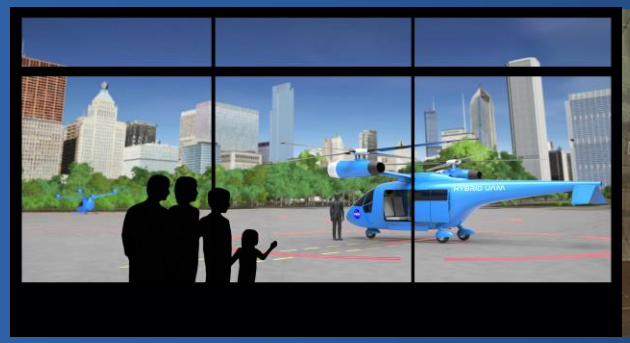
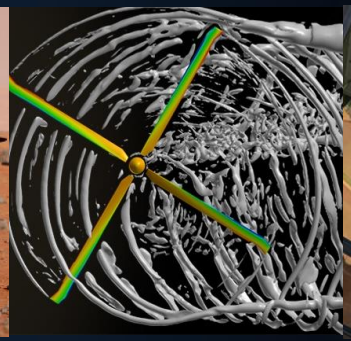
# Rotor Design for Mars Helicopters: Overcoming Aerodynamic Challenges for Future Mars Exploration

**Witold J. F. Koning,[1] B. Natalia Perez Perez,[1] Haley V. Cummings,[2] Ethan A. Romander[2] and Wayne Johnson[2]**

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**Advanced Modeling & Simulation (AMS) Seminar Series**
**NASA Ames Research Center, March 27th, 2025**




# Goal

*“Provide the methodology to optimize unconventional airfoils and use them effectively to optimize rotor hover performance at Mars conditions.”*

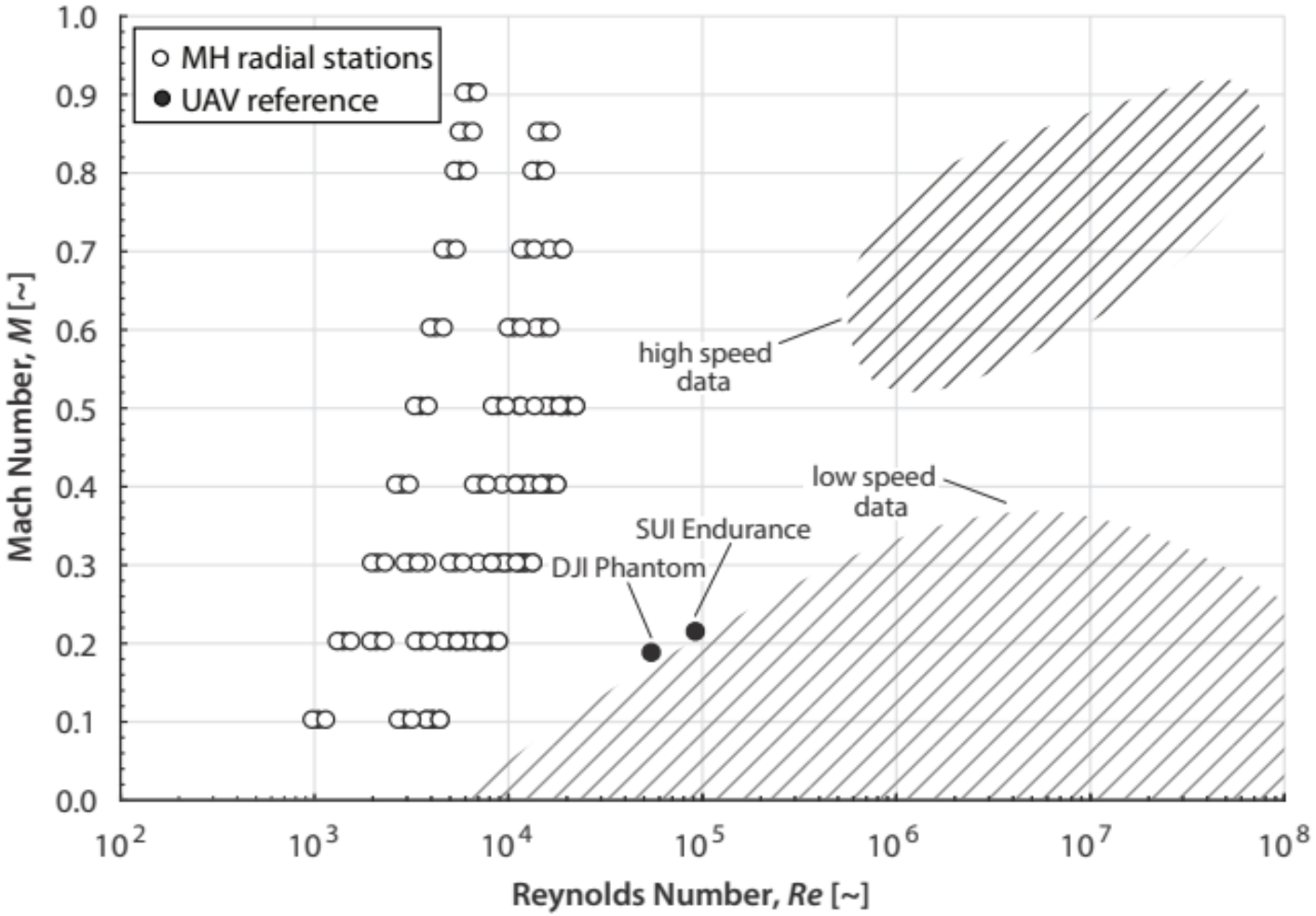
# Outline

- Why Flying a Helicopter on Mars is Hard
  - Challenges for efficient airfoil performance
  - Ingenuity's clf5605 airfoil
  - How to improve performance
- The ELISA Optimization Toolset
  - High-level Overview
  - Airfoil Parameterization and Optimization
  - Rotor Optimization
- Validation & Verification Efforts
- Conclusions



Mars Science Helicopter (MSH) hexacopter

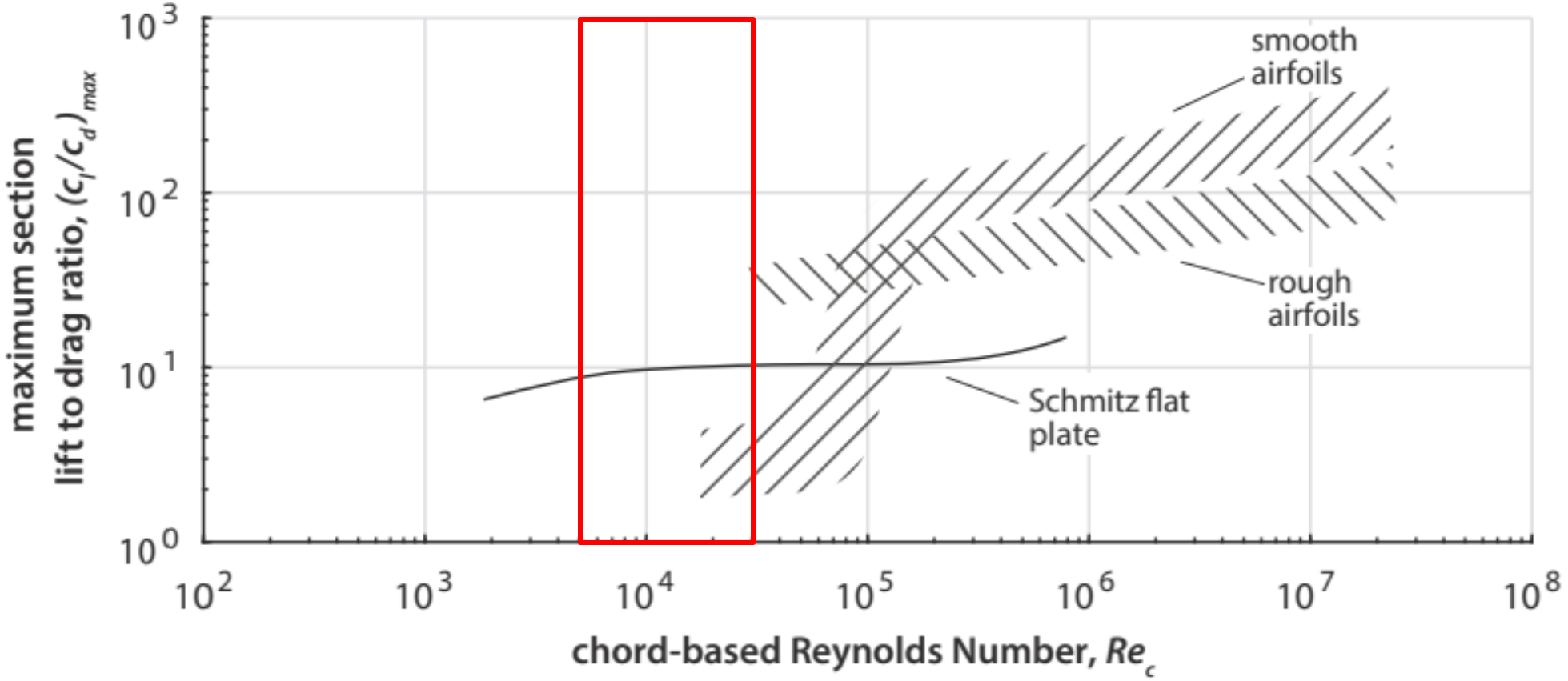
# Unexplored Aerodynamic Regime




- Low atmospheric density -> low Reynolds number
- Maximize rotor RPM to increase lift -> high (subsonic) Mach number

Koning, W. J. F., Johnson, W., Allan, B. G., "Generation of Mars Helicopter Rotor Model for Comprehensive Analyses," AHS Technical Meeting on Aeromechanics Design for Vertical Lift, Holiday Inn at Fisherman's Wharf, San Francisco, CA, January 16–18, 2018.

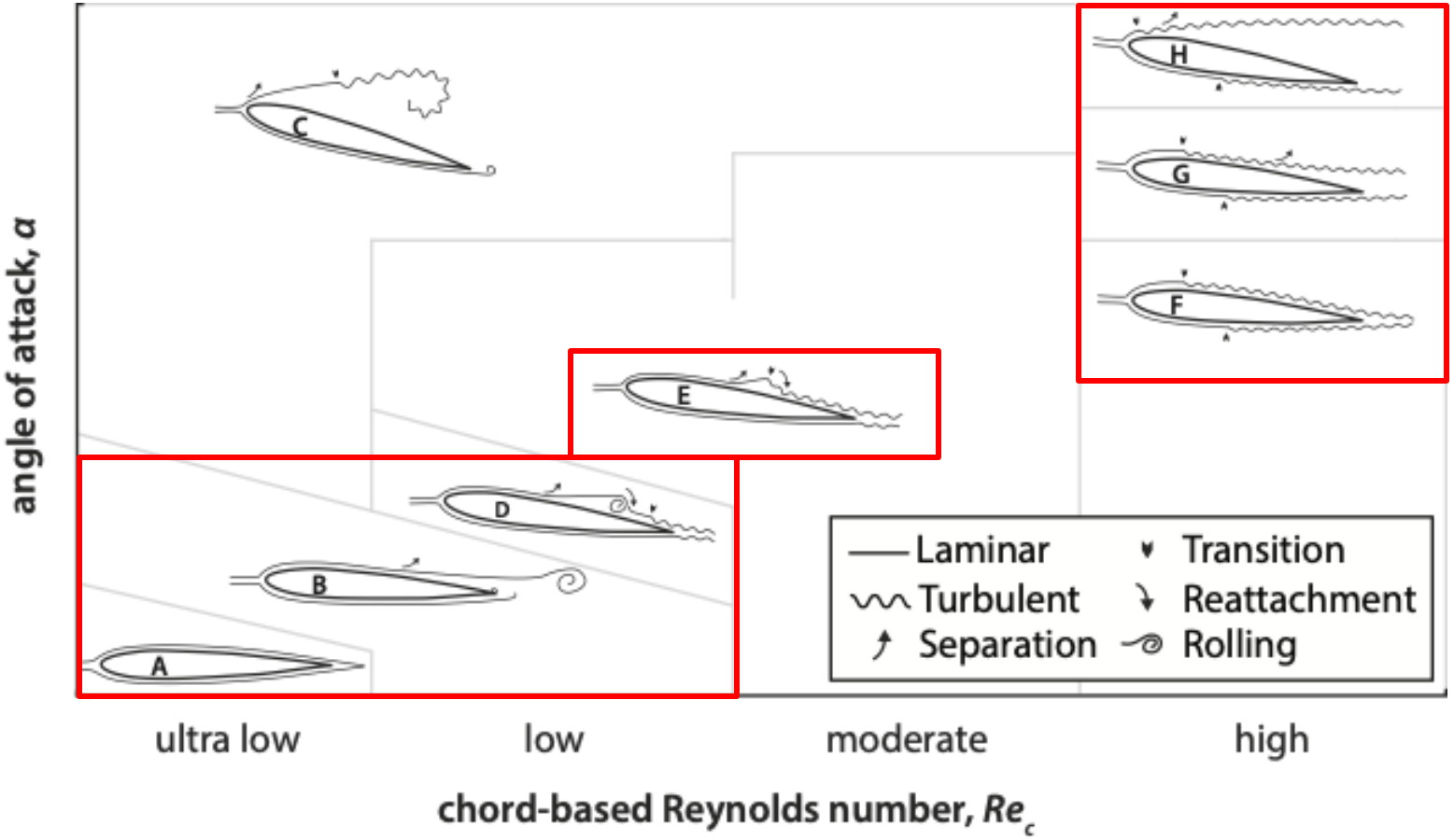
# Unexplored Aerodynamic Regime




- It doesn't look good for airfoil efficiency...

