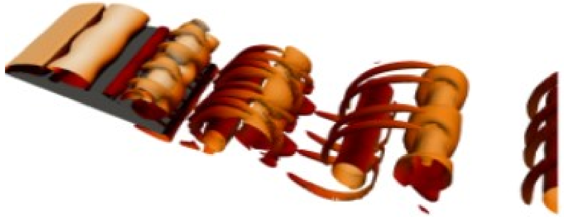

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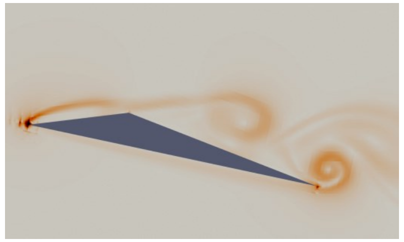

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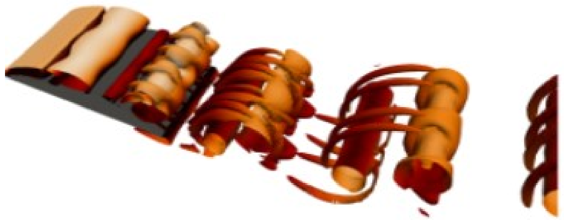

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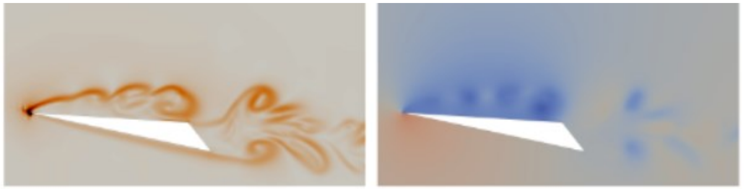

Next Steps

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Thank you

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