Surrogate Based Shape Optimization of a Low Boom Fuselage Wing Configuration

Jochen Kirz

German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology

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Motivation

Optimization of **simplified geometries** → → → **Design of low-boom, low-drag aircraft**

- Adding geometrical complexity
- Using higher cost CFD methods

Fuselage Wing Configuration

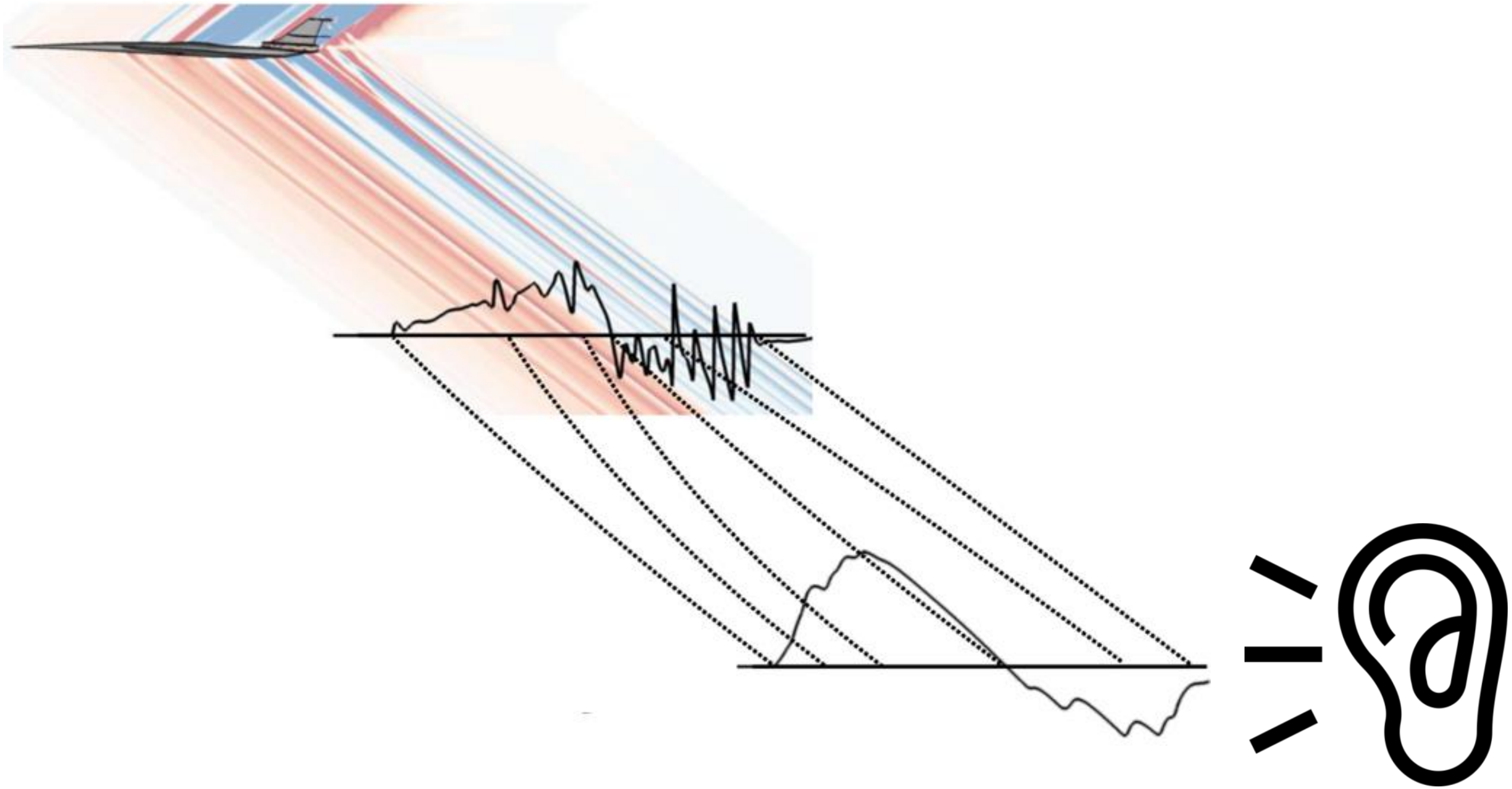
Lift
Achieve trimmed flight (lift=weight)
→ Development of required methods

Complex 3D Interactions of waves
Off-track loudness often louder than on-track loudness
→ Understanding of 3D aerodynamics and lowering the off-track loudness

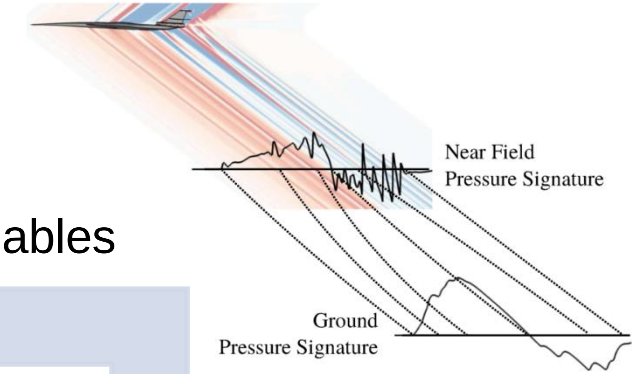
Outline

- Setup of the Optimization Process
  - ❖Overview
  - ❖Background
  - ❖Detailed Optimization Setup
- Optimization Results
- Summary and Outook

Optimization Process
Overview



Optimization Process
Overview



CATIA geometry generation

CENTAUR grid generation

DLR TAU-code near-field flow solver

ONERA ground propagation tool based on TRAPS Code

ONERA loudness calculation tool

Set of design variables

POT [Powerful Optimization Tools with surrogate modelling]

Loudness, drag

Optimization Process
Background

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CENTAUR grid generation

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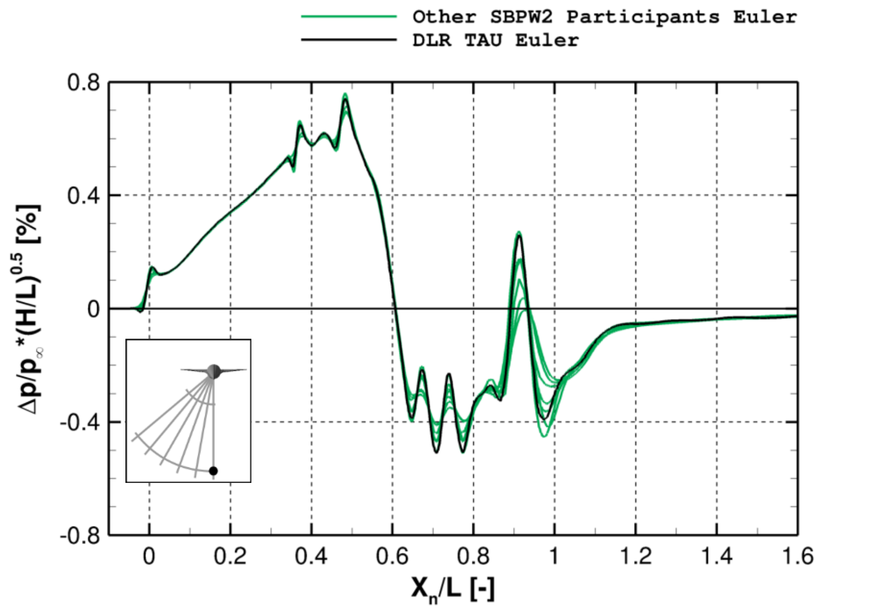
ONERA loudness calculation tool

Applied for SBPW1 and SBPW2 cases and compared to other participants



Kirz, J., and Rudnik, R., “DLR Simulations of the First AIAA Sonic Boom Prediction Workshop Cases,” AIAA Paper 2017-0276

Kirz, J., and Rudnik, R., “DLR TAU Simulations for the Second AIAA Sonic Boom Prediction Workshop,” AIAA Paper 2017–3253

Optimization Process
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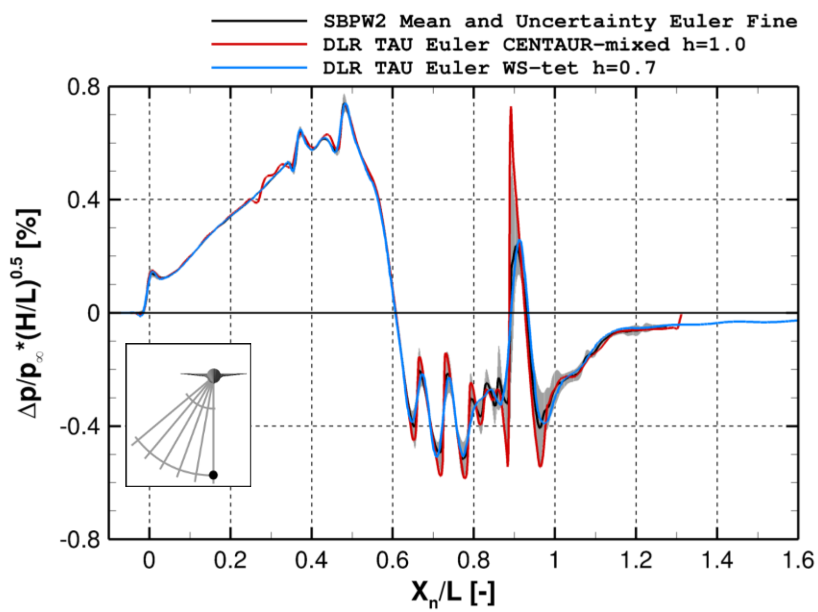

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Kirz, J., and Rudnik, R., "DLR TAU Simulations for the Second AIAA Sonic Boom Prediction Workshop," AIAA Paper 2017–3253

Optimization Process
Background

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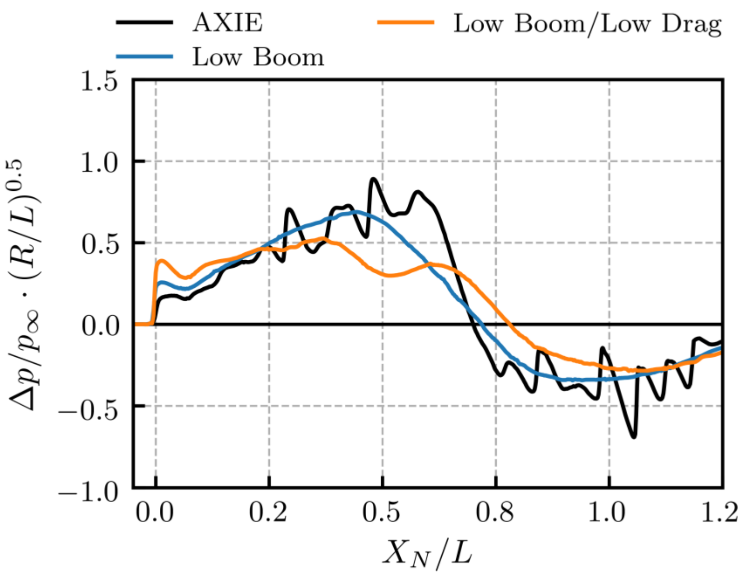
ONERA loudness calculation tool

Applied for multi-objective optimization of a low-boom, low-drag axisymmetric body



Kirz, J., “Surrogate Based Shape Optimization of a Low Boom Axisymmetric Body,” AIAA Paper 2018-2849