*Adapted from:* McMasters, J. and Henderson, M., "Low-speed single-element airfoil synthesis," Technical Soaring, vol. 6, no. 2, pp. 1–21, 1980.

# Low Reynolds Number Flow States




- Experimental flow states over NACA 0012

*Adapted from:* Wang, S., Zhou, Y., Alam, M. M., and Yang, H., "Turbulent Intensity and Reynolds Number Effects on an Airfoil at Low Reynolds Numbers," *Physics of Fluids*, Vol. 26, Nov. 2014, Paper 115107. https://doi.org/10.1063/1.4901969

# Ingenuity's Approach

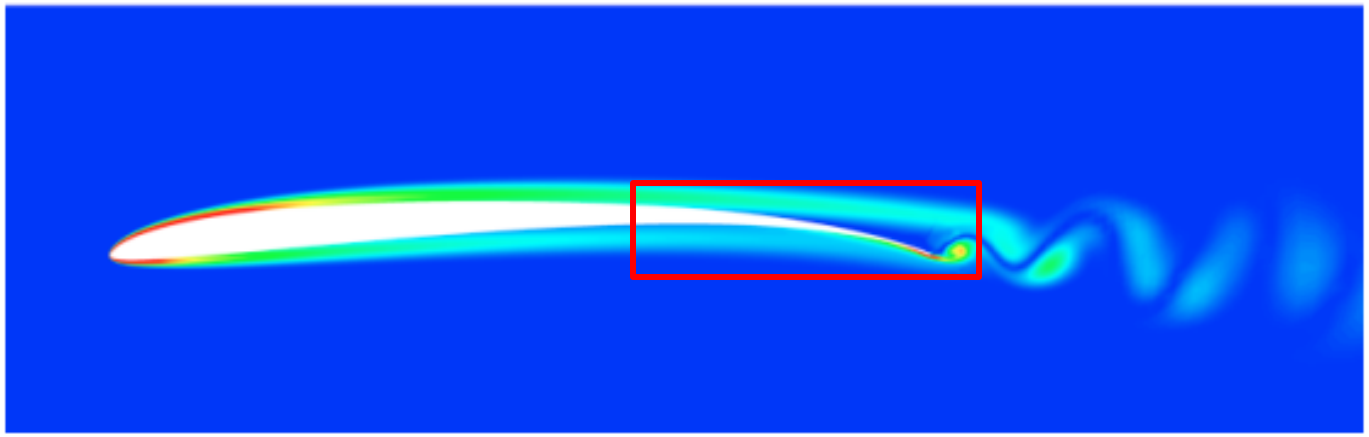


**Figure 19.** Attached laminar boundary layer with separation near trailing edge at $r/R = 0.76, \alpha = 1.00°, M = 0.50$ (vorticity magnitude, time-accurate, with transition model)

- Ingenuity's approach was to try and maintain a laminar boundary layer as long as possible
- The Continuous Laminar Flow (CLF) airfoil: clf5605
- The only good choice to be made at the time

Koning, W. J. F., Johnson, W., Grip, H., "Improved Mars Helicopter Aerodynamic Rotor Model for Comprehensive Analyses," Presented at the 44th European Rotorcraft Forum, Delft, the Netherlands, 18-21 September 2018.

# Ingenuity's Approach

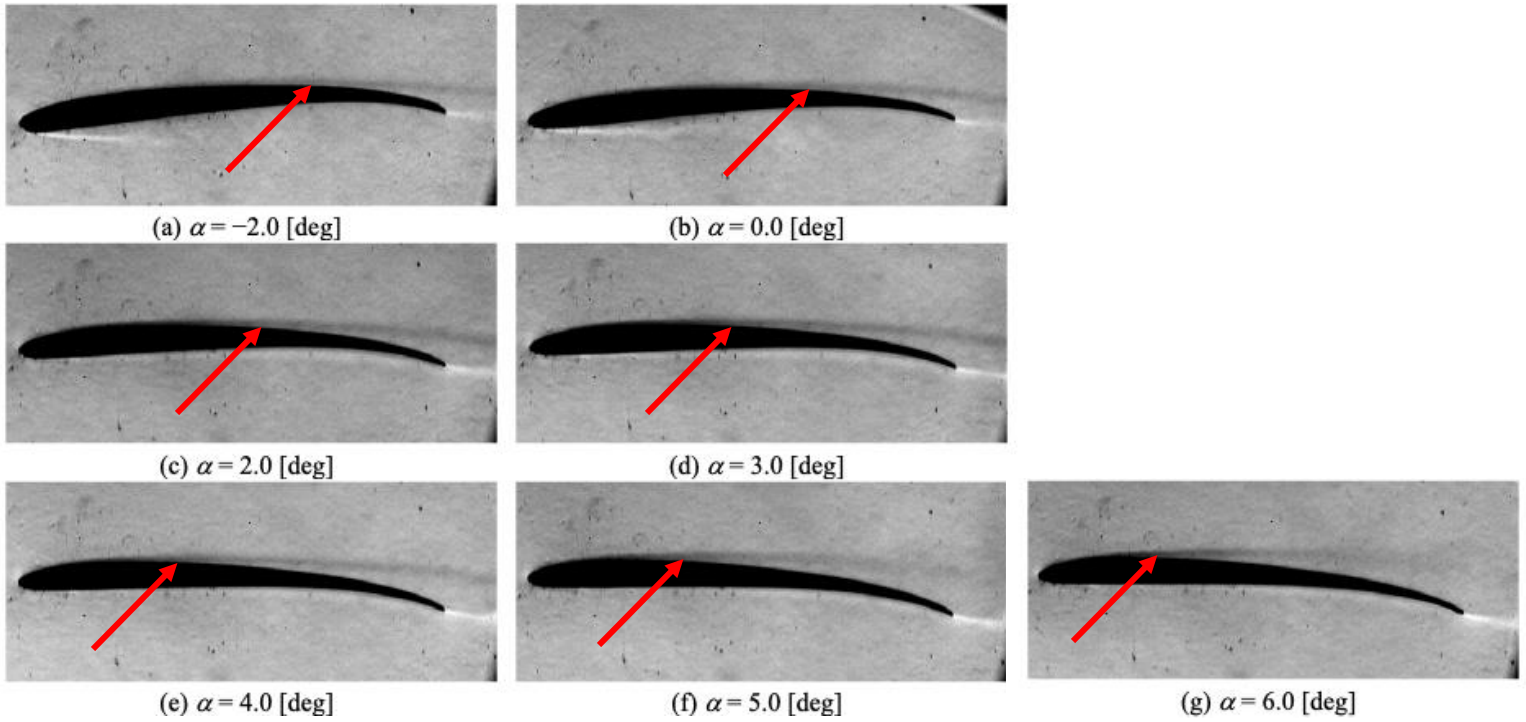



Figure 13. Instantaneous Schlieren images of flow over the clf5605-us-s model.

- However, it seems that it is not entirely possible, and separation is still happening, even at low-moderate angles of attack
- Recent tunnel results (collaboration with Tohoku University, Japan, and Imperial College, London) have confirmed this
- Re = 20,000, M = 0.60

Koning, W.J.F., Perez Perez, N., Cummings, H., Nagata, T., Kanzaki, Y., Kasai, M., Miyagi, M., Nonomura, T., Asai, K., Caros, L., Buxton, O., Vincent, P., "Experimental Results for Mars Rotorcraft Airfoils (roamx-0201 and clf5605) at Low Reynolds Number and Compressible Flow in a Mars Wind Tunnel," NASA–TM–20240004230.

# Back to the Drawing Board

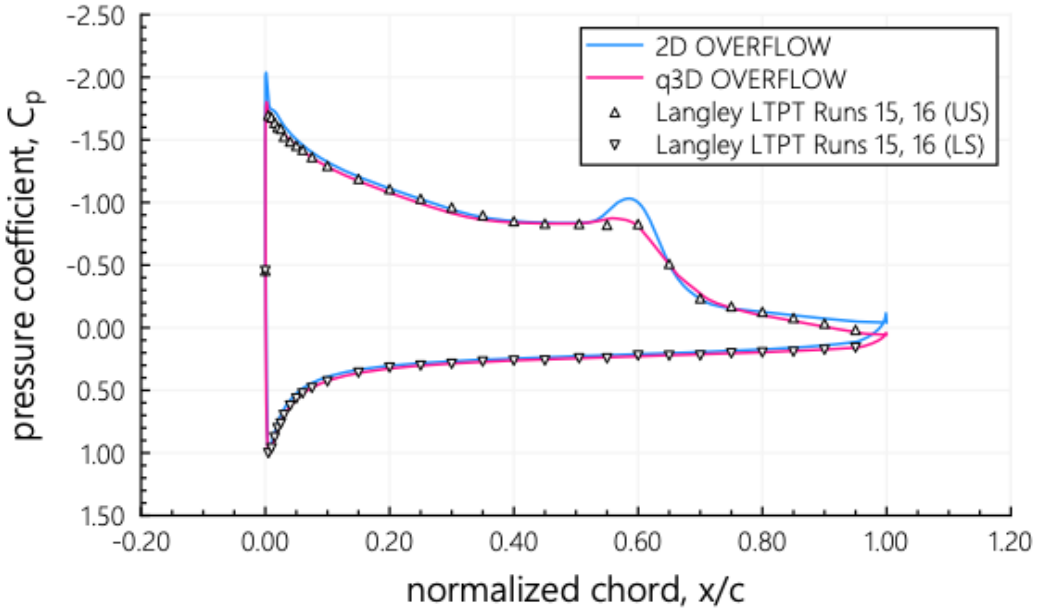
- So…what else can we do?
  - Cambered plates look promising, but why?
  - Try to provoke separation-reattachment, but how?

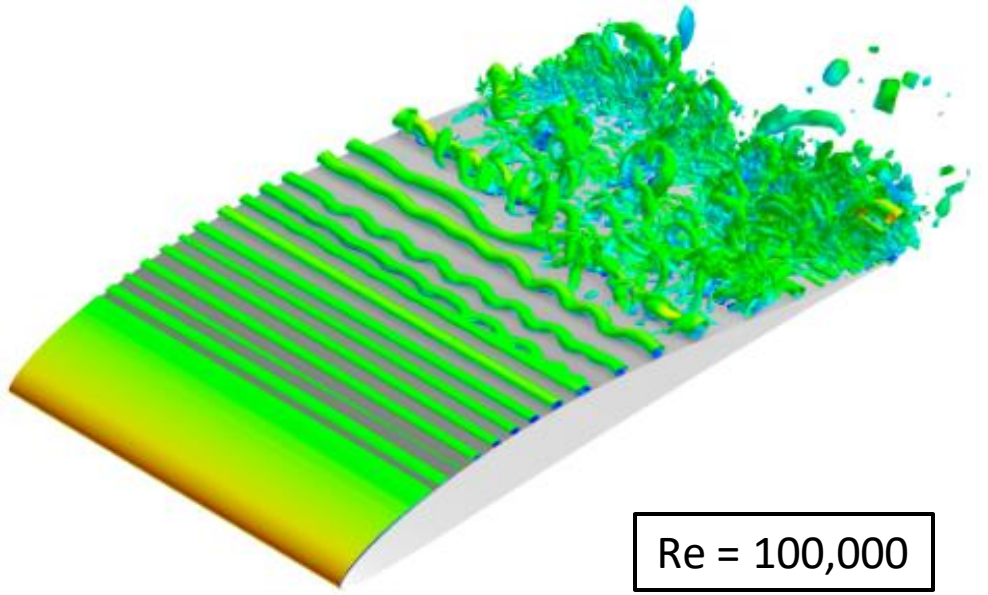
Table 1. Overview of candidate airfoil shapes evaluated for $Re_c$ =

| Airfoil Geometry | Re and FST Sensitivity | Hysteresis With Condition | Demonstrated Concept | Co |
|---|---|---|---|---|
| Conventional airfoil  | Large sensitivity possible | Hysteresis possible (laminar separation bubble induced) | If outside of critical Reynolds number region; used for small unmanned aerial vehicles (UAVs) | Ca Re low tra op for |
| Tripped airfoil, rough airfoil  | If transition is fixed, sensitivity is minimized | Hysteresis possible if bubble occurs before trip | Difficult to ensure trip works below *Re* = 30,000; uncertain at higher *Re* < 100,000 | Tra be co un dy |
| Cambered plate, curved plate  | Leading-edge separation of large angle-of-attack range reduces sensitivity | Hysteresis less likely because of majority of operating conditions with leading-edge separation | Used for small UAVs or manned aerial vehicles (MAVs) | Po iss thi (t/ |
| Corrugated airfoil  | Separation at corrugation features likely to reduce sensitivity | Hysteresis less likely because of separation at corrugation features | No rotary-wing experiments using corrugated airfoils known | Pe co Re |
| Polygonal airfoil  | Separation at corrugation features likely to reduce sensitivity | Hysteresis less likely because of separation at corrugation features | No rotary-wing experiments using polygonal airfoils known | Po sti inc to |

