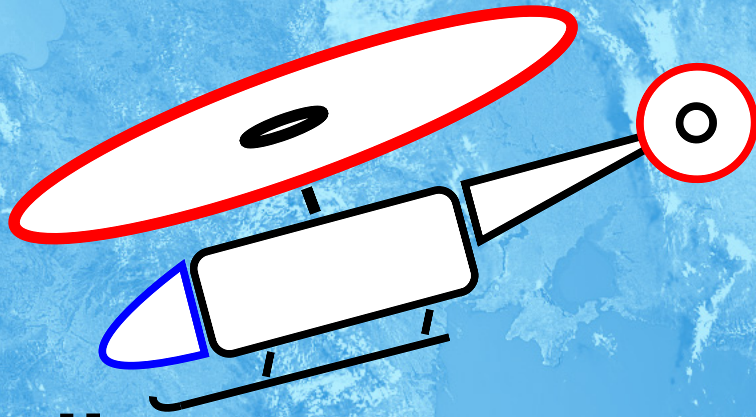
# Successive Optimization Of Airfoils, Planform And Twist For Aerodynamic Performance Of Helicopter Rotor Blades



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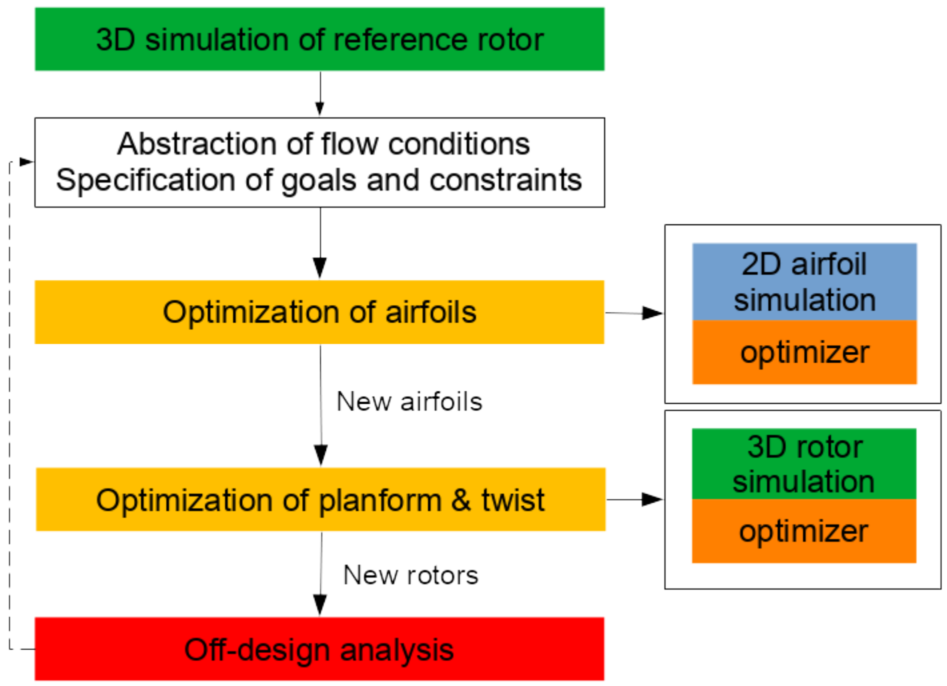
DLR

# Motivation & Introduction

- We want better rotor blades!
- The aerodynamic & acoustic design of a helicopter rotor blades includes
  - Airfoil design
  - Planform design
  - Twist distribution
- Including parameters all parameters in a single pass too difficult
- The shown approach fuses existing design approaches with numerical optimization:
  - Airfoil design is done in the 'classical' sense: 2D analysis
  - Optimize planform & twist of the rotor with the new airfoils
- DLR currently develops a new rotor blade including the structural dynamic design and manufacturing constraints. Only aerodynamic design shown here