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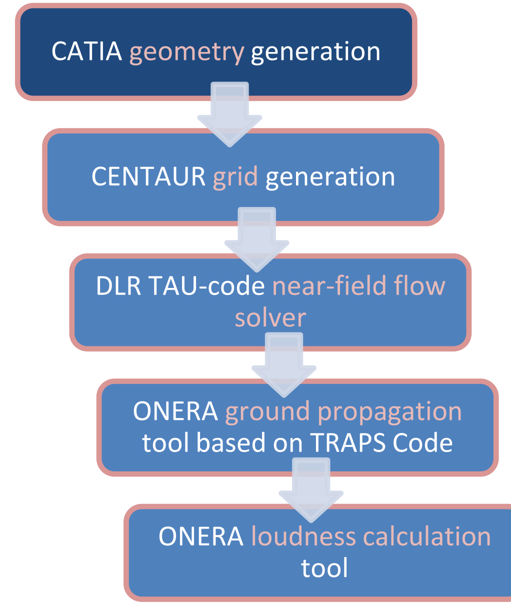
Optimization Process
Geometry



JAXA Wing Body (JWB)

- Wing-body configuration designed by Ueno et al. for the *Second AIAA Sonic Boom Prediction Workshop* to represent the on-track equivalent area distribution of the more complex NASA C25D geometry[1]

- CAD model based on universal parametric aircraft CAD model developed at DLR[2]

[1] Ueno, A., Kanamori, M., and Makino, Y., "Multi-fidelity Low-boom Design Based on Near-field Pressure Signature," AIAA Paper 2016–2033

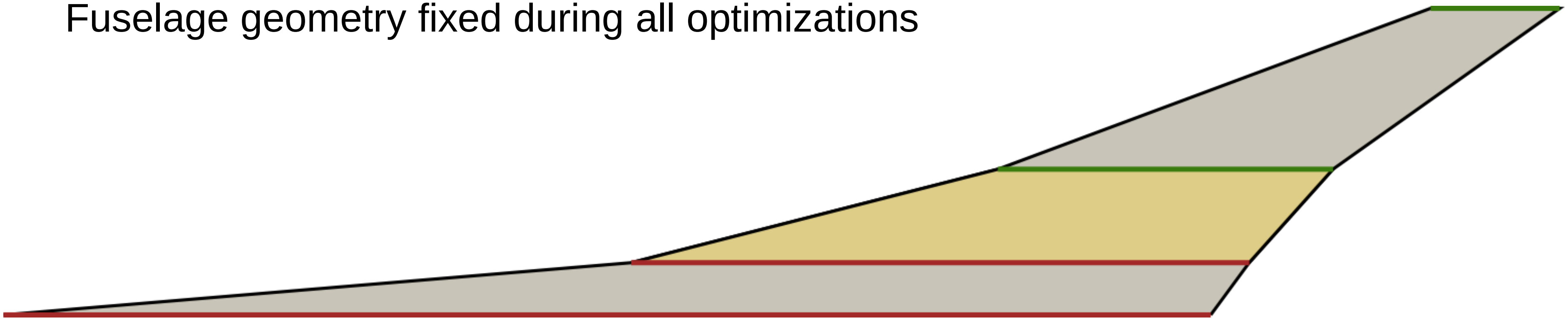
[2] Ronzheimer, A., "CAD in Aerodynamic Aircraft Design," DLRK Paper 450117, 2017.

Optimization Process
Geometry Parameterization

Three Consecutive Optimizations

- Outer airfoil (green)
- Inner airfoil (red)
- Wing twist, sweep, dihedral

Fuselage geometry fixed during all optimizations

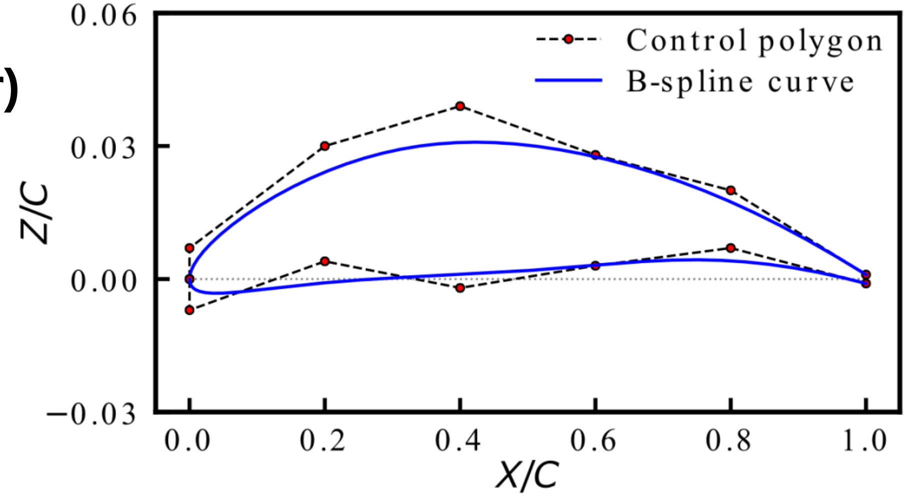


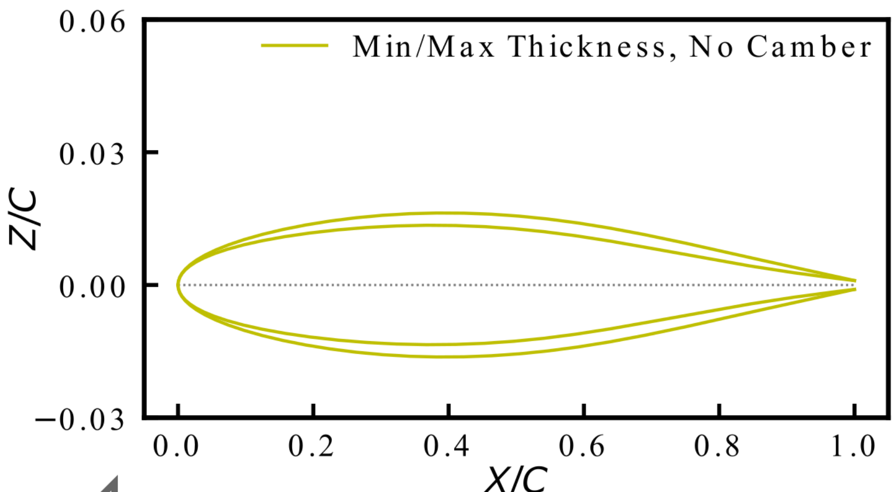
Optimization Process
Geometry Parameterization

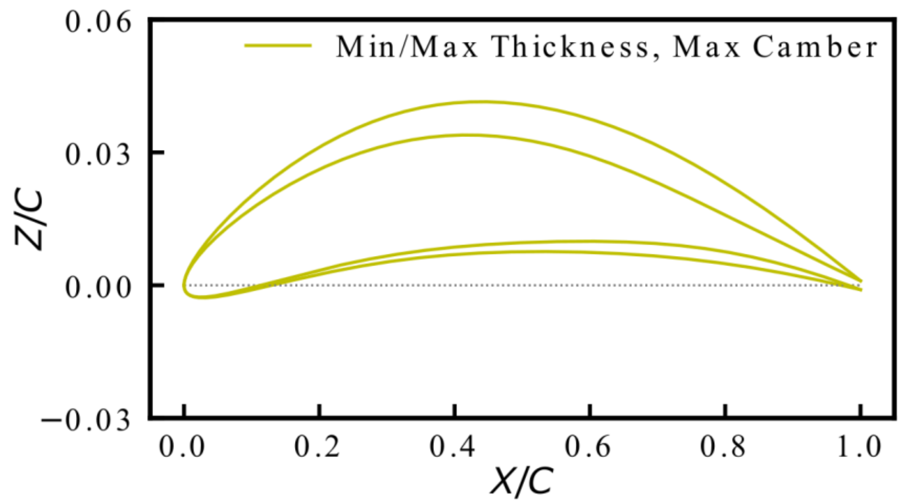
Airfoil Parameterization (inner & outer)

- B-splines with 6 control points for each side (upper/lower)
- Nose radius fixed
- Trailing edge thickness fixed

→ 8 design variables







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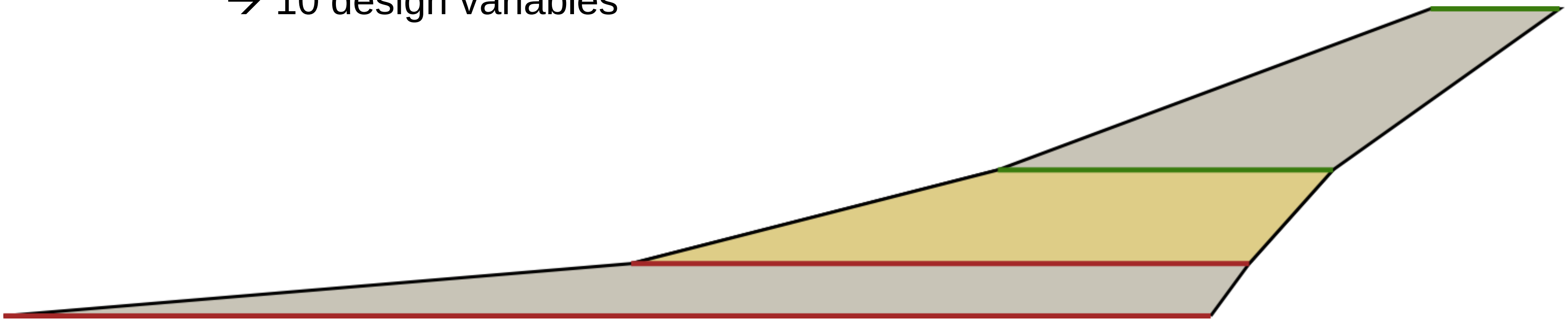
Optimization Process
Geometry Parameterization

Wing twist, sweep, dihedral

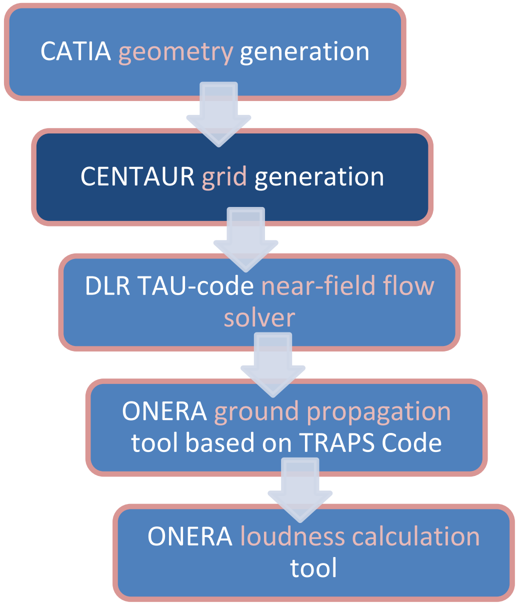
- 4 design variables for the twist — at the root, kinks and tip
- 3 design variables for the sweep
- 3 design variables for the dihedral

(sweep and dihedral: between those locations)