Koning, W.J.F., "Airfoil Selection for Mars Rotor Applications," NASA/CR–2019–220236

# Reattachment Without Turbulence?



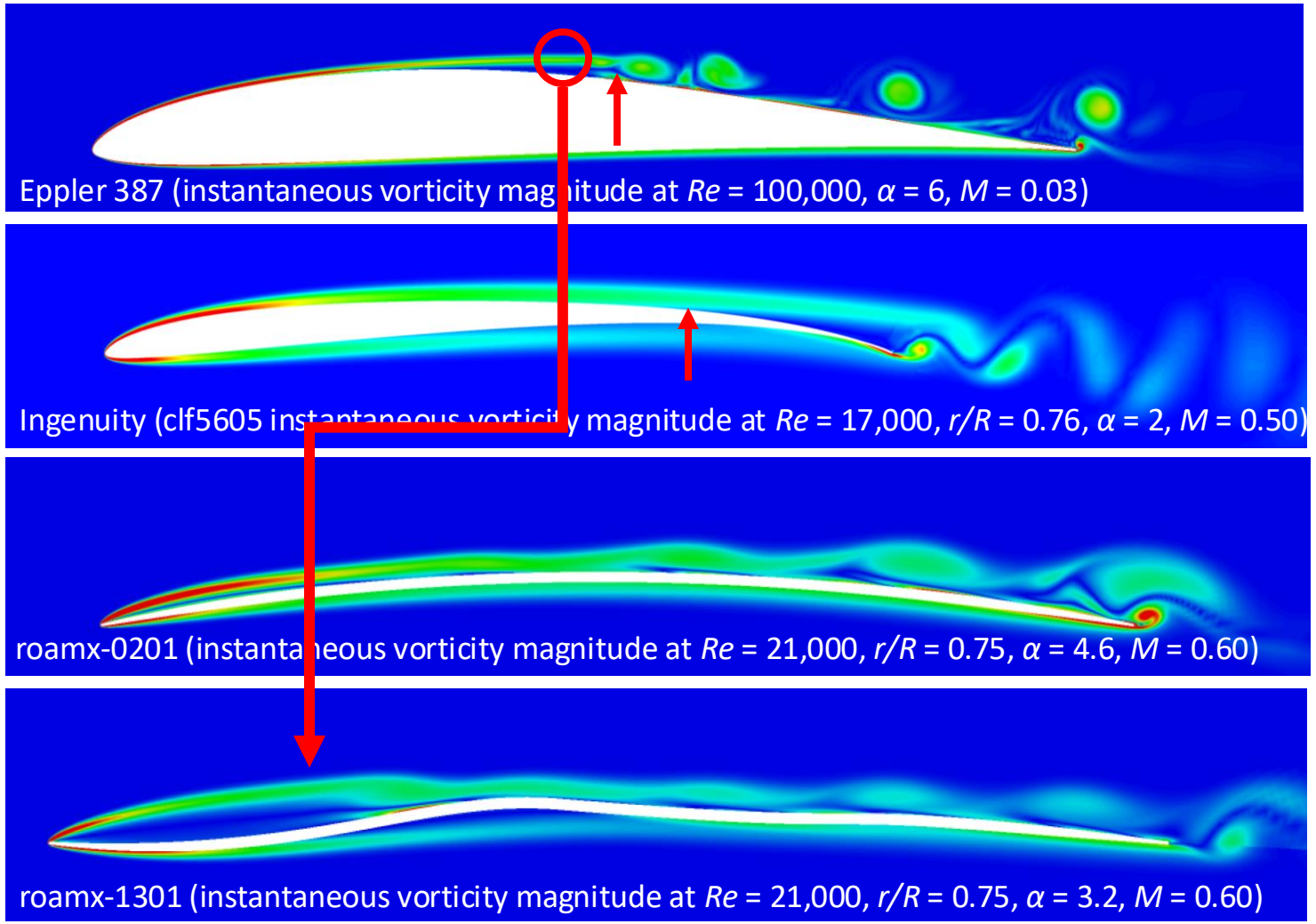



Re = 100,000

- Chance for transition of Tollmien-Schlichting waves is very low at extremely low Reynolds numbers.
- So how can we provoke transition and reattachment?

Koning, W., Romander, E., Cummings, H., Perez Perez, B.N. and Buning, P., "On Improved Understanding of Airfoil Performance Evaluation Methods at Low Reynolds Numbers," Journal of Aircraft, Volume 60, No. 2, March 2023.

# Reattachment Without Turbulence?




**Conventional airfoils**

- Laminar separation bubbles at low Re
  - T-S based transition to small-scale turbulence (steady reattachment)
  - Large-scale instabilities vortex shedding (unsteady reattachment)

**Ingenuity**

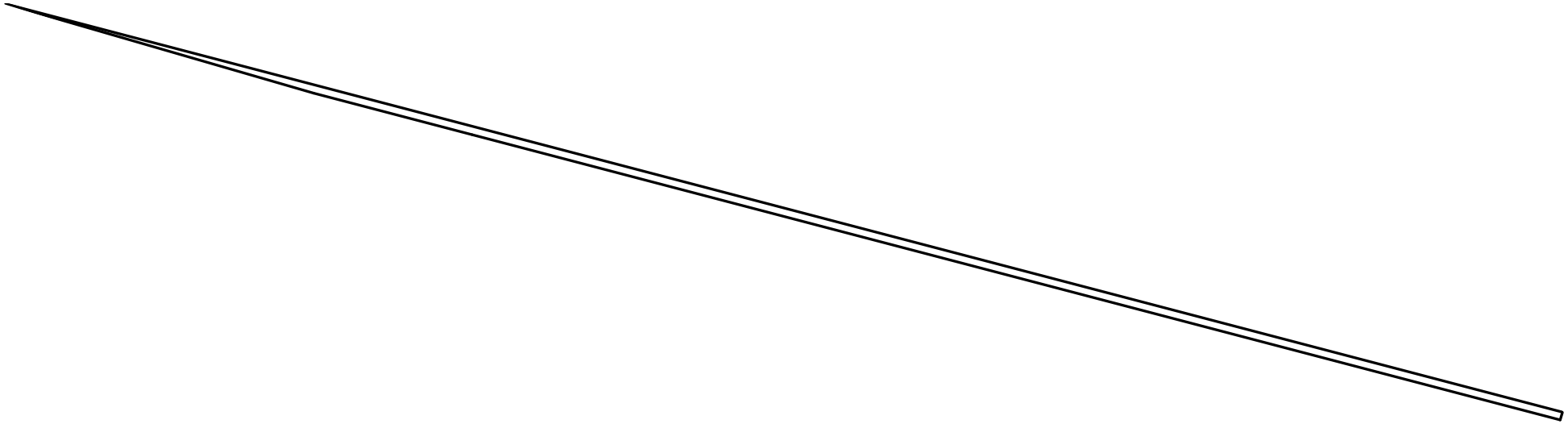
- Re too low for LSB or classic BL trips
- Solution: prolong laminar BL as long as possible
- Still separates; not truly full laminar BL

**ROAMX / unconventional airfoils**

- Trigger large-scale instabilities with sharp leading edge
- Separation location fixed
- Time-averaged ‘turbulent’ reattachment at very low Re
  - Parallel idea to mechanisms realizing conventional high Re performance
  - No trailing edge separation, higher adverse pressure gradient (APG) resistance
  - 1301 concept creates space for instabilities to develop - an ‘air trip’ if you will

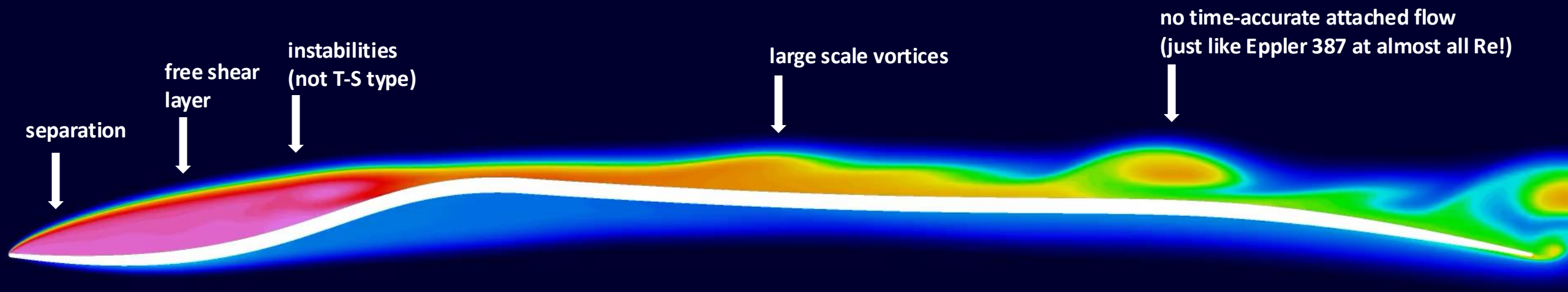
Koning, W., Romander, E., Cummings, H., Perez Perez, B.N. and Buning, P., "On Improved Understanding of Airfoil Performance Evaluation Methods at Low Reynolds Numbers," Journal of Aircraft, Volume 60, No. 2, March 2023; Koning, W. J. F., Johnson, W., Grip, H., "Improved Mars Helicopter Aerodynamic Rotor Model for Comprehensive Analyses," Presented at the 44th European Rotorcraft Forum, Delft, the Netherlands, 18-21 September 2018; Koning, W., Perez Perez, N., Cummings, H., Romander, E., Johnson, W., "ELISA: A Tool for Optimization of Rotor Hover Performance at Low Reynolds Number in the Mars Atmosphere," Journal of the American Helicopter Society, Volume 69, Number 4, October 2024, pp. 1-15(15).

# Reattachment Without Turbulence?



Koning, W.J.F., Romander, E.A., Johnson, W., "Optimization of Low Reynolds Number Airfoils for Martian Rotor Applications Using an Evolutionary Algorithm" Presented at the AIAA Science and Technology Forum and Exposition (AIAA SciTech), Orlando, Florida, USA, January 6–10, 2020.

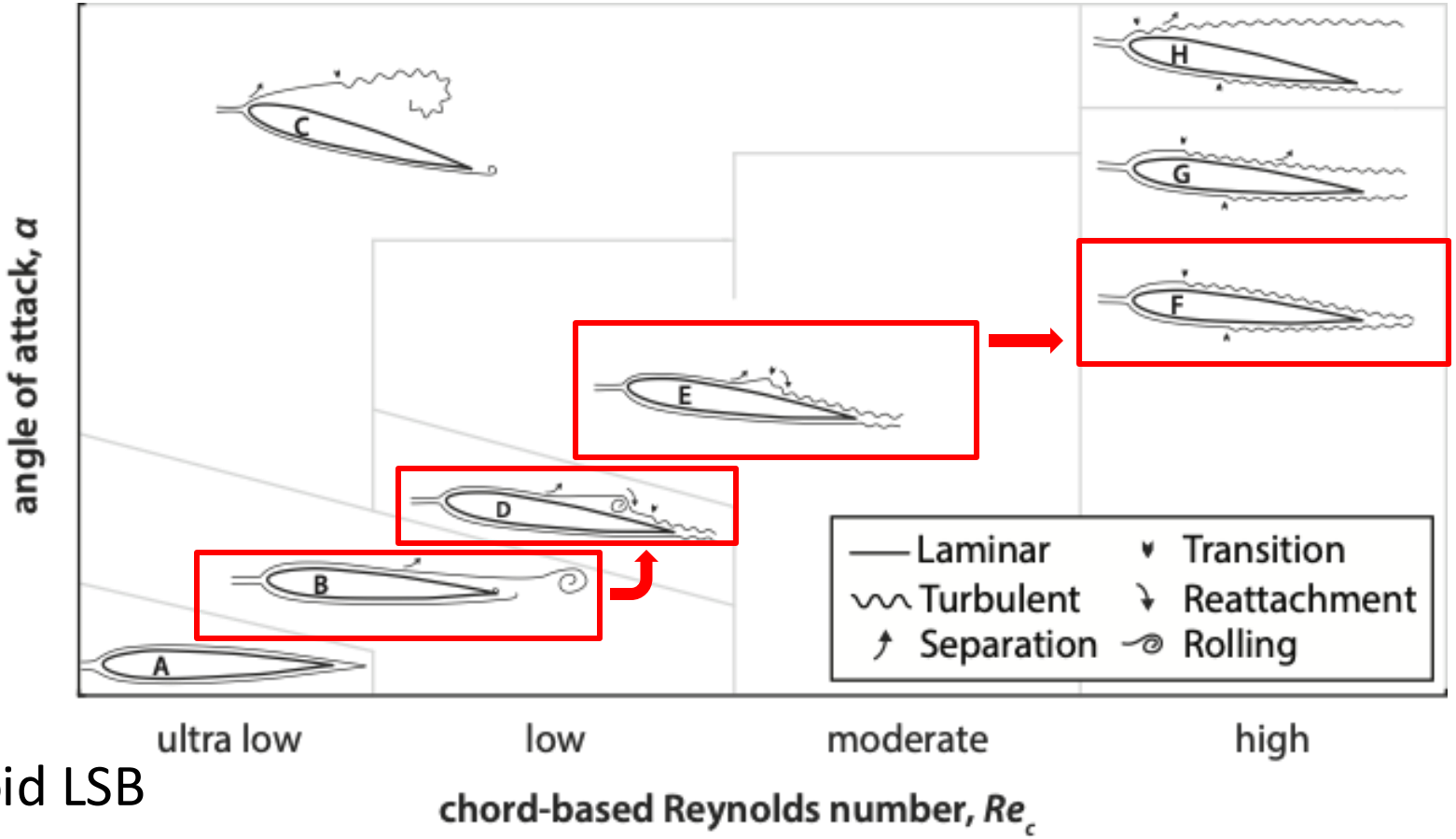
# Novel Airfoil Geometries




- roamx-1301 parameterization
- High-performance at low Reynolds number conditions
  - Forced leading edge separation results in separated shear layer;
  - Separated shear layer instabilities and interaction with airfoil;
  - Shear layer ‘gets caught’ further downstream;
  - Time-averaged $C_p$ looks like attached flow (similar to Eppler 387 at higher Re)

Koning, W., Perez Perez, N., Cummings, H., Romander, E., Johnson, W., "ELISA: A Tool for Optimization of Rotor Hover Performance at Low Reynolds Number in the Mars Atmosphere," Vertical Flight Society Sixth Decennial Aeromechanics Specialists' Conference, Santa Clara, CA, February 2024.