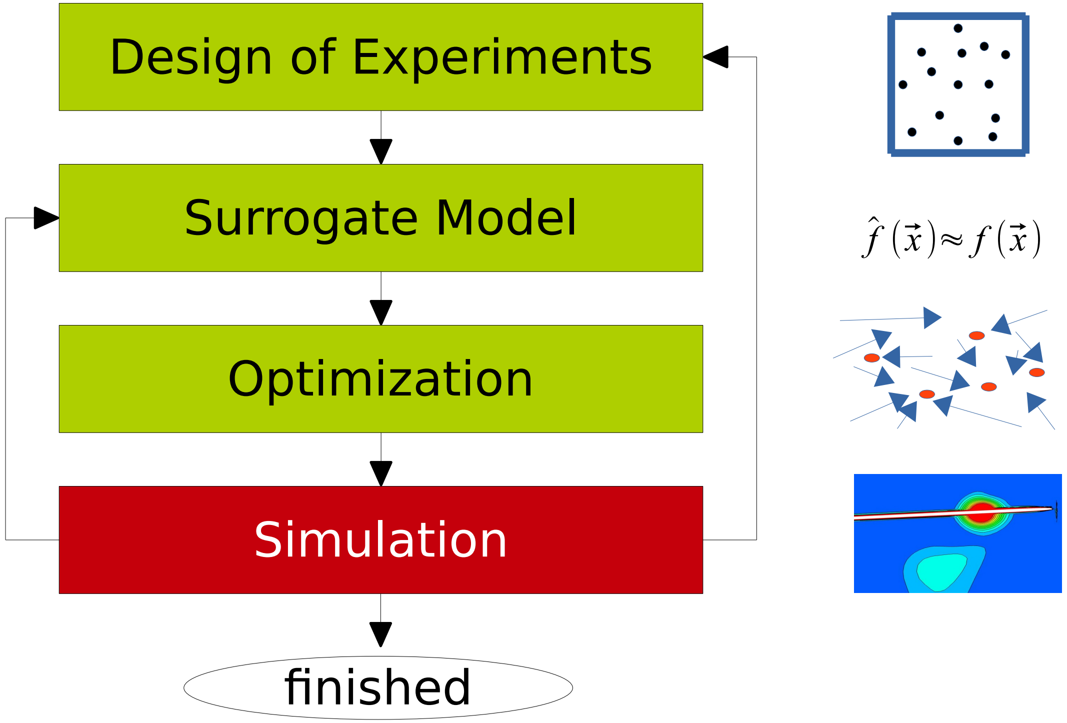
# Overview

- Motivation and Introduction
- Methodology
  - Optimization
  - Airfoil Simulation*
  - Rotor Simulation
- Design
  - Airfoils*
  - Planform & Twist
- Off-Design Analysis
- Summary & Outlook

* work presented at 48th European Rotorcraft Forum, Winterthur Switzerland, 2022 [11]

# Methodology Optimization

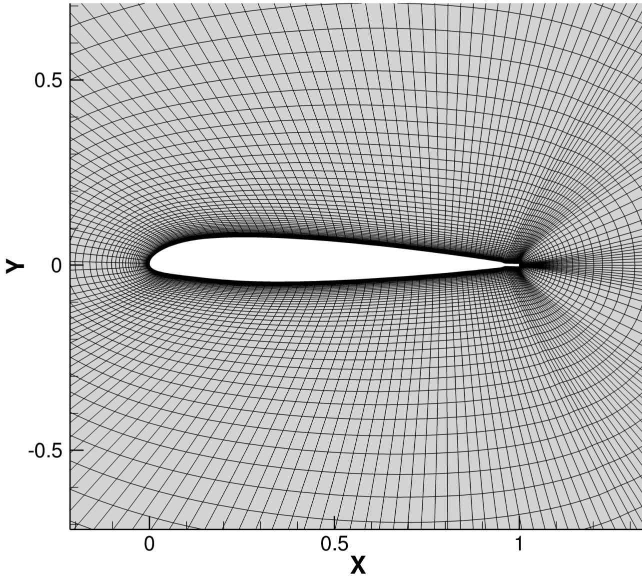
- Surrogate based optimization [19] using
  - MacQueen's method as a Design of Experiments [17]
  - Kriging with regularization/noise constant as surrogate model [18]
  - Chained optimization strategy
    - DoE to initialize population
    - Differential evolutionary [20] (with NSGA-II sorting [21] for multi-objective optimization)
    - Simplex algorithm [22] for local refinement.



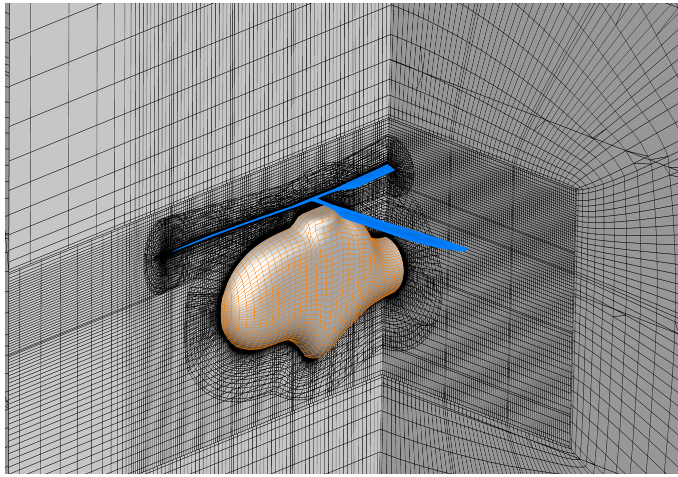
# Methodology Simulation

- DLR's legacy flow solver FLOWer used [26]
- Steady simulation for airfoils: Local time stepping with SGS [27]
- Dual time stepping / BDF2OPT with γ=0.48 for rotors
- Implicit residual smoothing and 3V multigrid
- MUSCL & SLAU2 [28,29,30] for inviscid fluxes with 3rd order for airfoils / 4th order for rotors
- Viscous fluxes 2nd order MUSCL & SLAU2
- SA turbulence model [31] with DDES-R extension for rotor simulations [37,38]
- Empirical transition prediction:
  - $c_{p,min}$ in case of shocks
  - AHD for TS-waves [32]
  - Laminar separation
  - C1 crossflow criterion (for rotors only)
  - Bypass transition Mayle (for rotors only)
  - Attachment line Pfenninger/Poll (for rotors onl)
- 8th order langrage interpolation for Chimera
- <u>FS-coupled with comprehensive code HOST [39] for rotor simulation</u>