→ 10 design variables

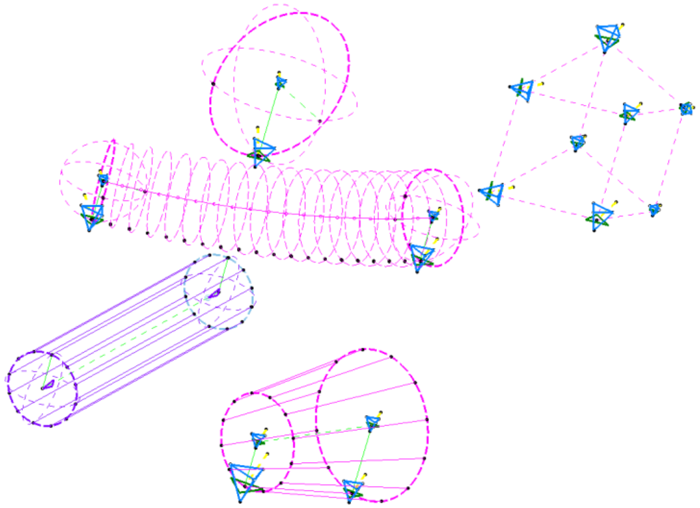


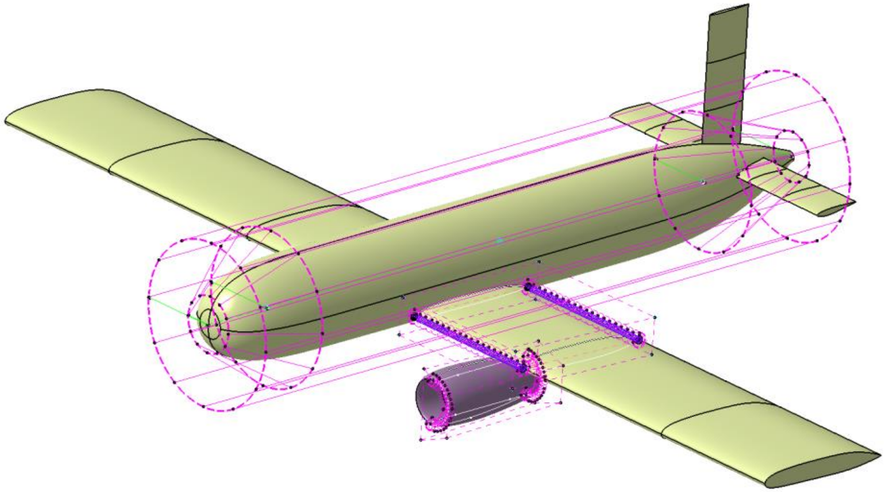
Optimization Process
Grid Generation



CATIA to CENTAUR Sources Toolbox (CCS)

- CATIA source primitives for typical CENTAUR sources
  → Sources moving with geometry
- Automatic sets of source primitives for complex geometries (wing segments, fuselage, engine)
  → Grid element sizes based on curvature



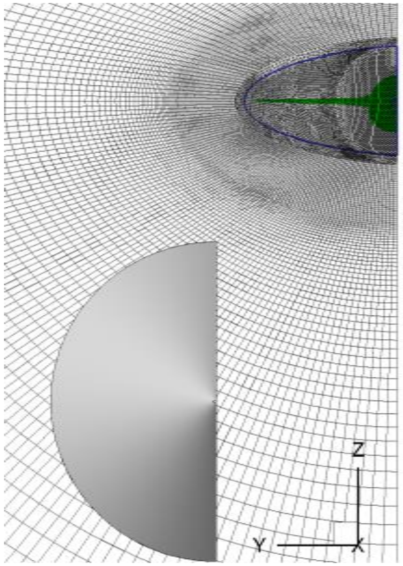


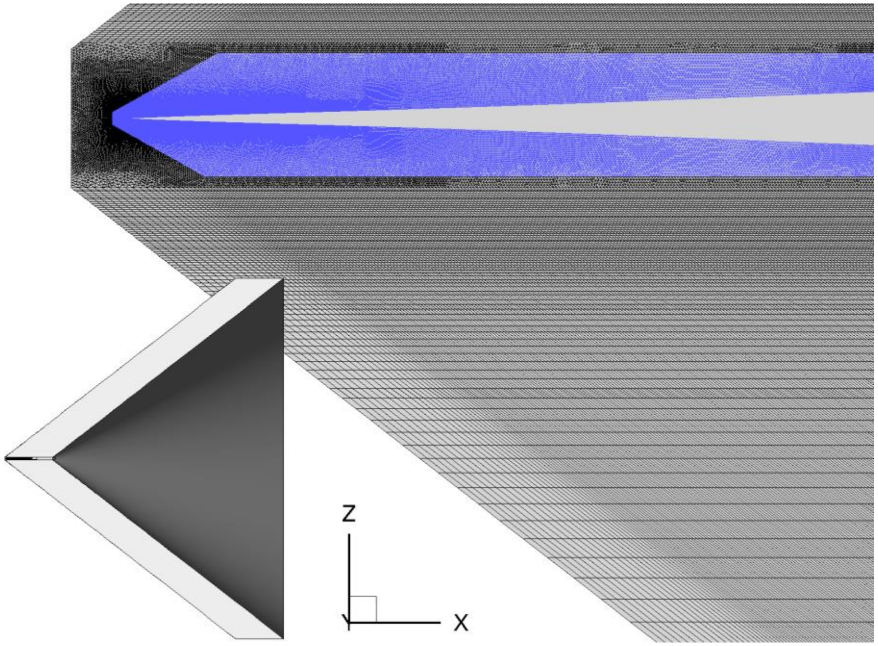
Optimization Process
Grid Generation

Hybrid Inviscid CENTAUR Grids

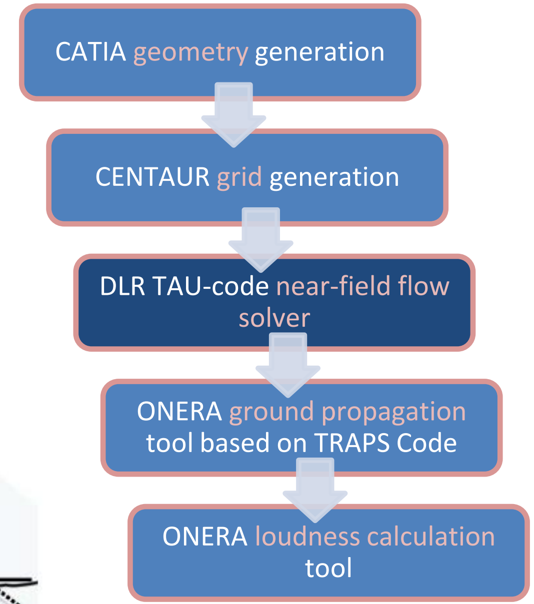
- Modular grid generation approach
- Tetrahedral near-body grid
    - Generated for 0° angle of attack
    - Elliptical cross section
- Fully structured far-field
    - Aligned to the Mach cone
    - 7 body lengths in radial direction

→ approx. 13,000,000 grid nodes





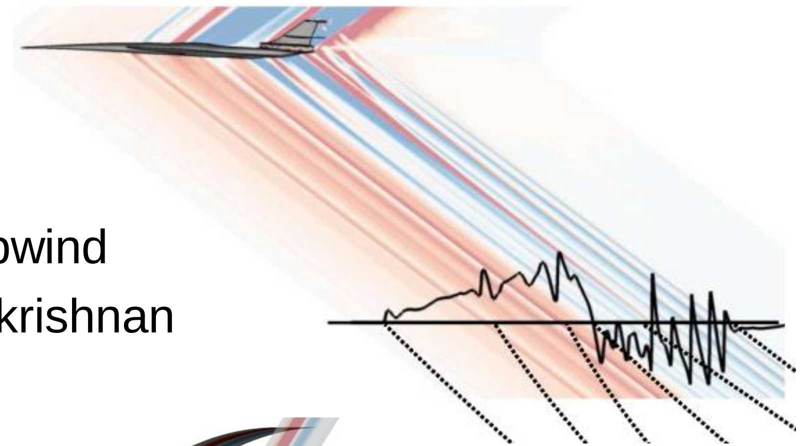
Optimization Process
Near-Field Signature Calculation

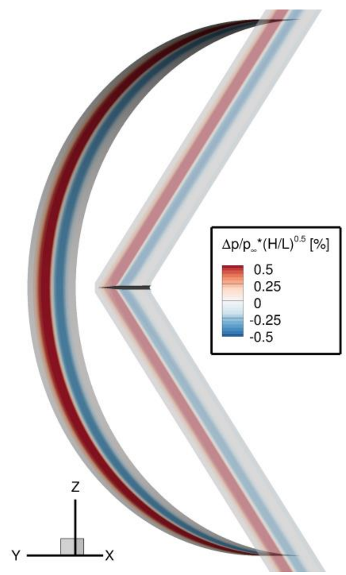


DLR TAU Code

- Euler simulations
- LUSGS timestepping
- 2nd order AUSMDV upwind scheme with Venkatakrishnan limiter

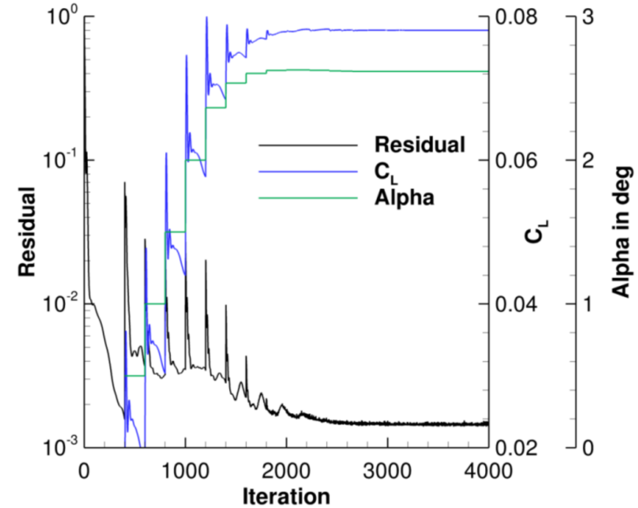
- Mach = 1.6
- Altitude = 15.760 m





Near-field pressure signatures extracted at 5 body lengths

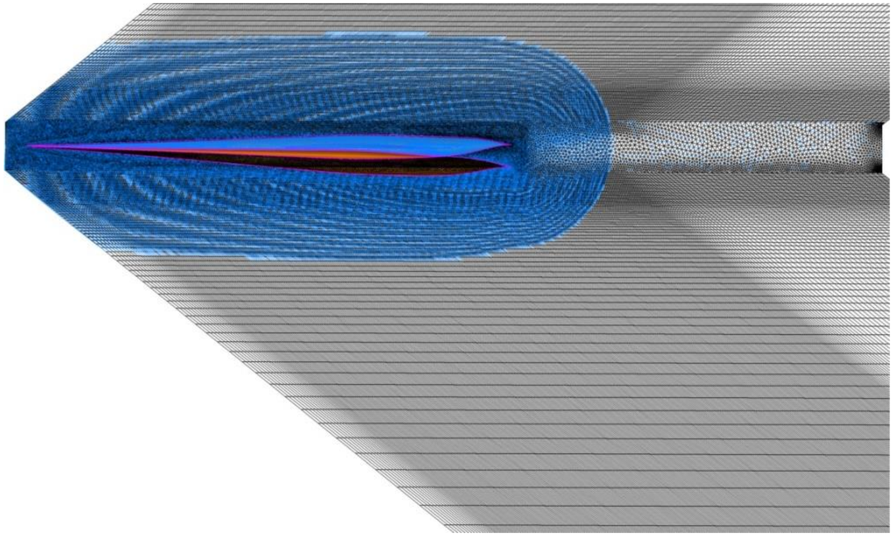
Optimization Process
Target Lift Simulations

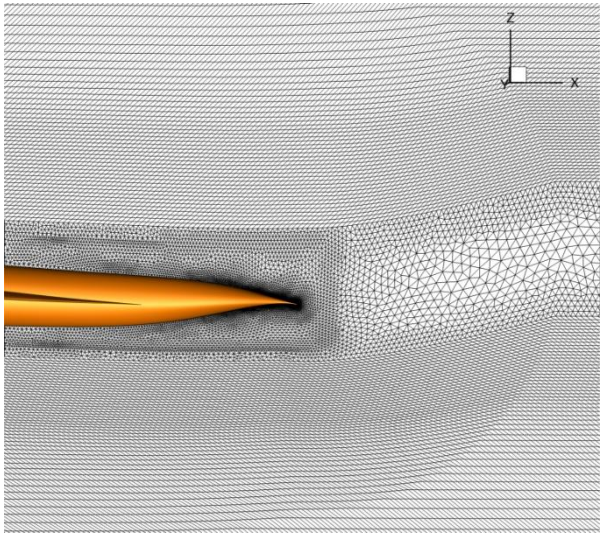


Method for the adjustment of the angle of attack

Keep alignment of the far-field grid to the Mach cone

- Grid deformation technique applied[1]
- Modification (ΔC_L<0.0001): Ackeret's formula used to calculate deformation angles every 200 iterations





[1] Kirz, J., "Grid Setups and Numerical Simulations of a Low Boom Concept at Off Design Flight Conditions," DLRK Paper 450243, 2017.