# Back: Low Reynolds Number Flow States




- Normally, avoid LSB
- Here, only means to increase performance

*Adapted from:* Wang, S., Zhou, Y., Alam, M. M., and Yang, H., "Turbulent Intensity and Reynolds Number Effects on an Airfoil at Low Reynolds Numbers," *Physics of Fluids*, Vol. 26, Nov. 2014, Paper 115107. https://doi.org/10.1063/1.4901969

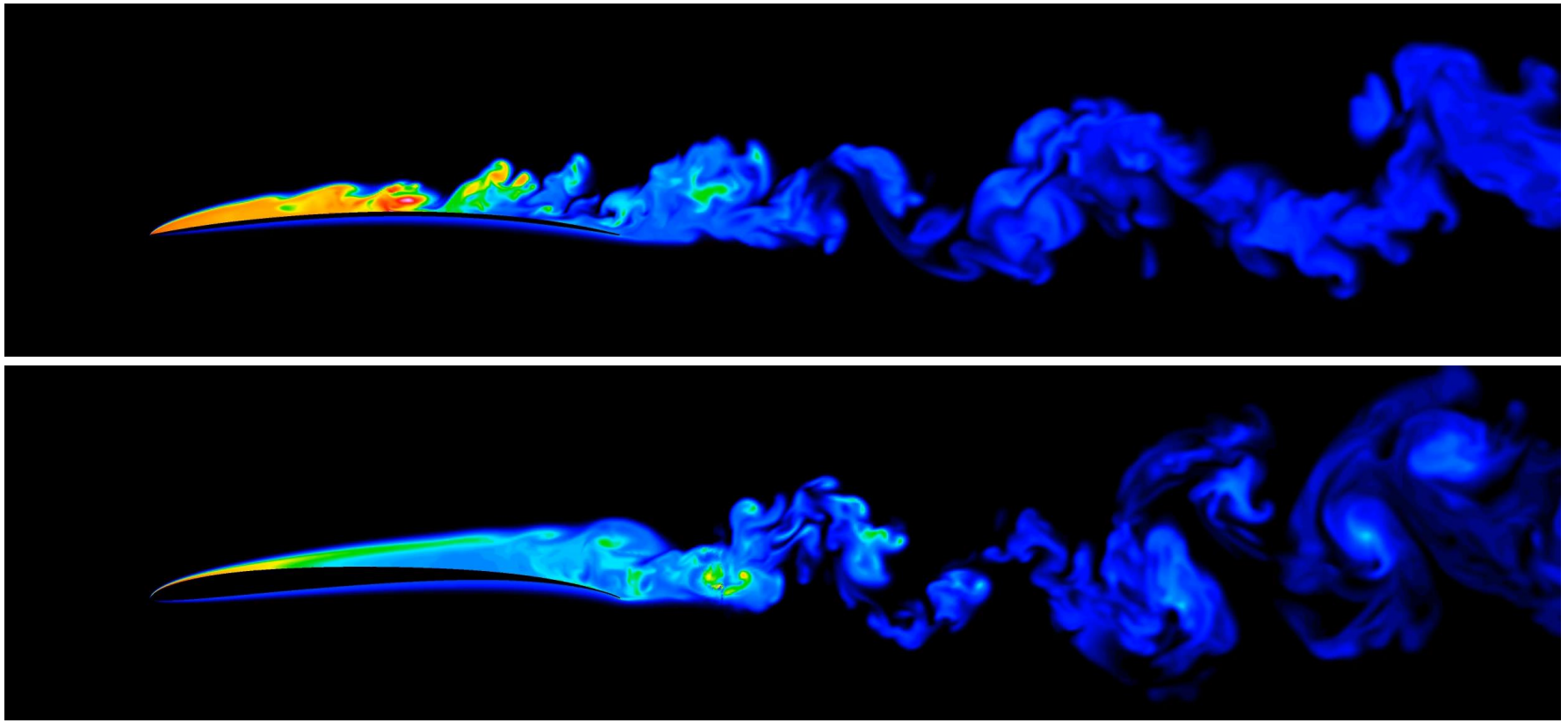
# The Start of ROAMX

- Chance for transition of Tollmien-Schlichting waves is very low at extremely low Reynolds numbers.
- Provoke separation and instabilities using a sharp leading edge.
- The Evolutionary Algorithm for Iterative Studies of Aeromechanics (ELISA) was developed under the Rotor Optimization for the Advancement of Mars eXploration (ROAMX) project to perform coupled airfoil and rotor optimization and investigate optimal aerodynamic efficiency

Cummings, H., Perez Perez, B.N., Koning, W., Johnson, W., Young, L., Haddad,F., Romander, E., Balaram,J.B., Tzanetos, T., Bowman, J., Wagner, L., Withrow–Maser, S., Isaacs, E., Toney, S., Shirazi, D., Conley, S., Pipenberg, B., Datta, A., Lumba, R., Chi, C., Smith, J.K., Cornelison, C., Perez, A., Nonomura, T., Asai, K., "Overview and Introduction of the Rotor Optimization for the Advancement of Mars eXploration (ROAMX) Project," Presented at the VFS Aeromechanics for Advanced Vertical Flight Technical Meeting, San Jose, CA, Jan 25-27, 2022.

# ELISA: High-level Overview

- Strong difference in flow fields
- Re = 20,000, M = 0.60, alpha = 6 degrees
- Quasi-3D, Unsteady “laminar” NS in OVERFLOW



# ELISA: High-level Overview

- The Evolutionary aLgorithm for Iterative Studies of Aeromechanics (ELISA)
- Dual consecutive Genetic Algorithms (GA) to perform sequential airfoil and rotor optimization
  - Airfoil optimization (section performance, OVERFLOW)
  - Rotor optimization (hover performance, CAMRAD II)
    - Linking the collection of optimal airfoils (as function of angle of attack) to the rotor optimization

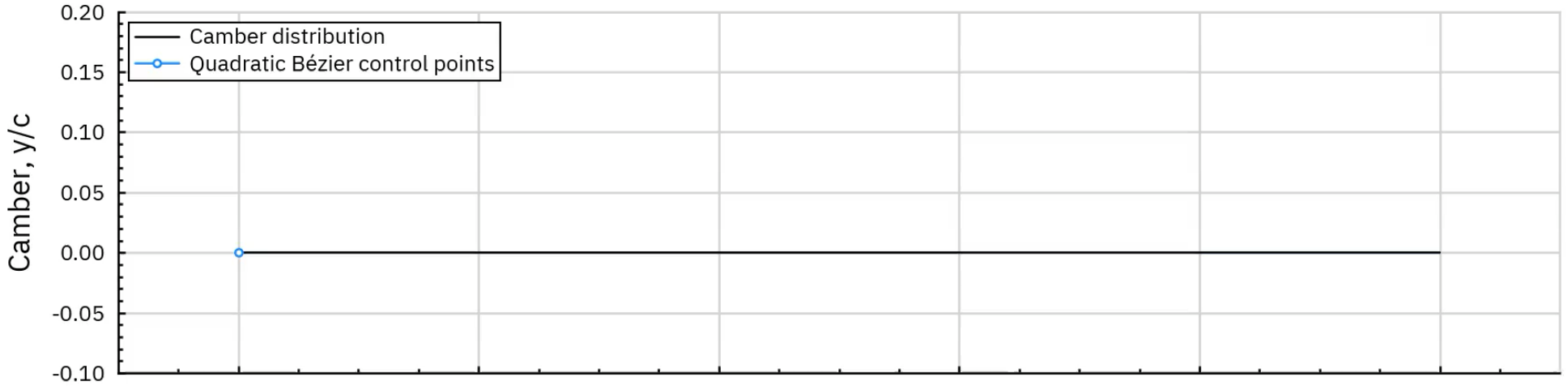
Koning, W., Perez Perez, N., Cummings, H., Romander, E., Johnson, W., "ELISA: A Tool for Optimization of Rotor Hover Performance at Low Reynolds Number in the Mars Atmosphere," Journal of the American Helicopter Society, Volume 69, Number 4, October 2024, pp. 1-15(15).

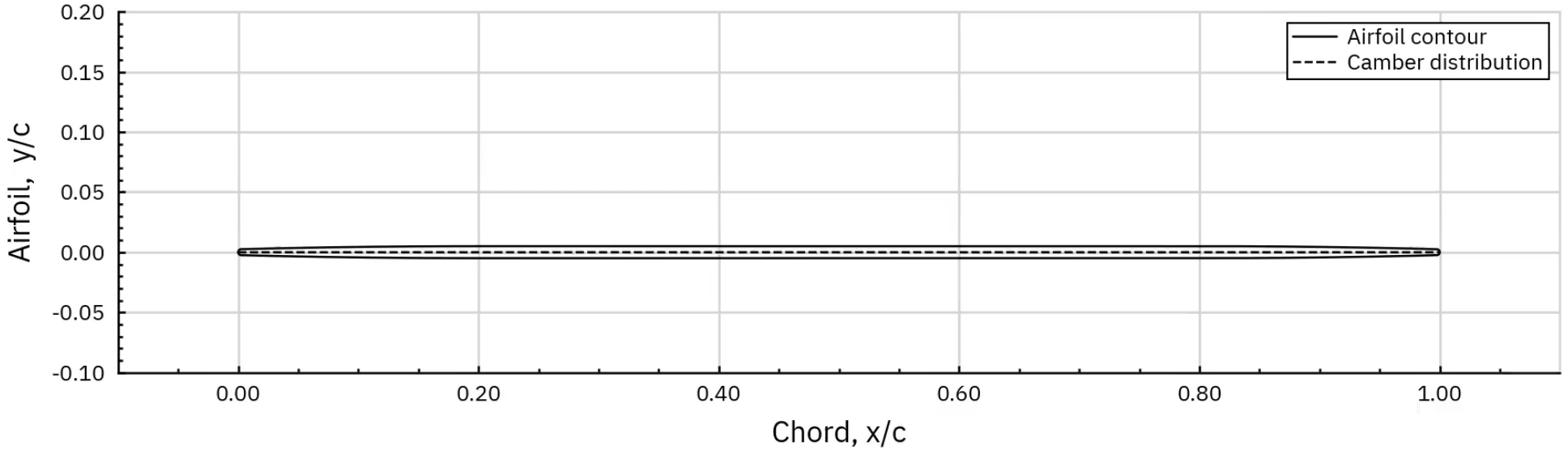
# ELISA: High-level Overview

- Multi-objective optimization with variety of objective choices
  - Up to three-objectives simultaneously
  - Airfoils: lift, drag, thickness ratio, (Reynolds number)
  - Rotors: blade loading, rotor power, (density)

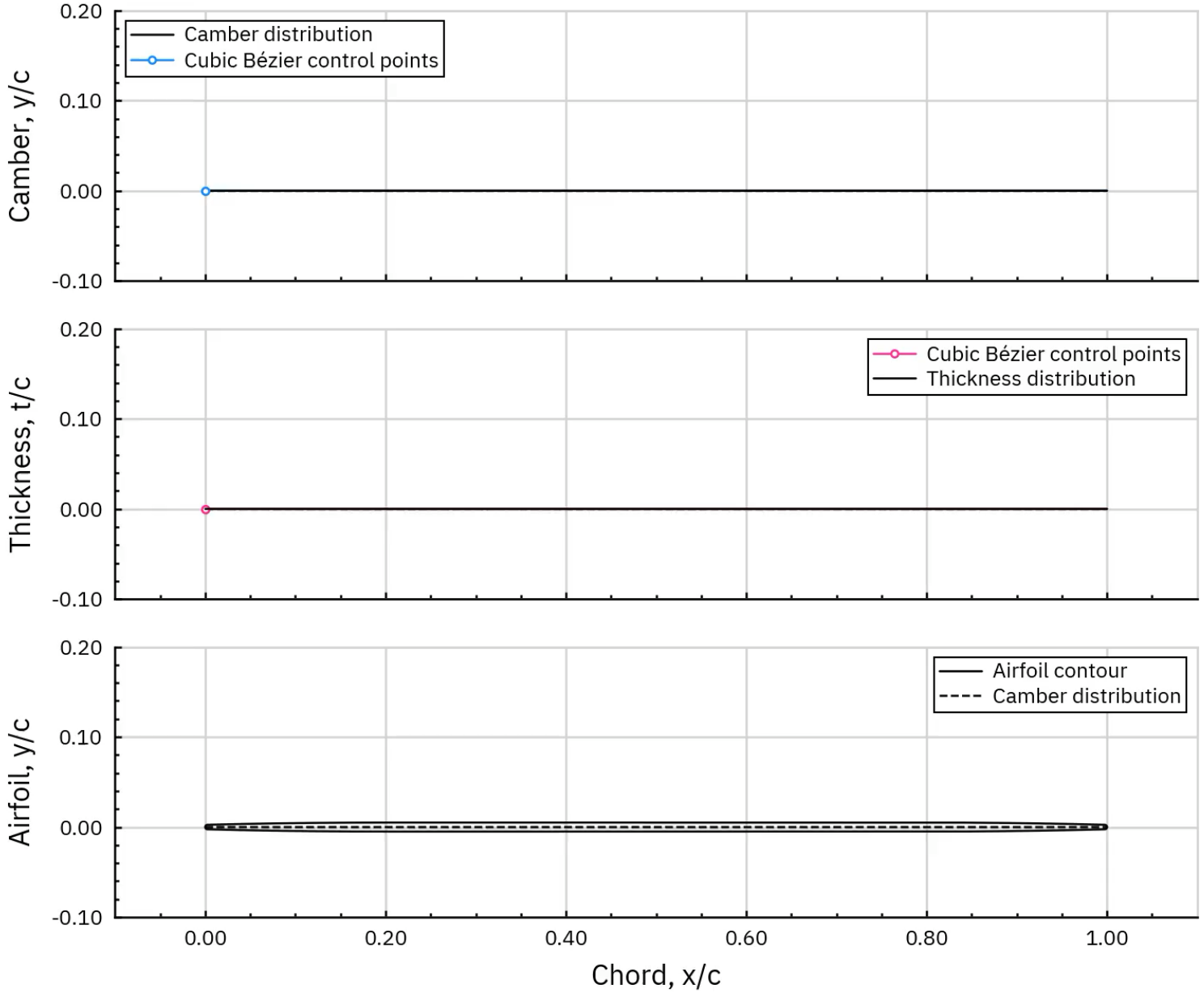
Koning, W., Perez Perez, N., Cummings, H., Romander, E., Johnson, W., "ELISA: A Tool for Optimization of Rotor Hover Performance at Low Reynolds Number in the Mars Atmosphere," Journal of the American Helicopter Society, Volume 69, Number 4, October 2024, pp. 1-15(15).

# ELISA: roamx-0201 Airfoil Parameterization

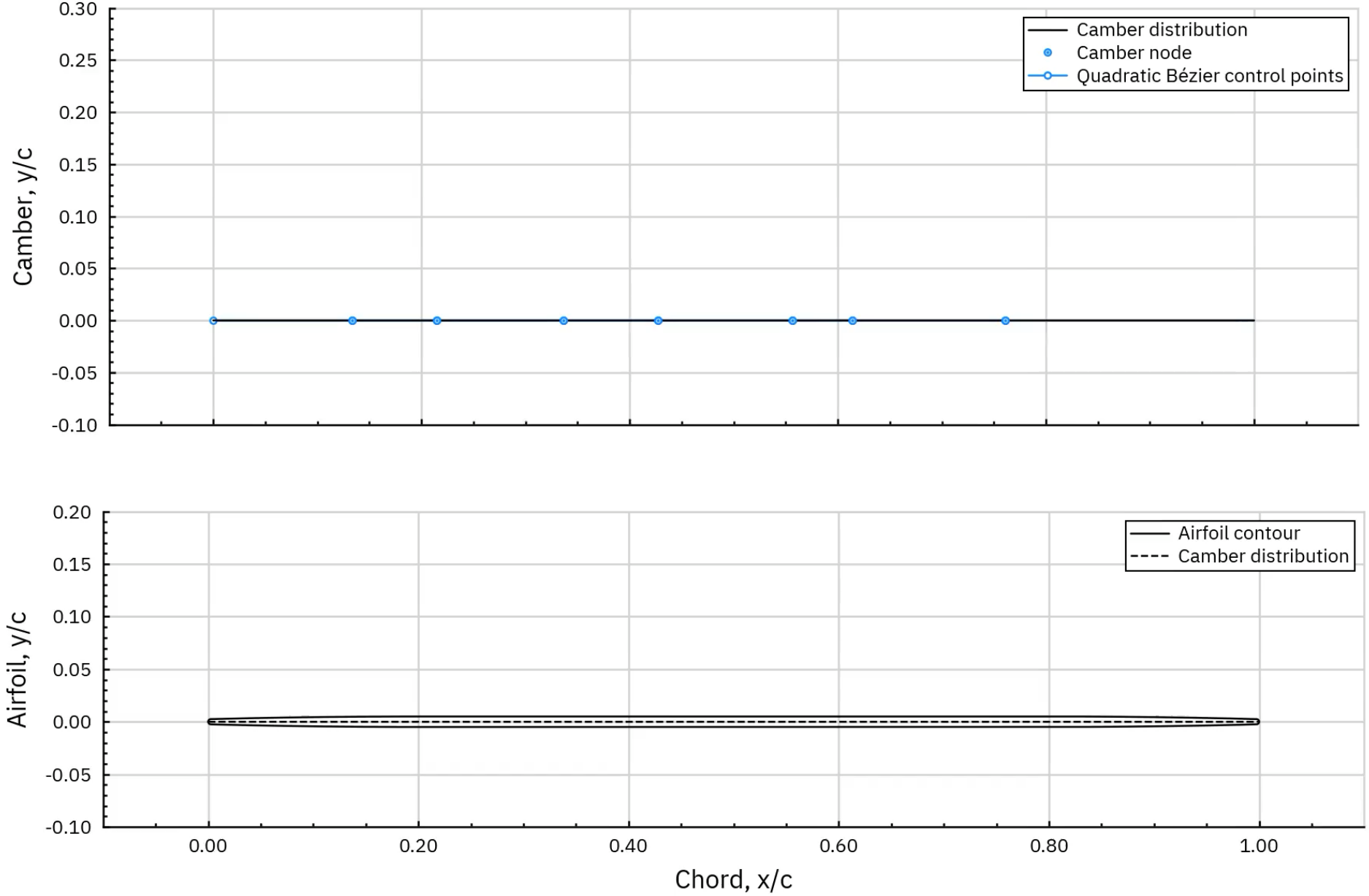


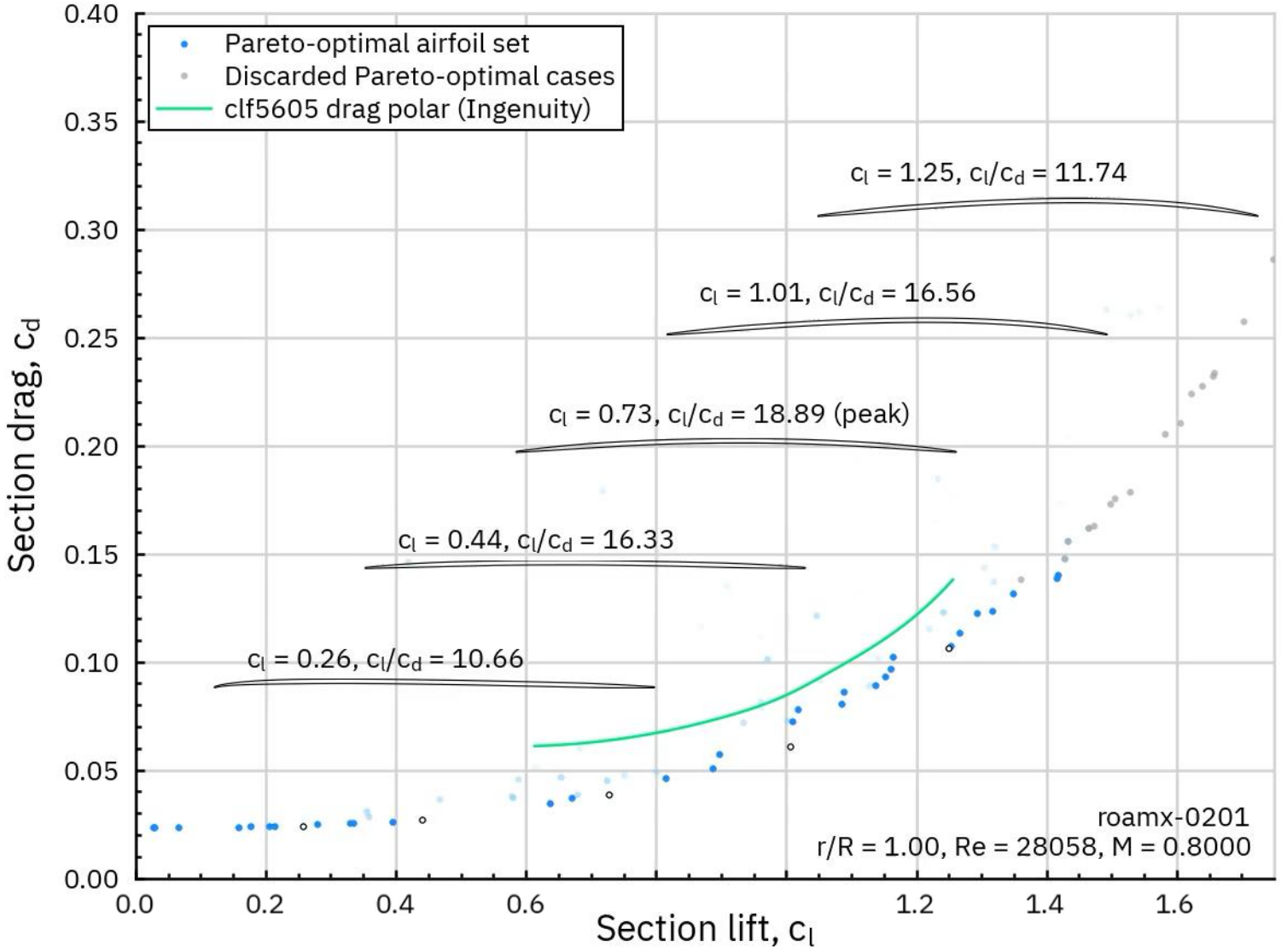
# ELISA: roamx-0303 Airfoil Parameterization