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Optimization Process
Propagation and Loudness

CATIA geometry generation

CENTAUR grid generation

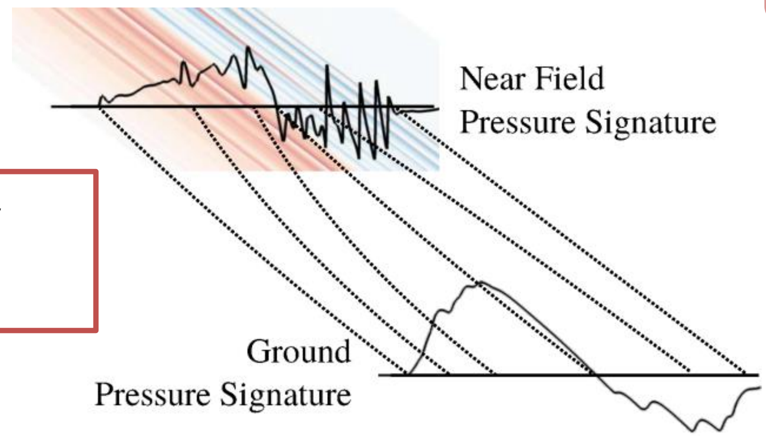
DLR TAU-code near-field flow solver

ONERA ground propagation tool based on TRAPS Code

ONERA loudness calculation tool

Ground propagation

- Ray tracing and signature aging based on linear theory
- Standard atmosphere



Developed and tested by ONERA

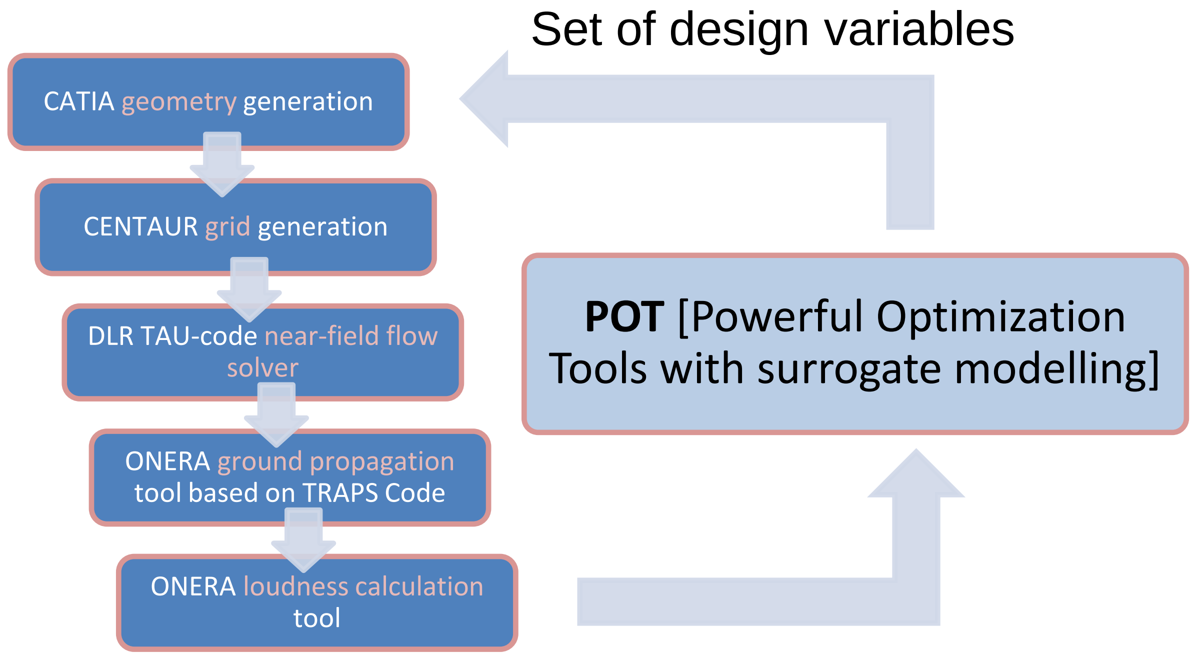
Loudness metrics

- Level of perceived loudness (PLdB)
- Maximum loudness as objective

Optimization Process
SBO Setup

Design of Experiments
- Centroidal Voronoi tessellatized (CVT) Latin Hypercube
- 80 Samples
- Simulations performed in parallel

Surrogate Model
- 3rd order Kriging
- Tuning of the model hyperparameters with the Differential Evolutionary algorithm



Multi-objective optimization
Maximum PLdB, drag coefficient

Stopping criterion
Pareto confidence reached

Outline

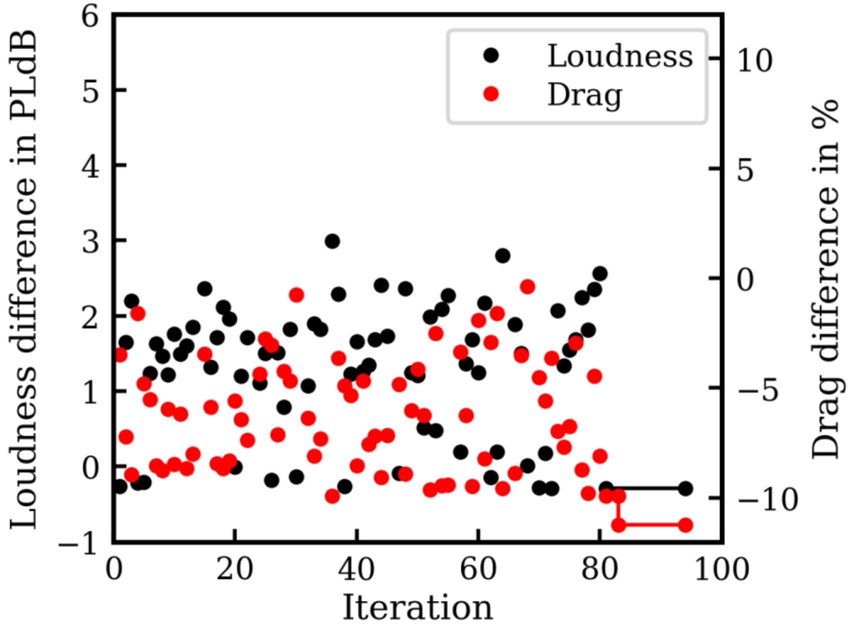
- Setup of the Optimization Process
  - ❖Overview
  - ❖Context
  - ❖Detailed Optimization Setup
- Optimization Results
  - ❖Optimization of the outer airfoil
  - ❖Optimization of the inner airfoil
  - ❖Optimization of the wing twist, sweep and dihedral
- Summary and Outook

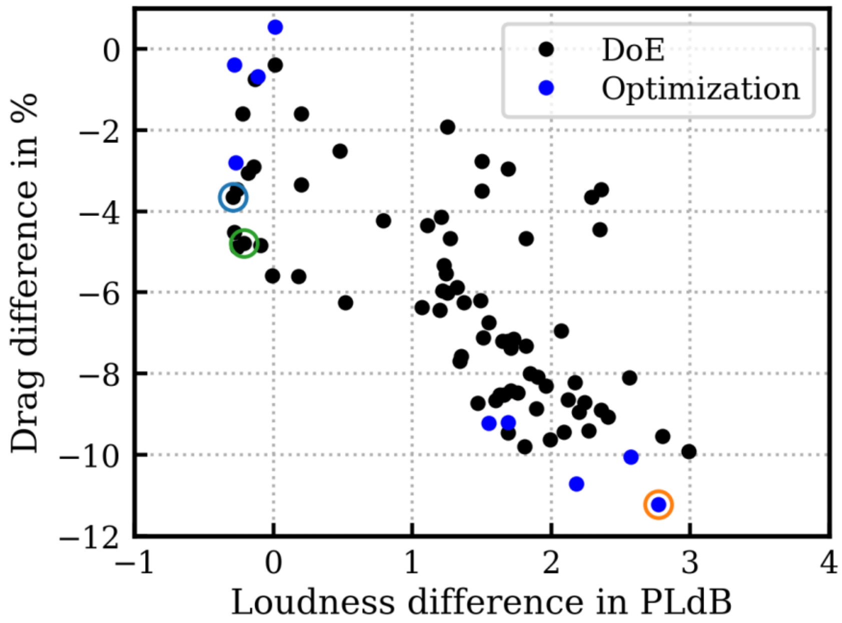
Results

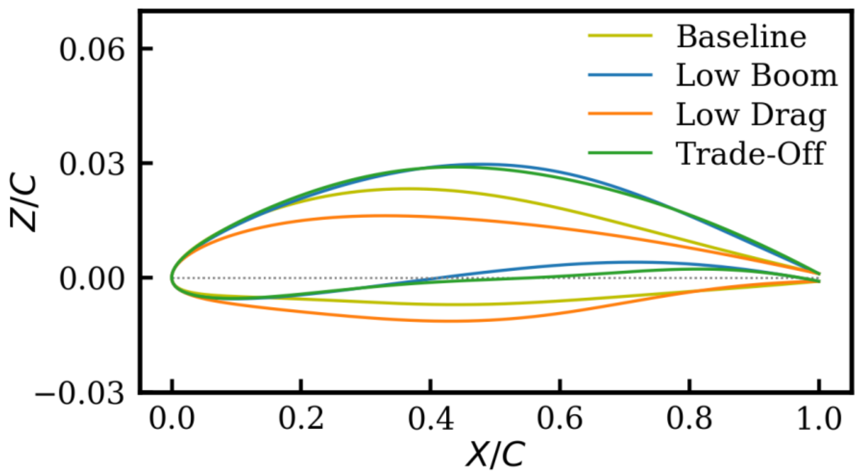
Optimization of the Outer Airfoil

Pareto confidence reached after 18 iterations

- Low boom: high camber airfoil
- Low drag: nearly symmetric

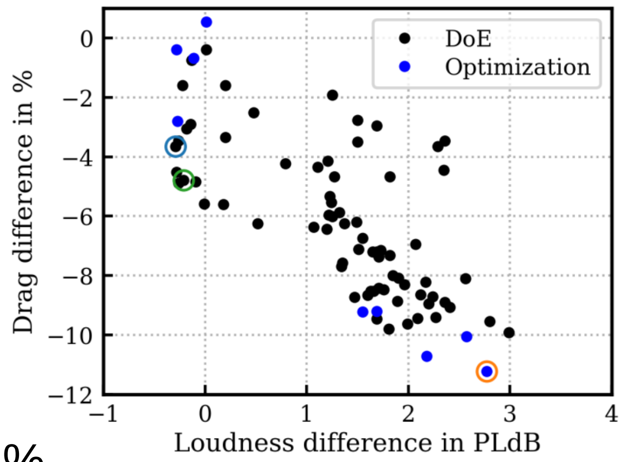






Results

Optimization of the Outer Airfoil

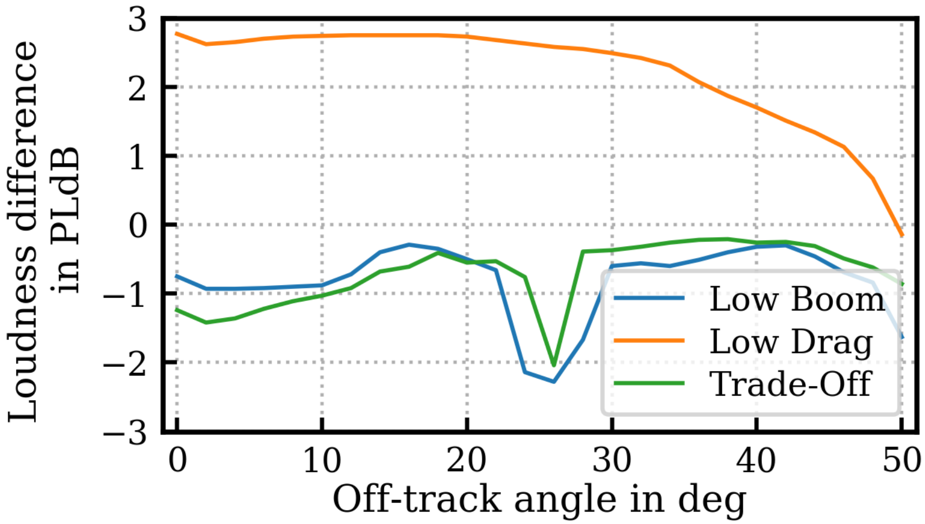


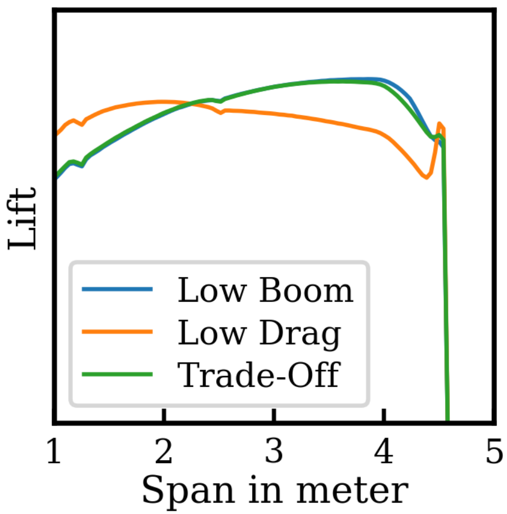
Low boom case

- Loudness decreased by 0.3 PLdB
- Drag reduced by 3.5%

Low drag case: lift distribution more elliptic

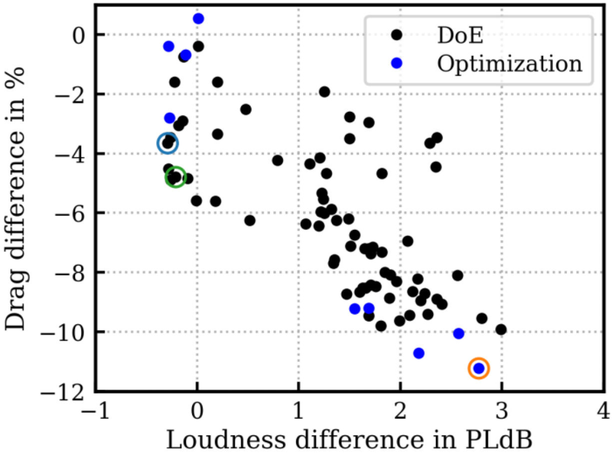
- Less induced drag, total drag decreased by 11.5%
- Generally high loudness