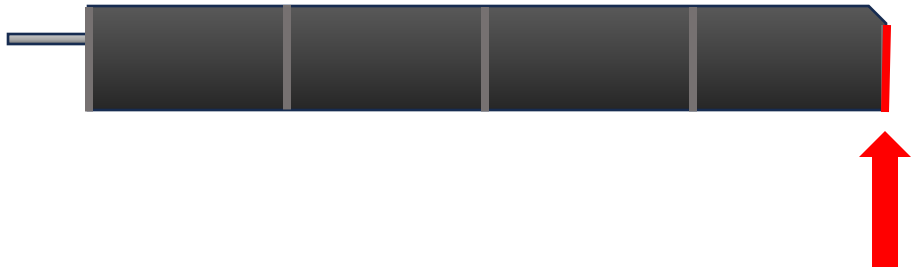


# ELISA: roamx-7201 Airfoil Parameterization



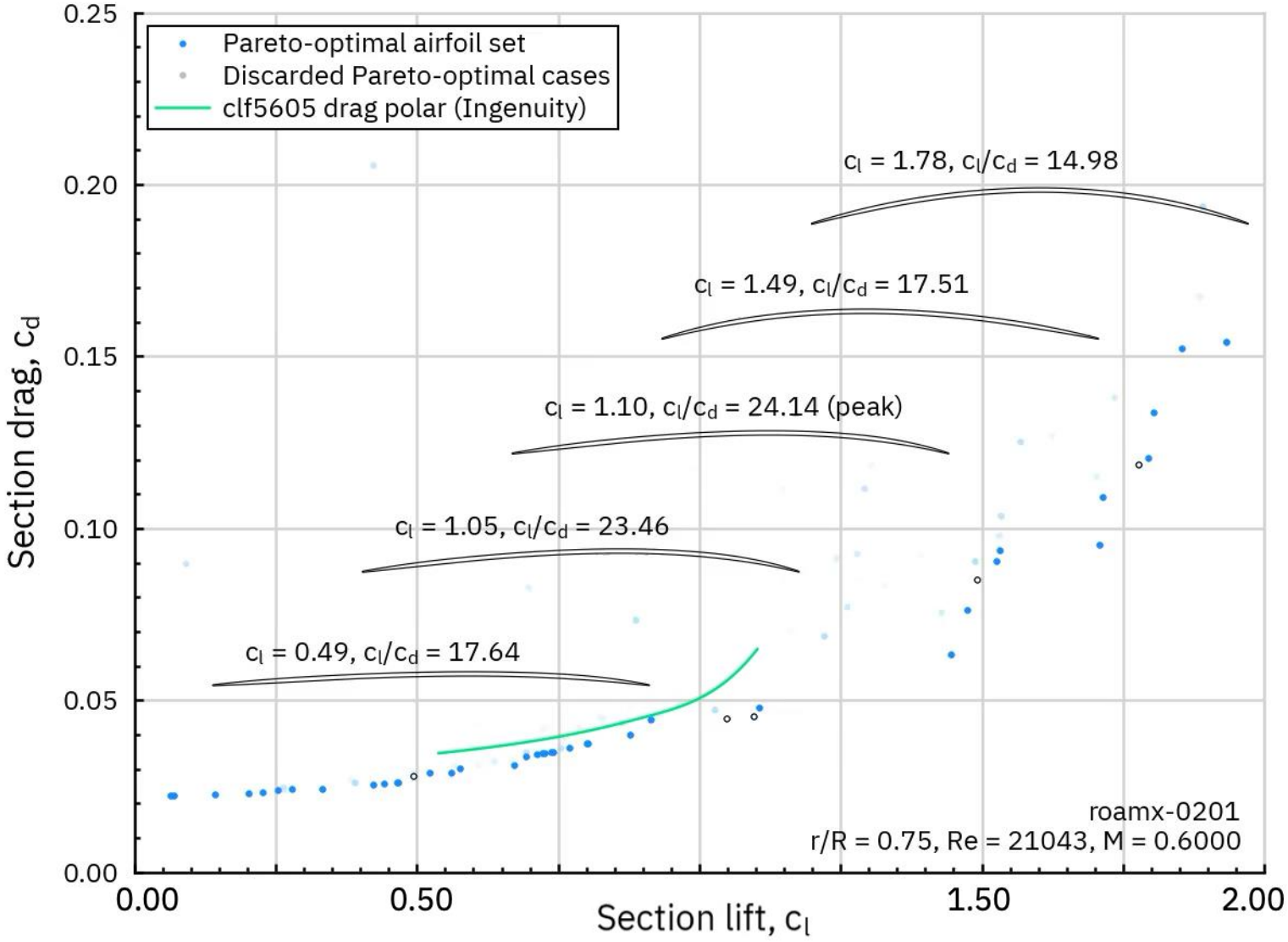
# Airfoil Optimization

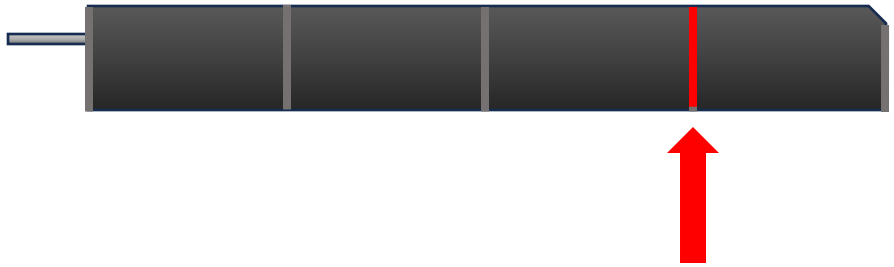


| Airfoil | $c_l/c_d$ (peak) | % change | $c_l/c_d$ ($c_l$ = 0.91) | % change |
|---|---|---|---|---|
| clf5605 | 12.15 | – | 12.15 | – |
| roamx-0201 | 19.99 | 65% | 19.58 | 61% |

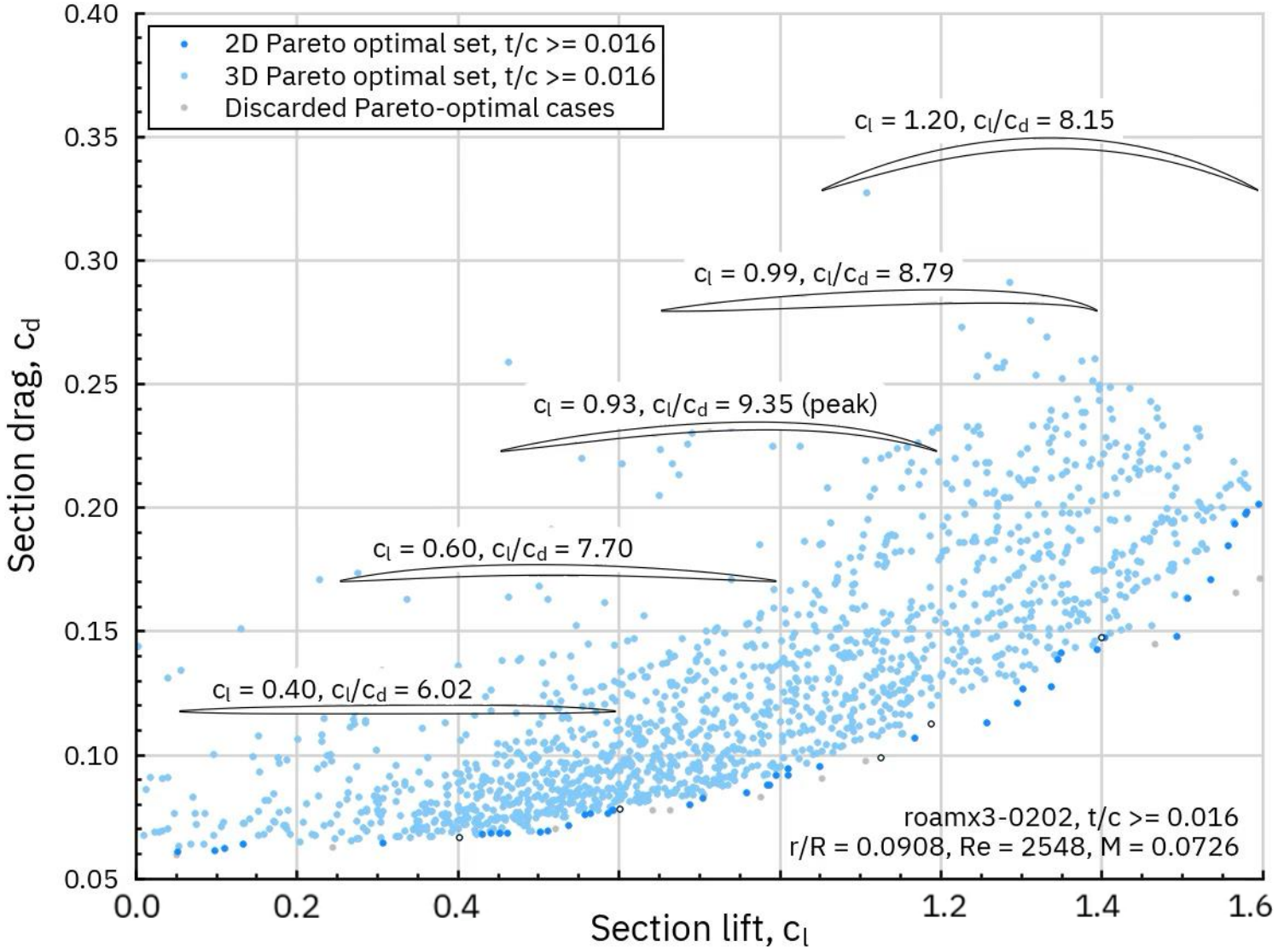
# Airfoil Optimization

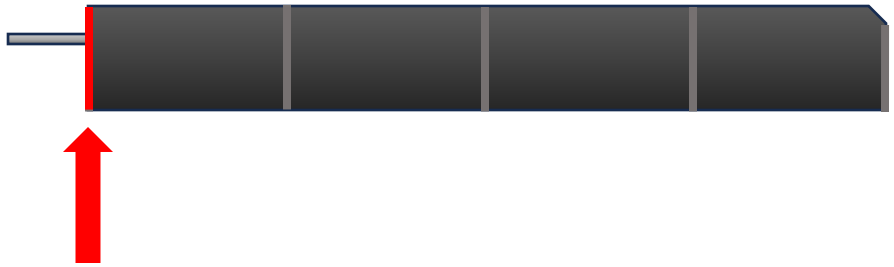


| Airfoil | $c_l/c_d$ (peak) | % change | $c_l/c_d$ ($c_l$ = 0.91) | % change |
|---|---|---|---|---|
| clf5605 | 20.06 | – | 20.06 | – |
| roamx-0201 | 24.70 | 23% | 23.82 | 19% |

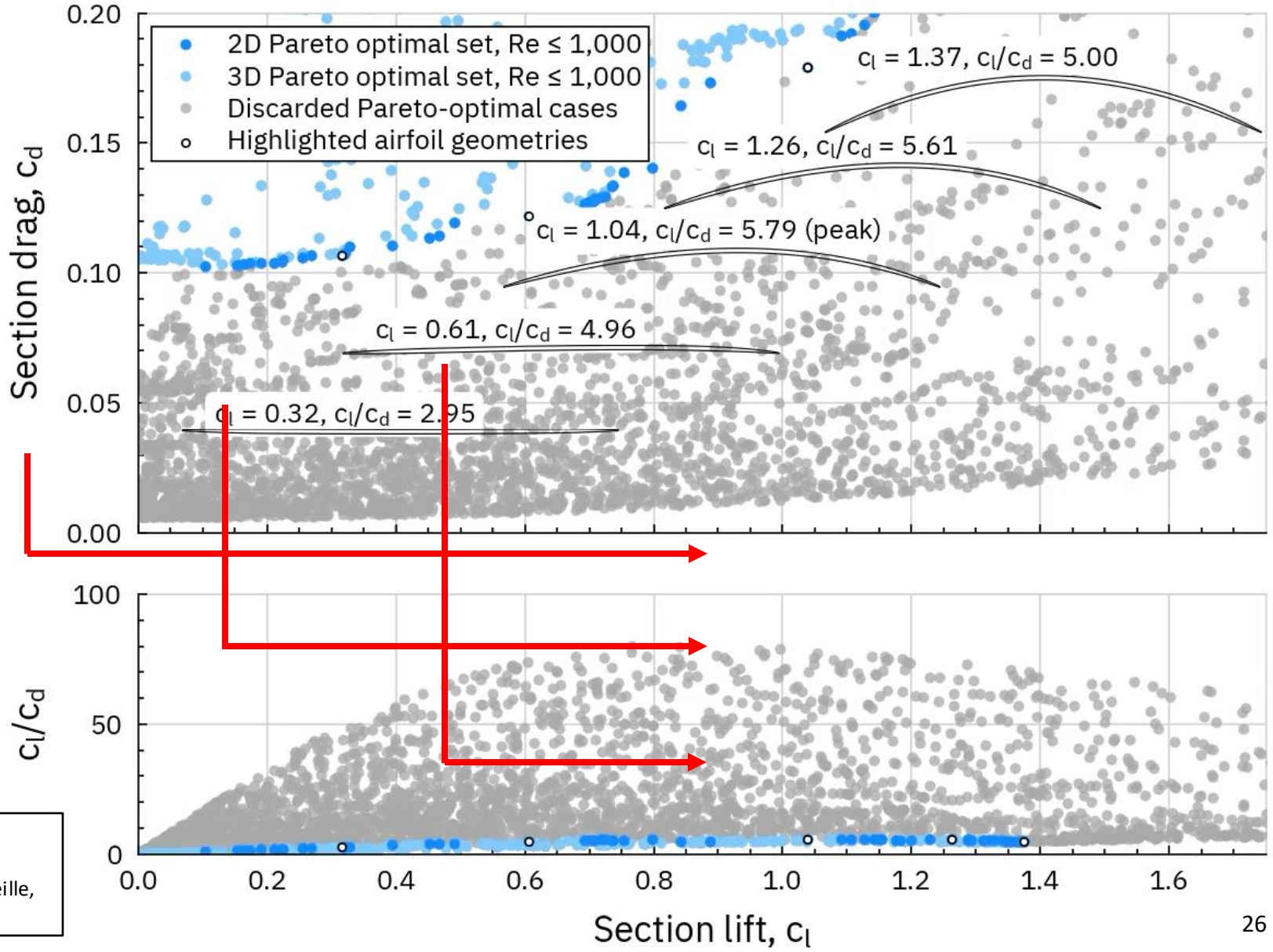
# Airfoil Optimization



# Airfoil Optimization

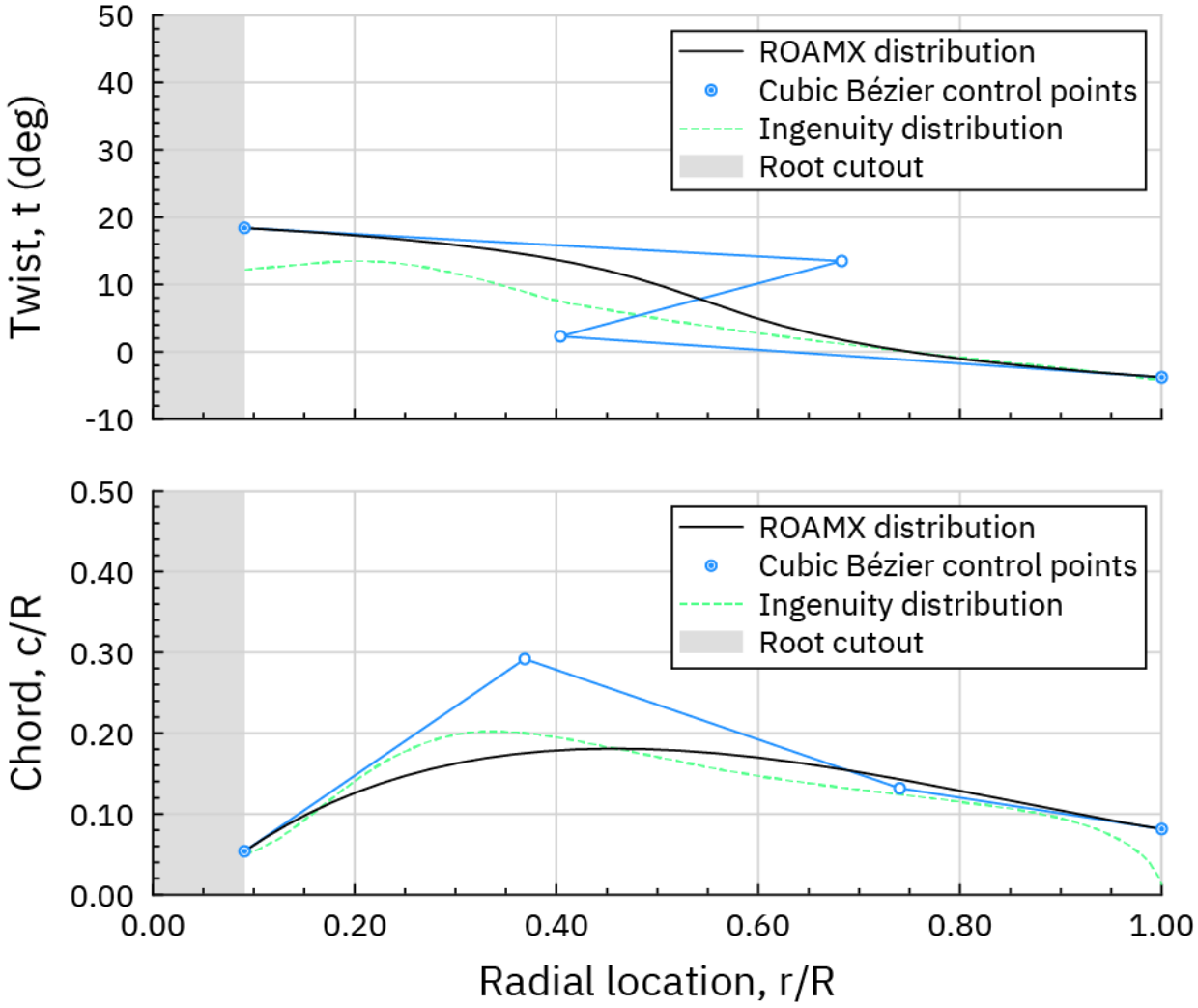
- Pareto optimal set and airfoil geometry
  - Coupling of Pareto front to Pareto-optimal airfoil decks





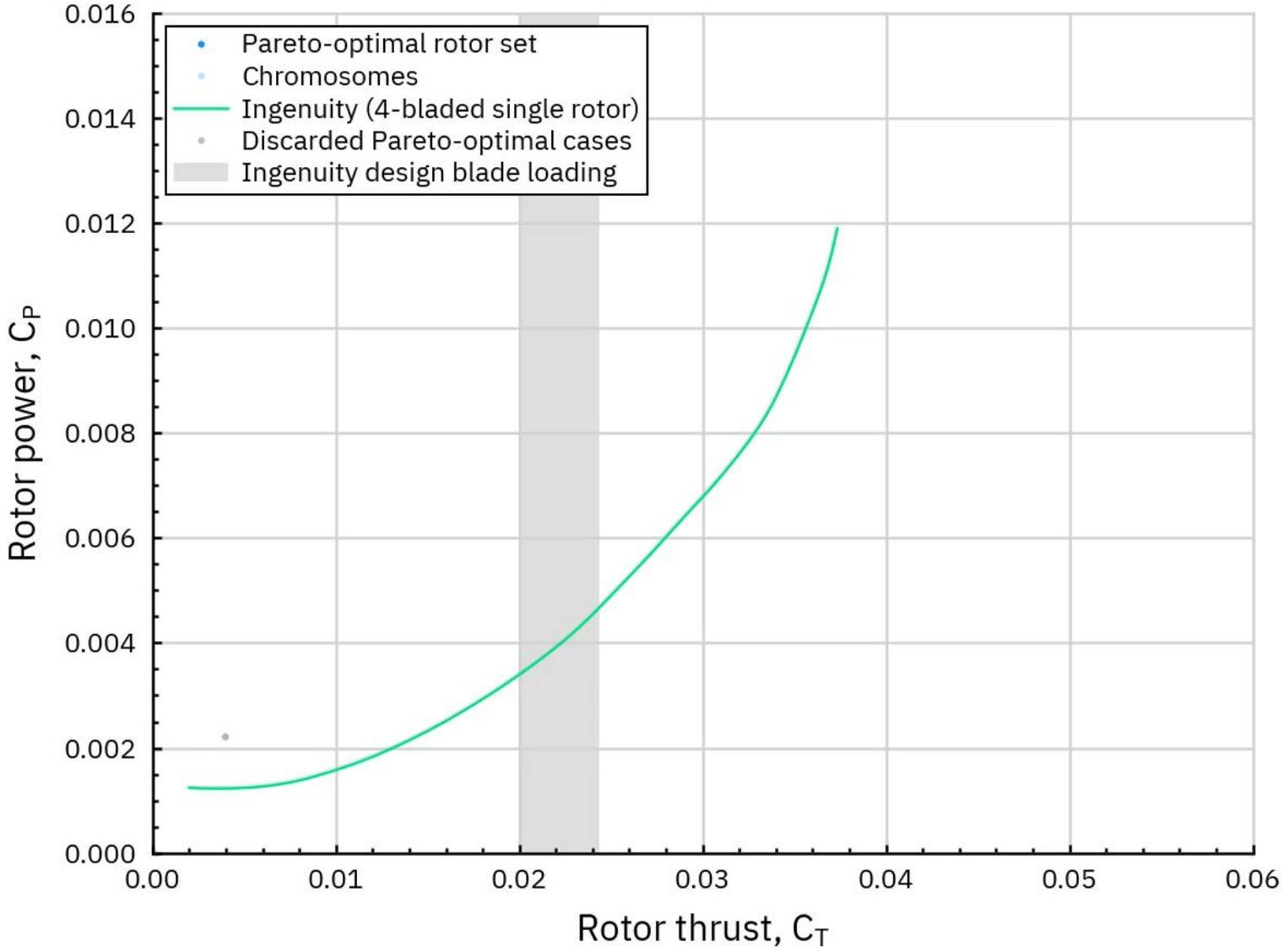
Koning, W., Perez Perez, N., Cummings, H., Romander, E., Johnson, W., "Overview of Rotor Hover Performance Capabilities at Low Reynolds Number for Mars Exploration," 50th European Rotorcraft Forum, Marseille, France 2024.

# Rotor Parameterization



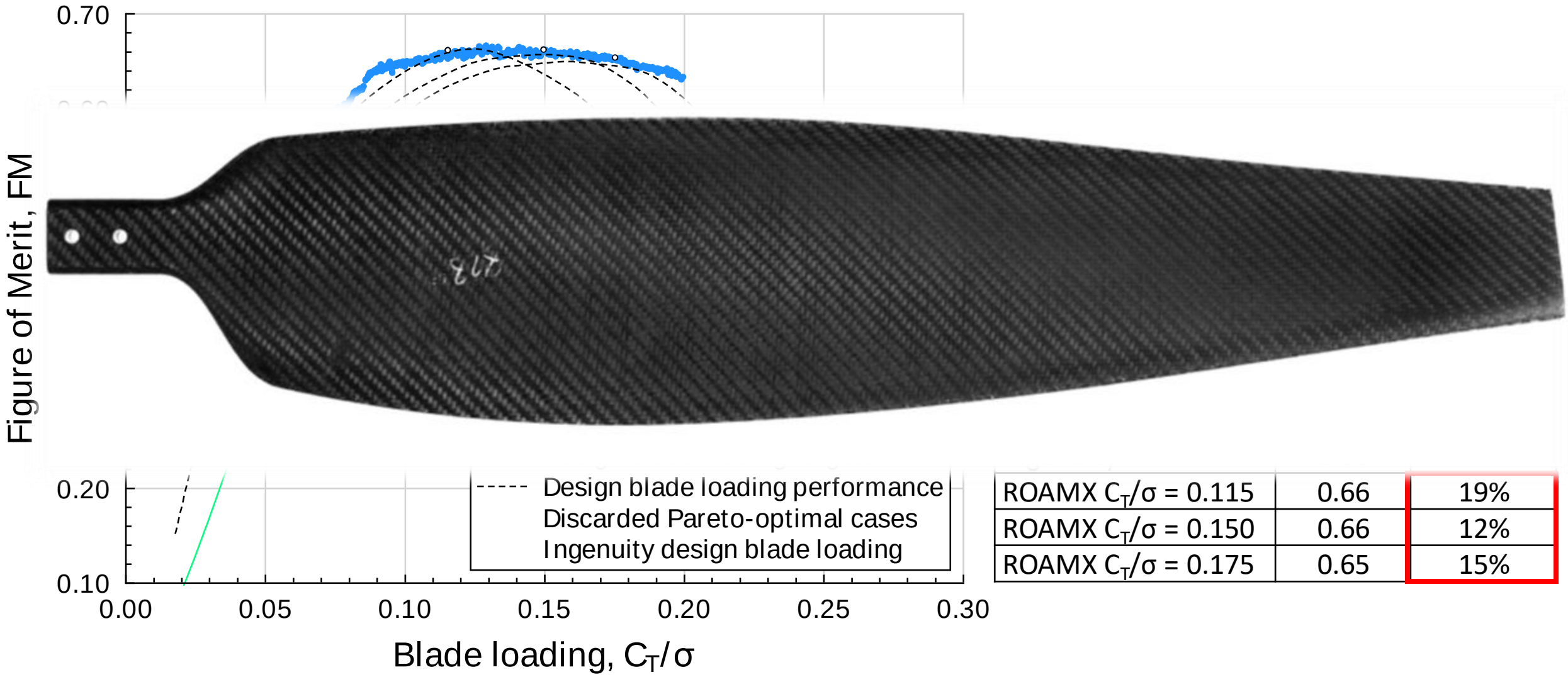

- Cubic Bézier curve for twist and planform
- Ingenuity reference

# Rotor Optimization



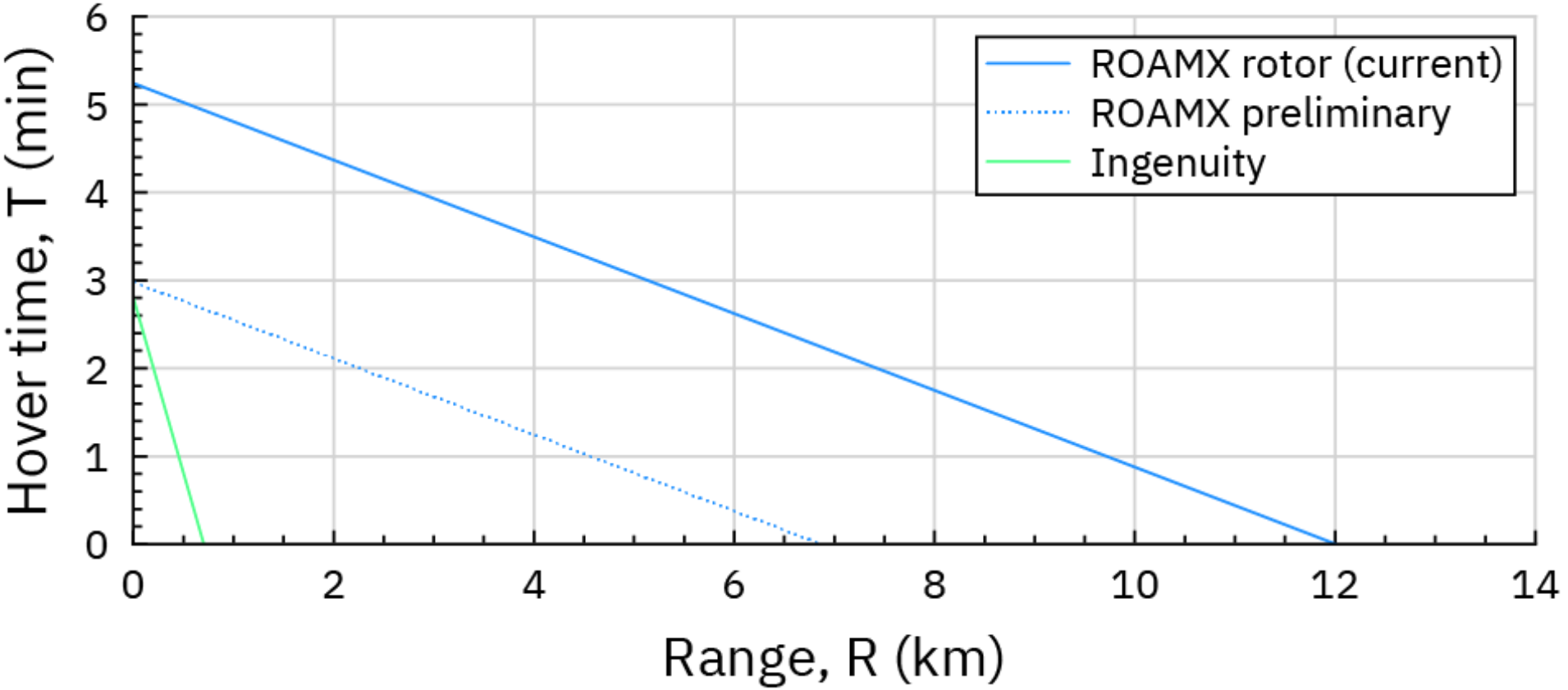

- ROAMX rotor optimization
  - Dual objective:
    - max. blade loading
    - min. rotor power
  - 6-bladed single rotor
  - $\sigma_{tw} = 0.25$
- Compared to Ingenuity modeled as single rotor
  - CAMRADII predictions using same CFD approach in OVERFLOW