Results

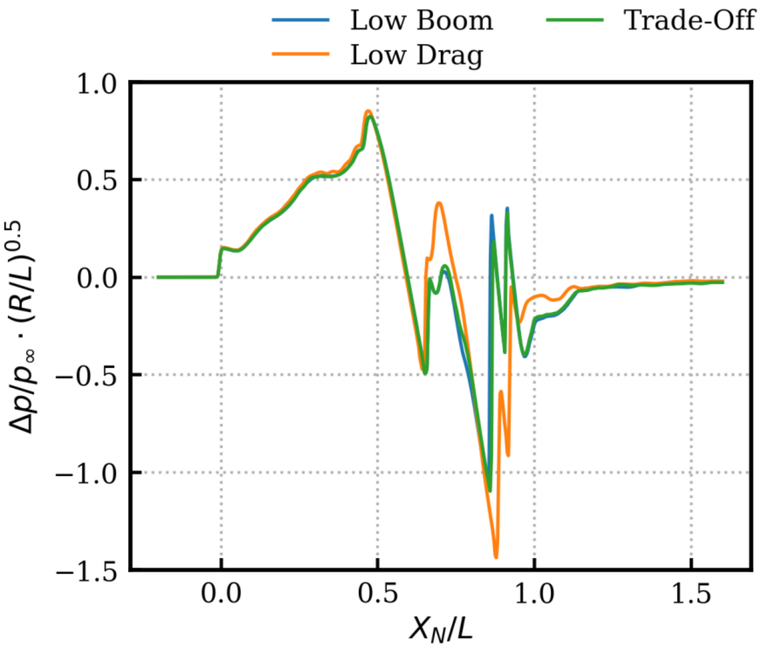
Optimization of the Outer Airfoil

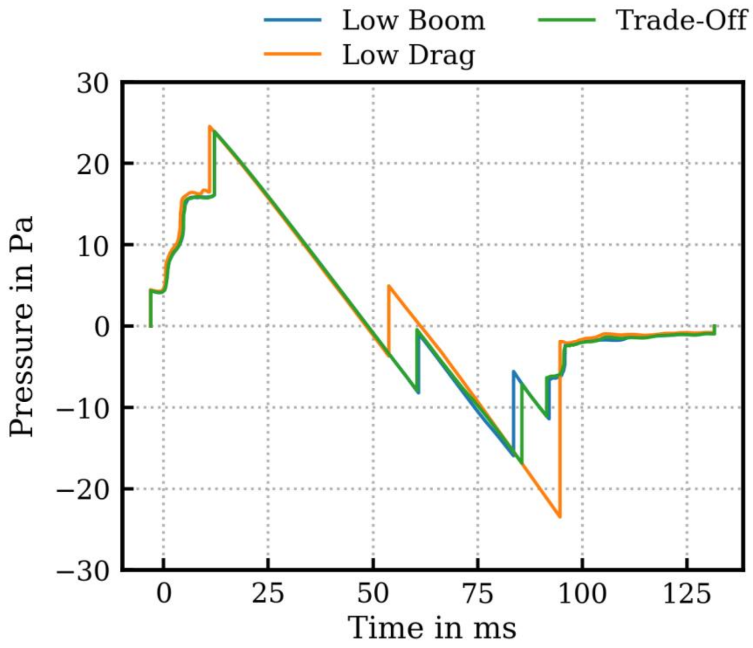


Low drag case

- Recompression at the wing
- Strong expansion at the aft part of the signature

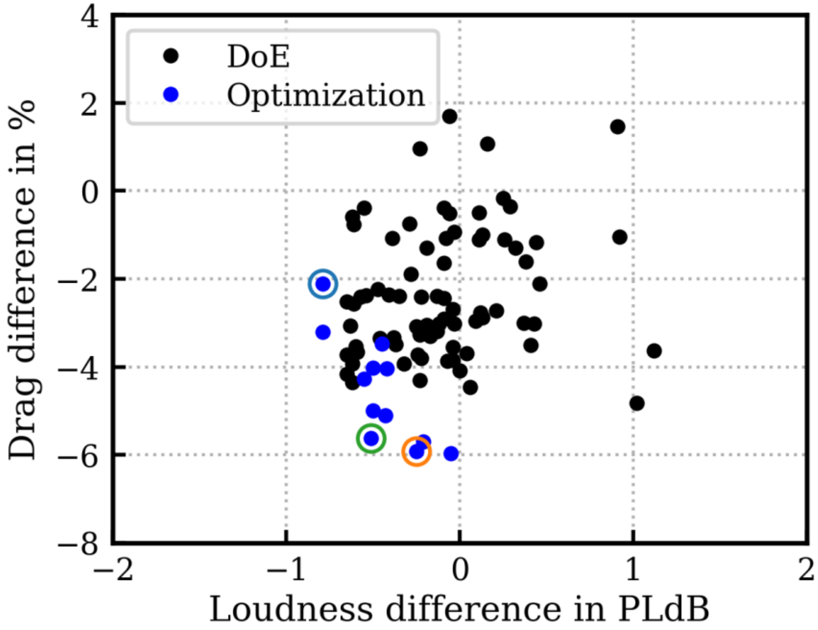
→ Higher loudness





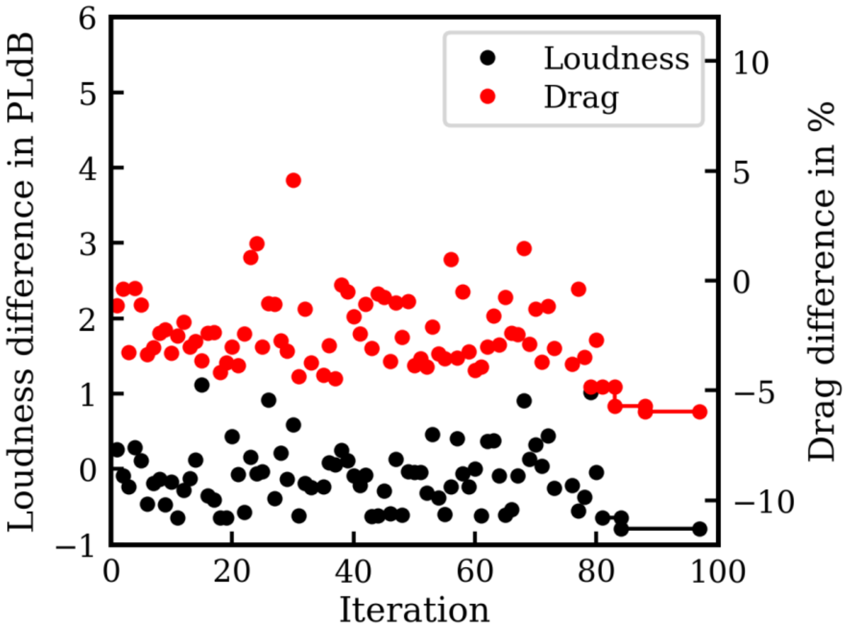
Results

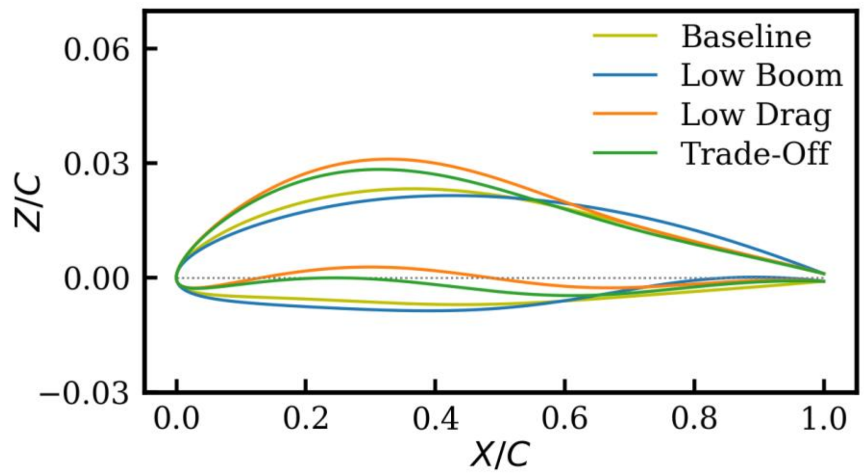
Optimization of the Inner Airfoil



Pareto confidence reached after 19 iterations

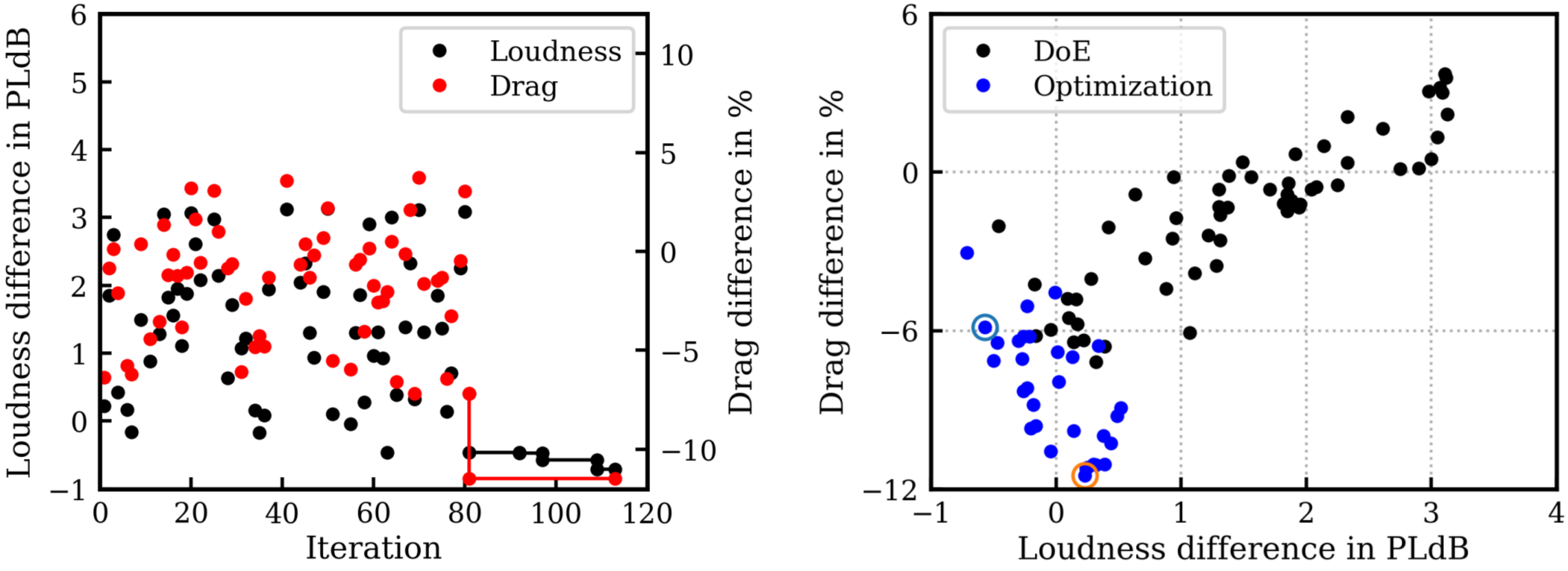
- Low boom: nearly symmetric airfoil
- Low drag: high camber airfoil





Results
Optimization of the Wing Twist, Sweep and Dihedral

Pareto confidence reached after 34 iterations

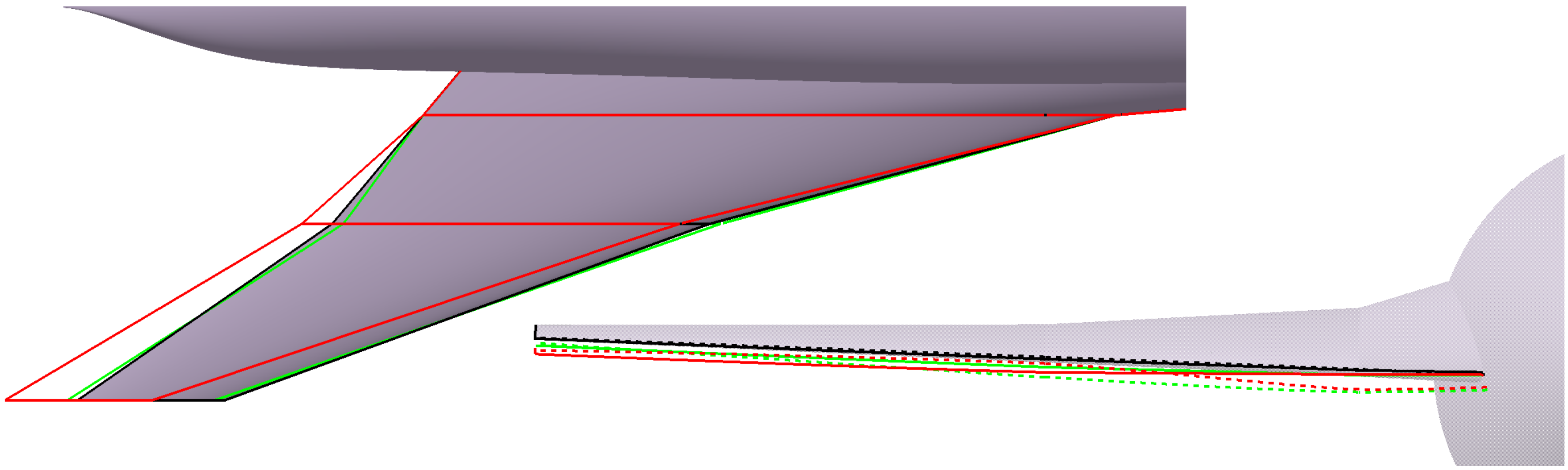


Results

Optimization of the Wing Twist, Sweep and Dihedral

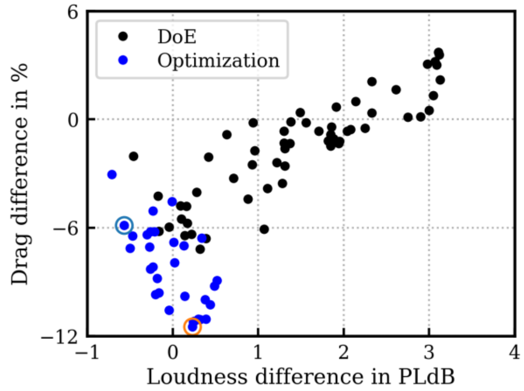
Pareto confidence reached after 34 iterations

- Low boom: very similar to baseline with increased incidence at the root
- Low drag: high sweep for the outboard wing



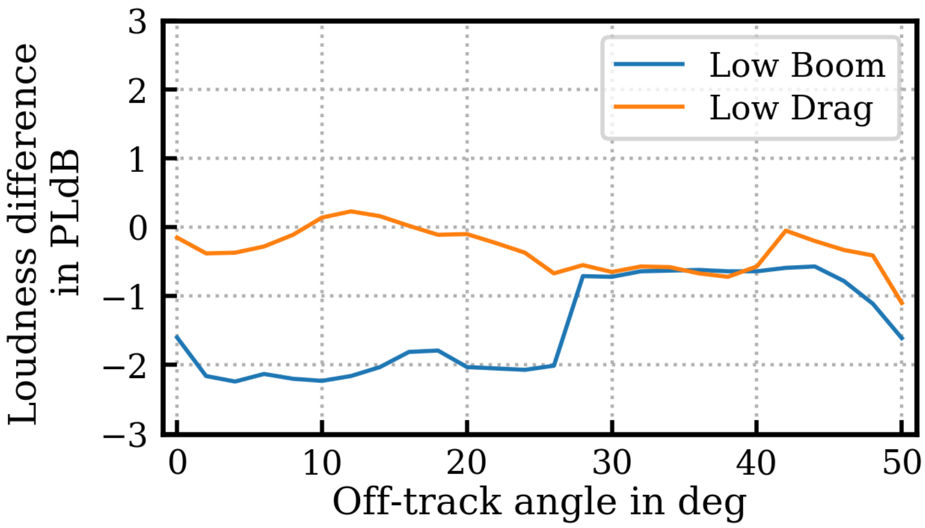
Results

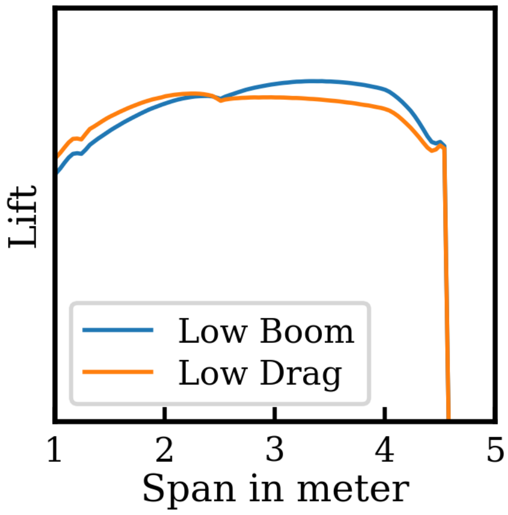
Optimization of the Wing Twist, Sweep and Dihedral



Correlation between lift distribution and off-track loudness

- Lowering the on-track loudness possible by decreasing the incident angle of the airfoils near the wing root





Summary and Conclusions

- Methods developed for the optimization of a supersonic configuration with lift
  - Automatic CATIA to CENTAUR sources
  - Grid deformation based on Ackeret‘s formula
- Fast convergence of the optimizations
- Improvements compared to baseline geometry
  - Maximum loudness decreased by 0.55 PLdB
  - Inviscid drag decreased by 6%
- Correlation between the spanwise lift distribution and the off-track loudness has been identified

Looking ahead

Optimization of **simplified geometries**

Design of **low-boom, low-drag aircraft**

❖ Adding geometrical complexity
❖ Using higher cost CFD methods

- Optimization of the fuselage
- Optimization of configurations with enhanced complexity
  - Full aircraft configurations including tail (pitching momentum trimmed)
  - Engine integration
- Variable fidelity optimizations (Euler and RANS)
- Supersonic natural laminar flow

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Acknowlegments

- Gérald Carrier (ONERA)
- Arno Ronzheimer, Gunther Wilke (DLR)
- Ueno et. al (JAXA)
- Low boom community

Thank you for your attention.
Questions?