# Rotor Optimization




| | | |
|---|---|---|
| ROAMX $C_T/\sigma$ = 0.115 | 0.66 | 19% |
| ROAMX $C_T/\sigma$ = 0.150 | 0.66 | 12% |
| ROAMX $C_T/\sigma$ = 0.175 | 0.65 | 15% |

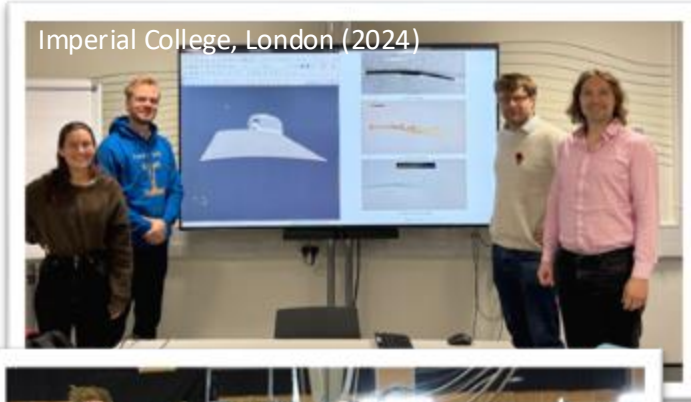
# Vehicle Performance

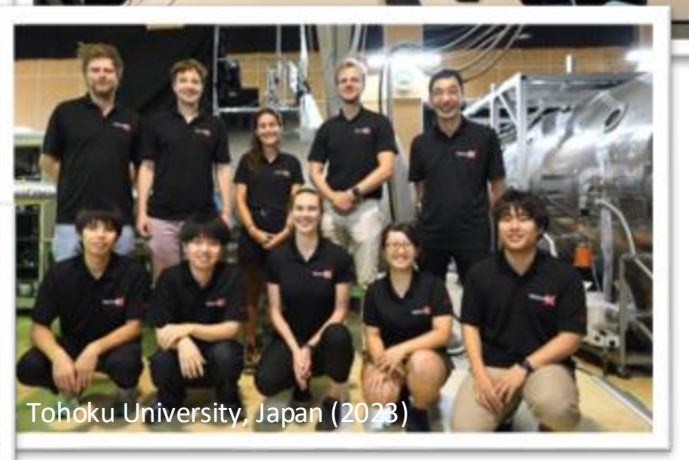



- NDARC performance estimates ($\rho = 0.017$ kg/m$^3$, 'Mars Condition 2')
- For Ingenuity-sized vehicle
- ELISA used for Mars Science Helicopter, Sample Recovery Helicopter

# Verification & Validation Efforts

- Airfoil main assumptions:
  - 2D CFD: Compare with q3D and fully-resolved DNS
    - Publication ETA: 2025
  - No turbulence model employed: Compare to fully-resolved DNS 2D & q3D
    - Publication ETA: 2025
  - No relevant experimental data available: Tohoku University (force, PSP, Schlieren), Japan


Imperial College, London (2024)


Tohoku University, Japan (2023)


Tohoku University, Japan (2023)

Koning, W.J.F., Perez Perez, N., Cummings, H., Nagata, T., Kanzaki, Y., Kasai, M., Miyagi, M., Nonomura, T., Asai, K., Caros, L., Buxton, O., Vincent, P., "Experimental Results for Mars Rotorcraft Airfoils (roamx-0201 and clf5605) at Low Reynolds Number and Compressible Flow in a Mars Wind Tunnel," NASA–TM–20240004230.

TOHOKU UNIVERSITY

NAGOYA UNIVERSITY

IMPERIAL

# Verification & Validation Efforts

- Airfoil main assumptions:
  - No relevant experimental data available: Tohoku University (force, PSP, Schlieren), Japan
  - Experiments
    - clf5605 (Ingenuity outboard)
    - roamx-0201 (ROAMX r/R = 0.75)
  - Re = 20,000, M = 0.60, alpha = -2 to 6 degrees

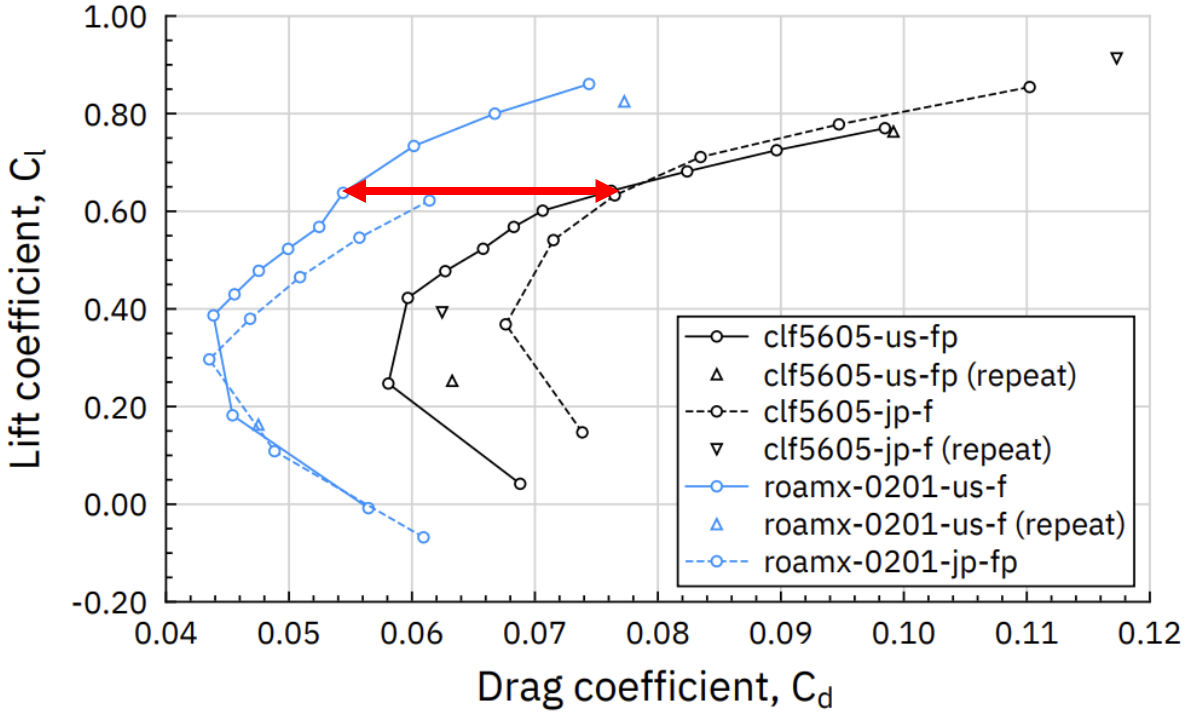



Figure 18. Comparison of drag polars.

Koning, W.J.F., Perez Perez, N., Cummings, H., Nagata, T., Kanzaki, Y., Kasai, M., Miyagi, M., Nonomura, T., Asai, K., Caros, L., Buxton, O., Vincent, P., "Experimental Results for Mars Rotorcraft Airfoils (roamx-0201 and clf5605) at Low Reynolds Number and Compressible Flow in a Mars Wind Tunnel," NASA–TM–20240004230.

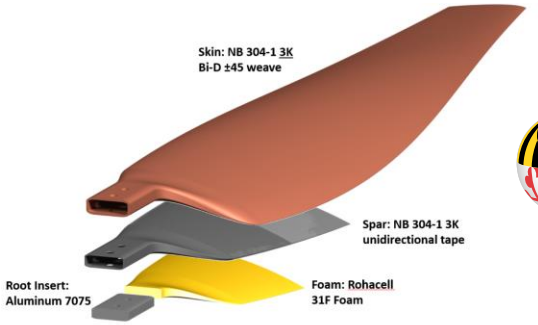
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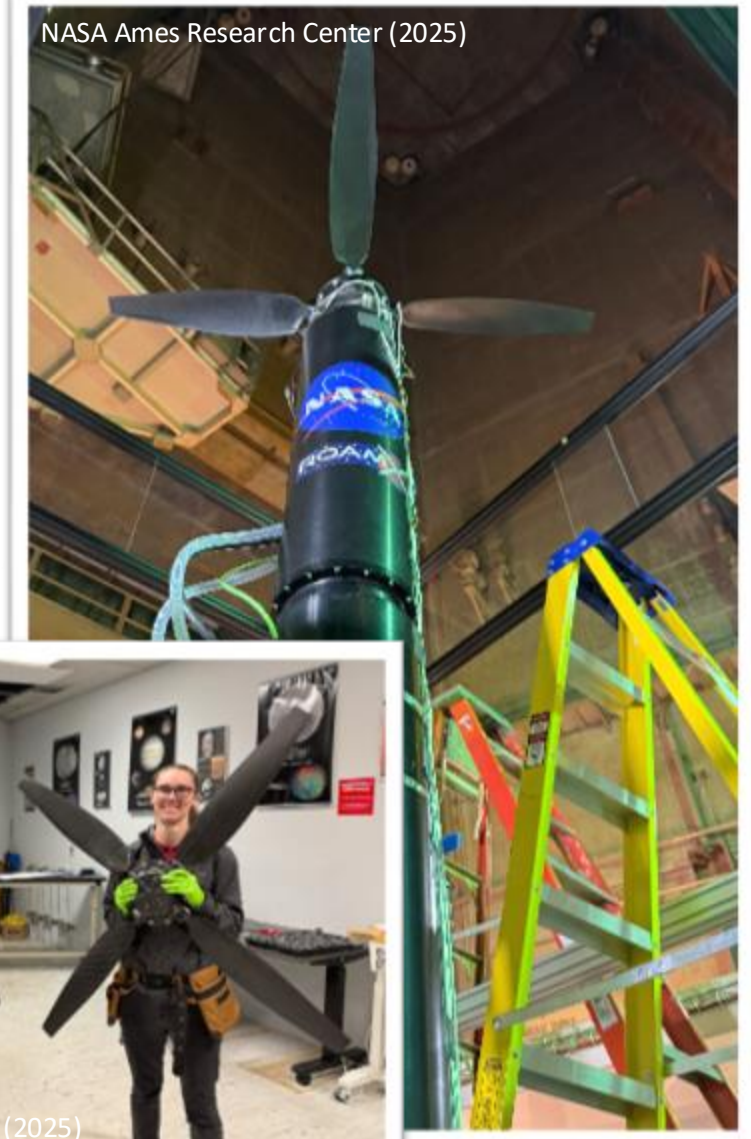
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# Validation Efforts

- Rotor main assumptions:
  - Modeled as rigid blade: University of Maryland, rotating blade structural analyses
    - Pitch axis to 0.40c
  - CAMRADII used outside of known regime:
    - Full-Scale experimental setup
      - Publication ETA: 2025
    - 3D CFD
      - Publication ETA: 2025




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Lumba, R., Chi, C., Datta, A., Koning, W., Perez Perez, N., Cummings, H., "Structural Design and Aeromechanical Analysis of Unconventional Blades for Future Mars Rotorcraft," Journal of the American Helicopter Society, Volume 68, Number 2, April, 2023.

# Conclusions

- Mars atmosphere poses serious difficulties for efficient airfoil operation
  - Near-certain separation of the laminar boundary layer
  - Reattachment of the mean flow possible with unconventional airfoils
- Rotor optimization using the Evolutionary aLgorithm for Iterative Studies of Aeromechanics (ELISA) optimization toolset was demonstrated
  - roamx airfoil parameterization
  - Airfoil optimization for radial stations
  - Rotor hover optimization
- Validation & verification efforts presented





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# Thank you!