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Backup Slides

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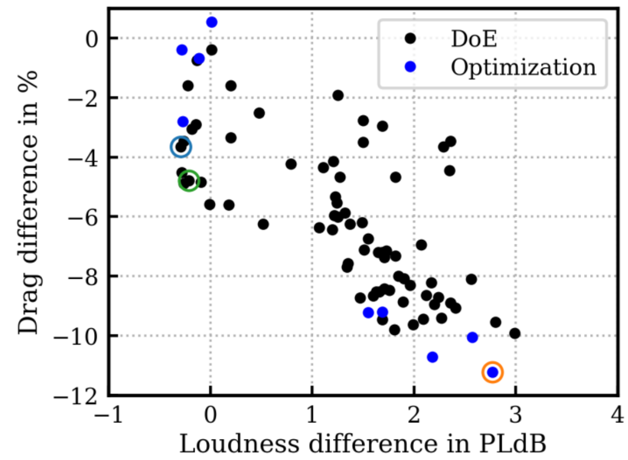
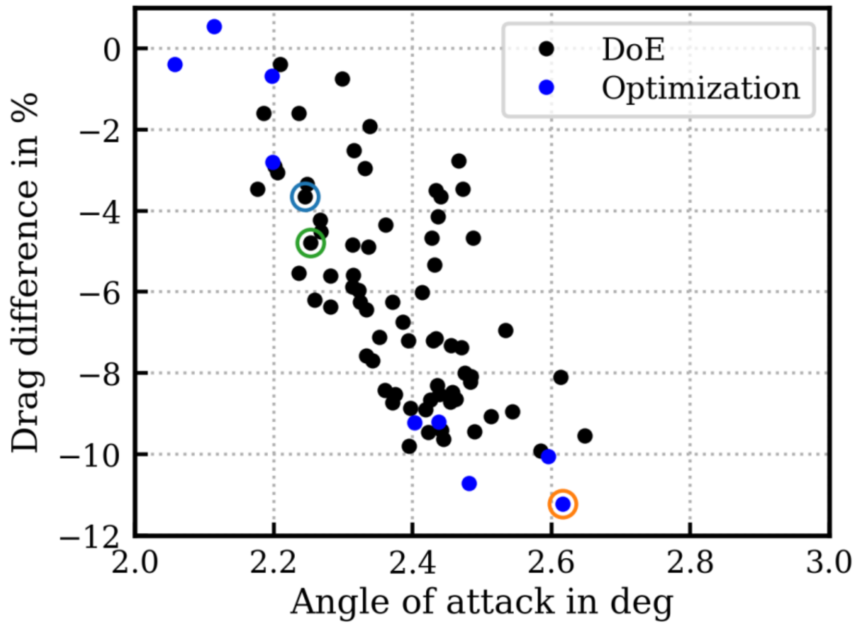
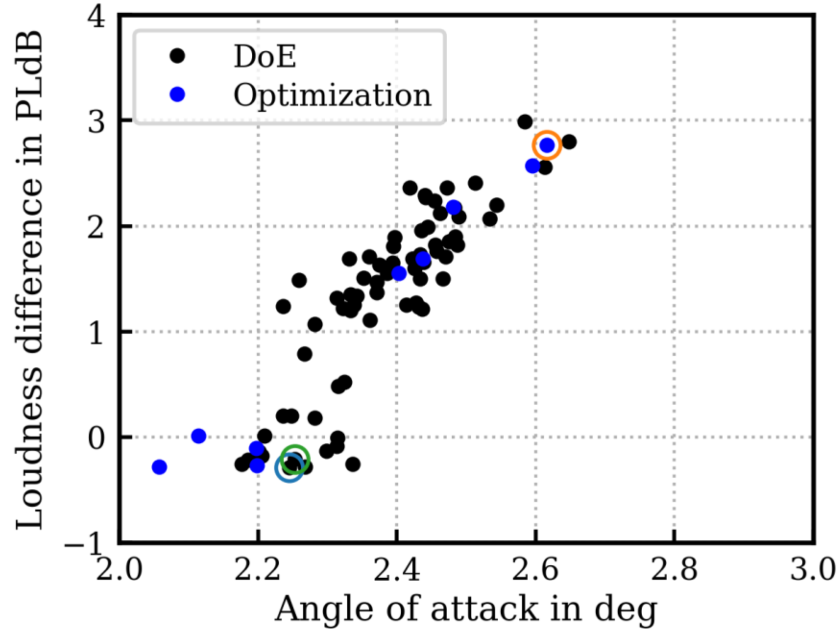
Results

Optimization of the Outer Airfoil

Correlation between the aircraft angle of attack and the loudness as well as drag

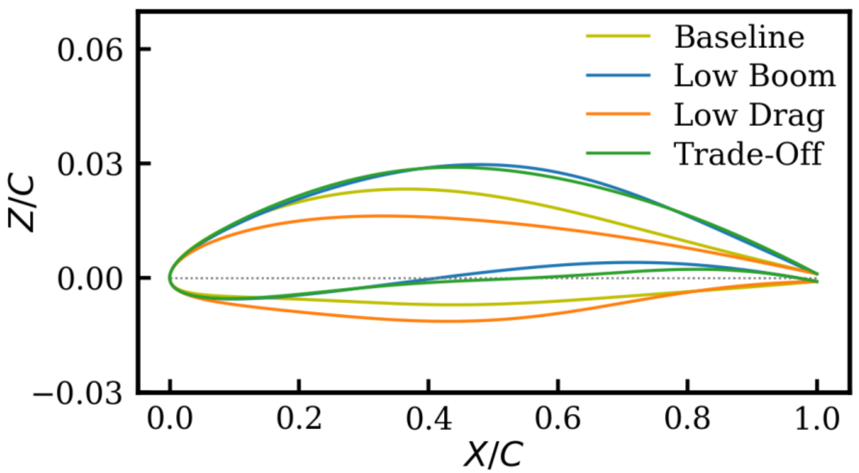


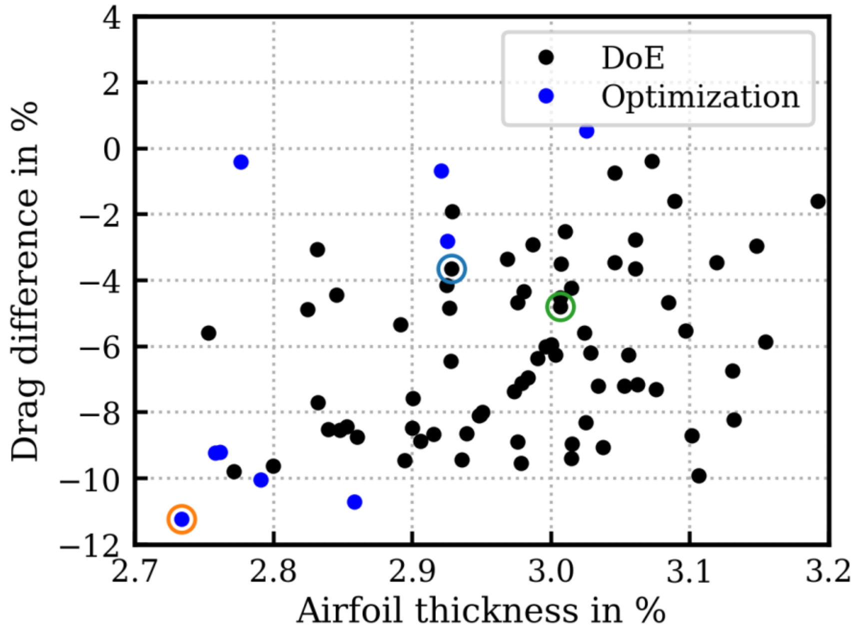


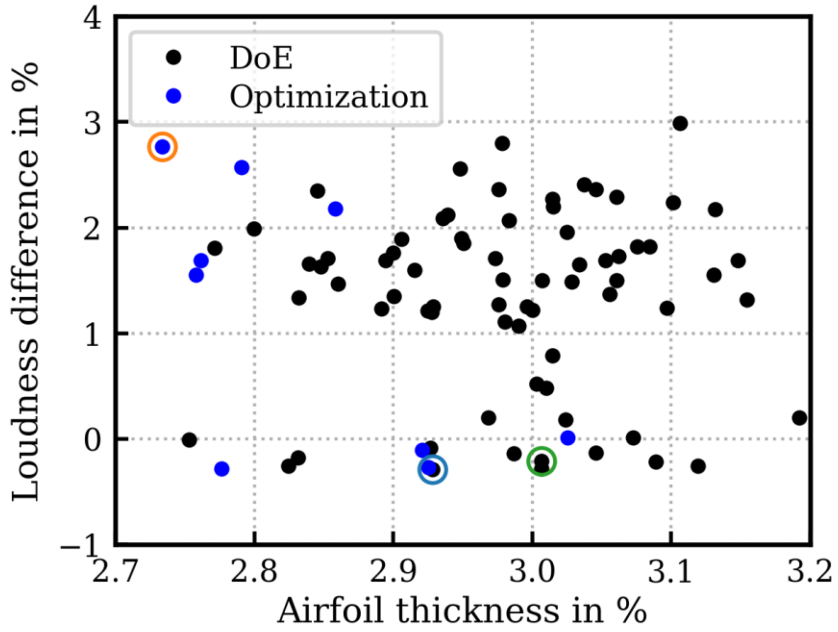


Results

Optimization of the Outer Airfoil

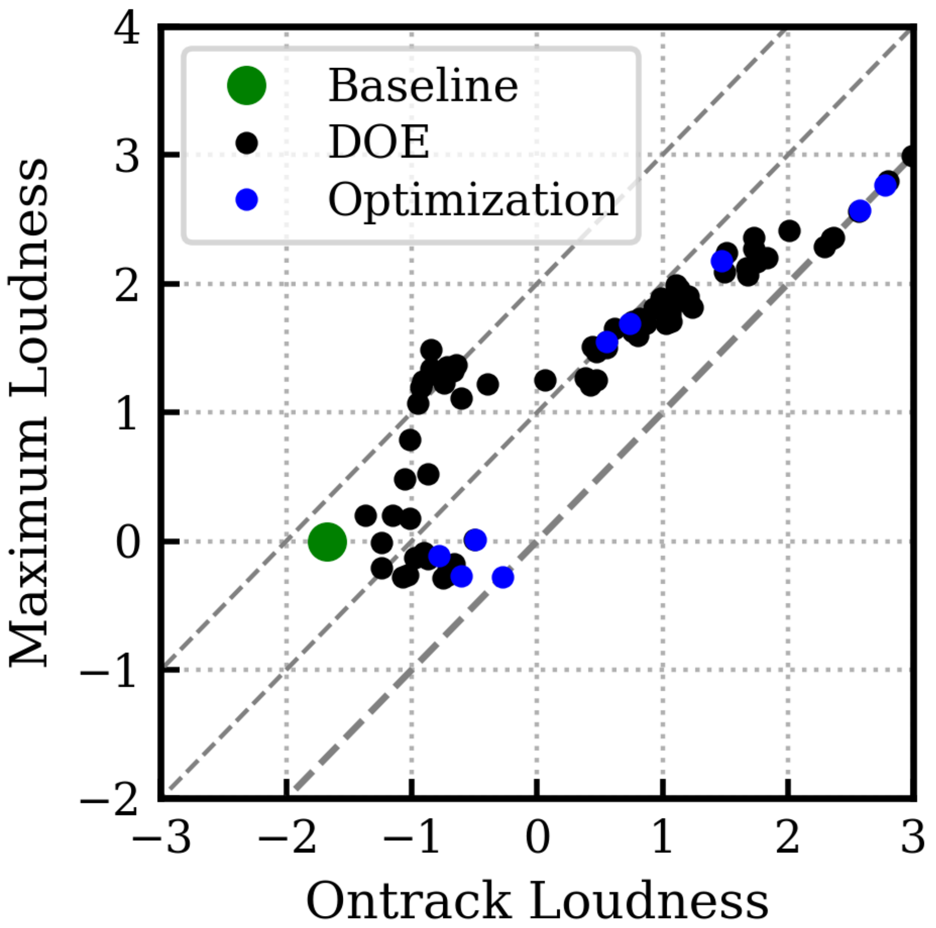






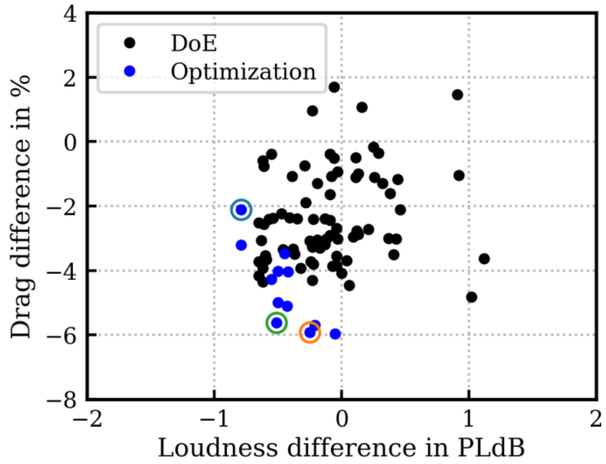
Results

Optimization of the Outer Airfoil



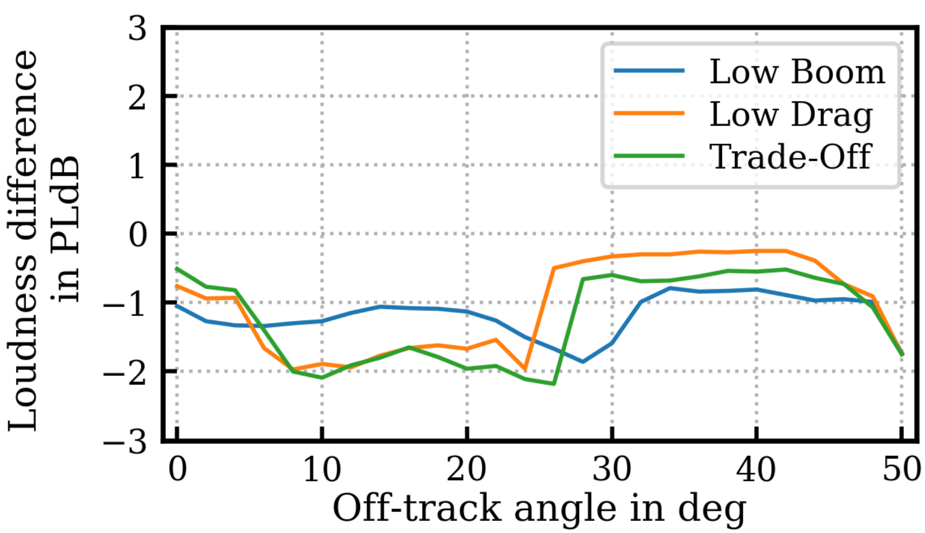
Results

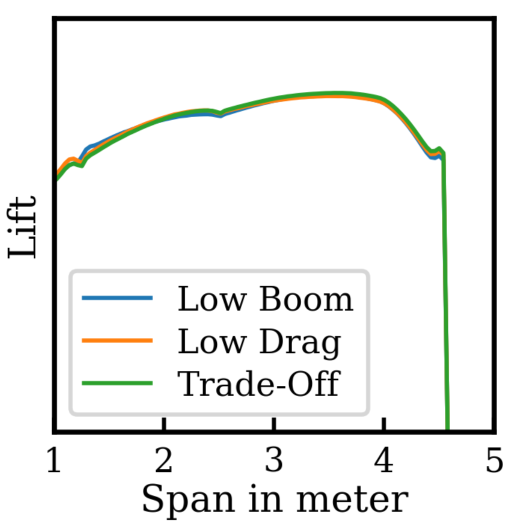
Optimization of the Inner Airfoil



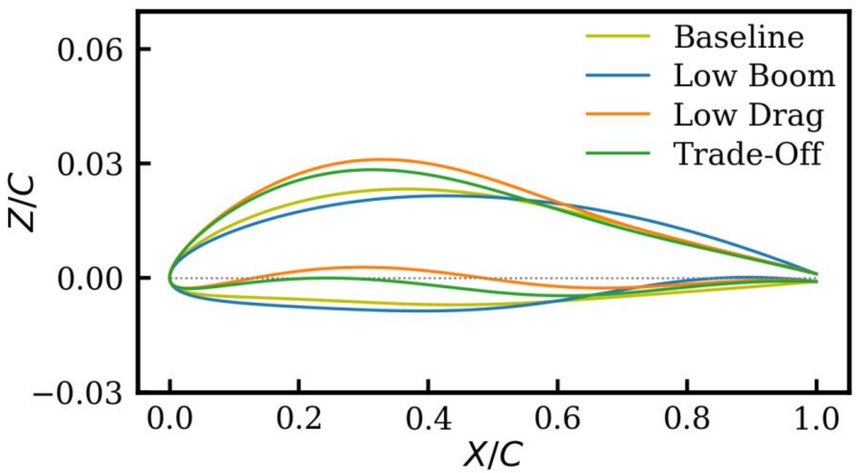
Pareto confidence reached after 19 iterations

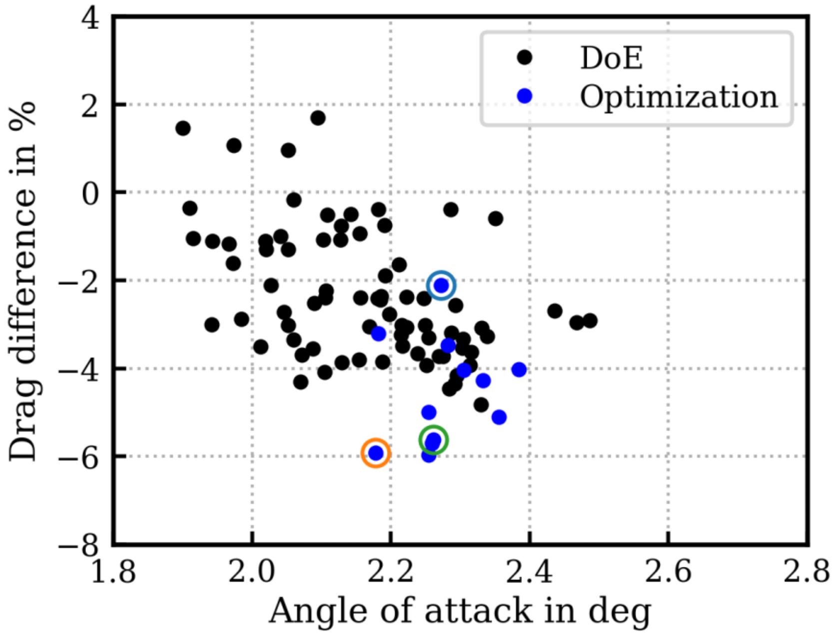
- Low boom: nearly symmetric airfoil
- Low drag: high camber airfoil

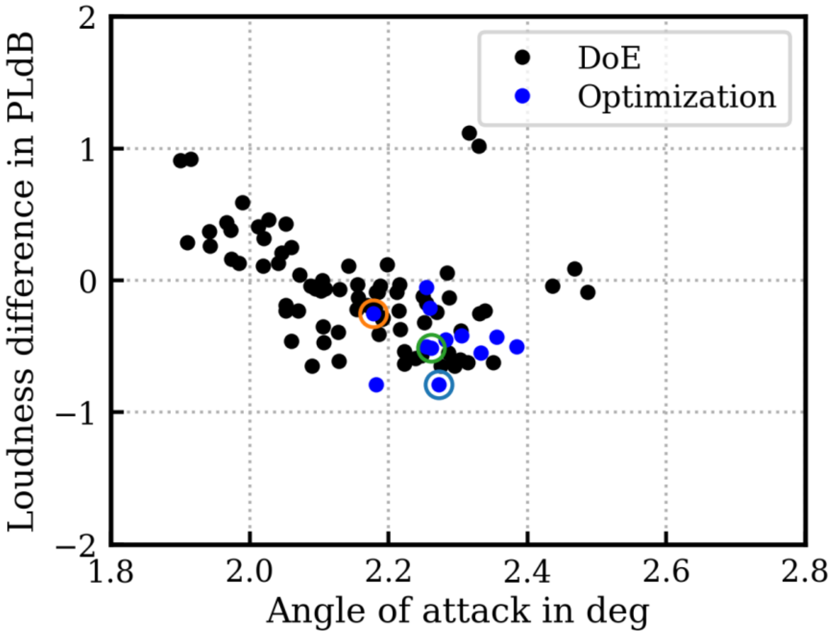




Results
Optimization of the Inner Airfoil

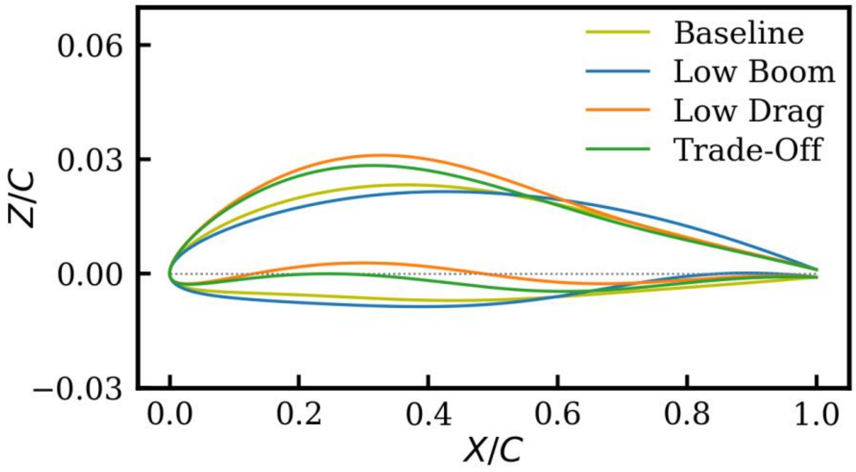


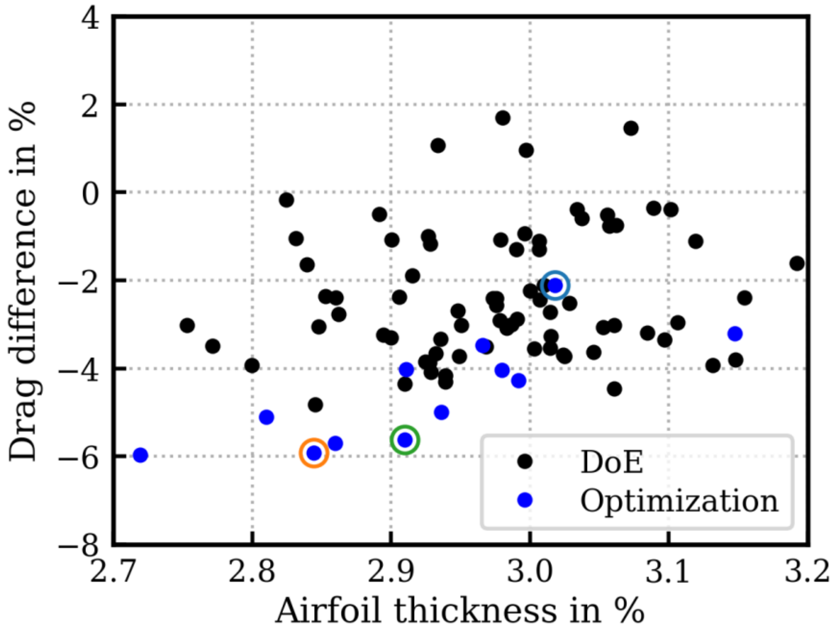


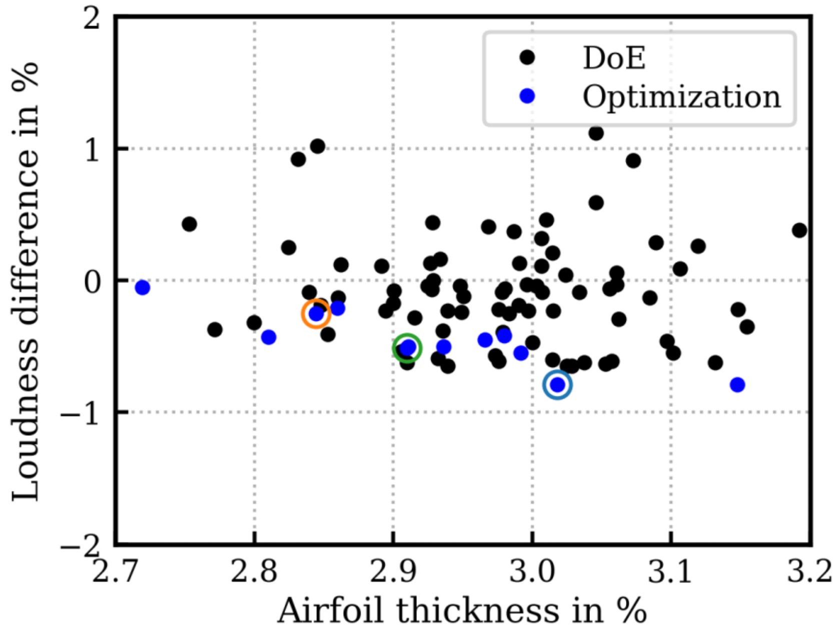


Results

Optimization of the Inner Airfoil







Results

Optimization of the Inner Airfoil