192x96 cells
for optimization




Forward flight
grid



Optimization: 670k cells hover, 2.2e6 cells forward flight
Off-Design: 2.9e6 hover, 4.9e6 forward flight

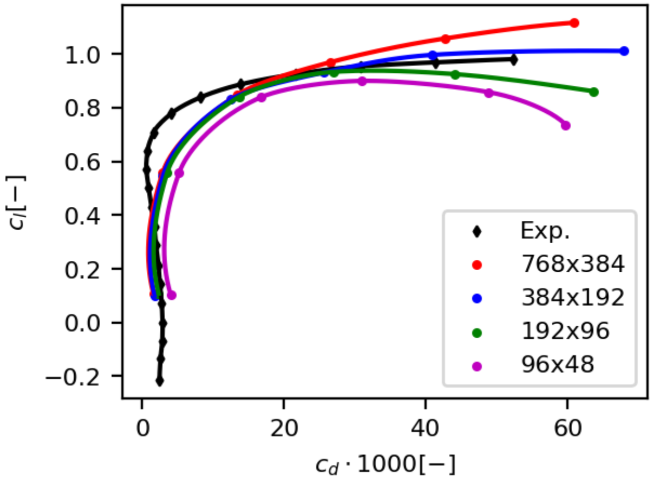
# Methodology Airfoil Simulation

- Validation against DSA9a wind tunnel test by Richter et al.[34]

- Finer grids overshoot maximum lift coefficient $c_{l,max}$

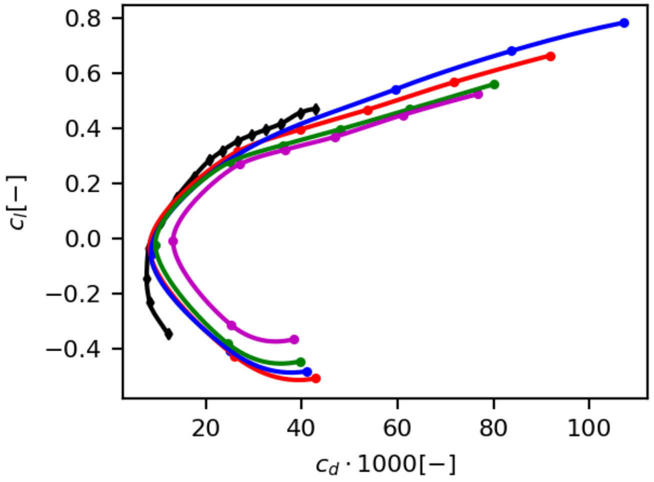
  → Wind tunnel blockage and side wall effects not modeled

- 3rd level (192x96 cells) reasonable trade-off between speed and accuracy

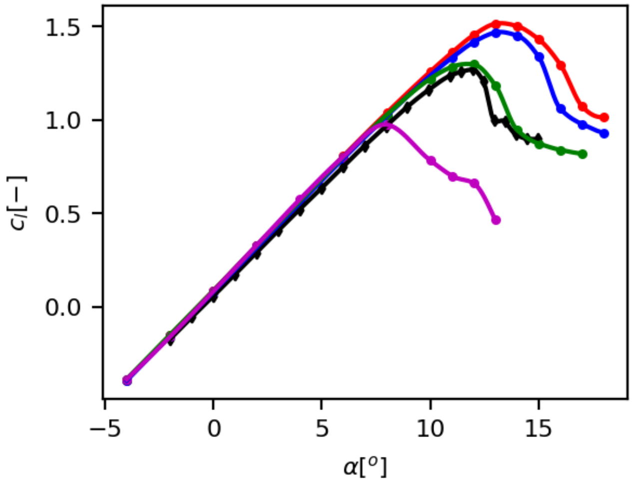


Mach 0.6

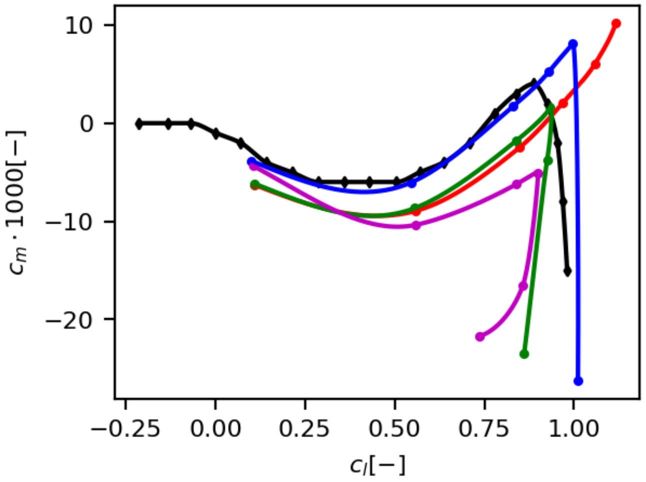
inviscid drag only!



Mach 0.85

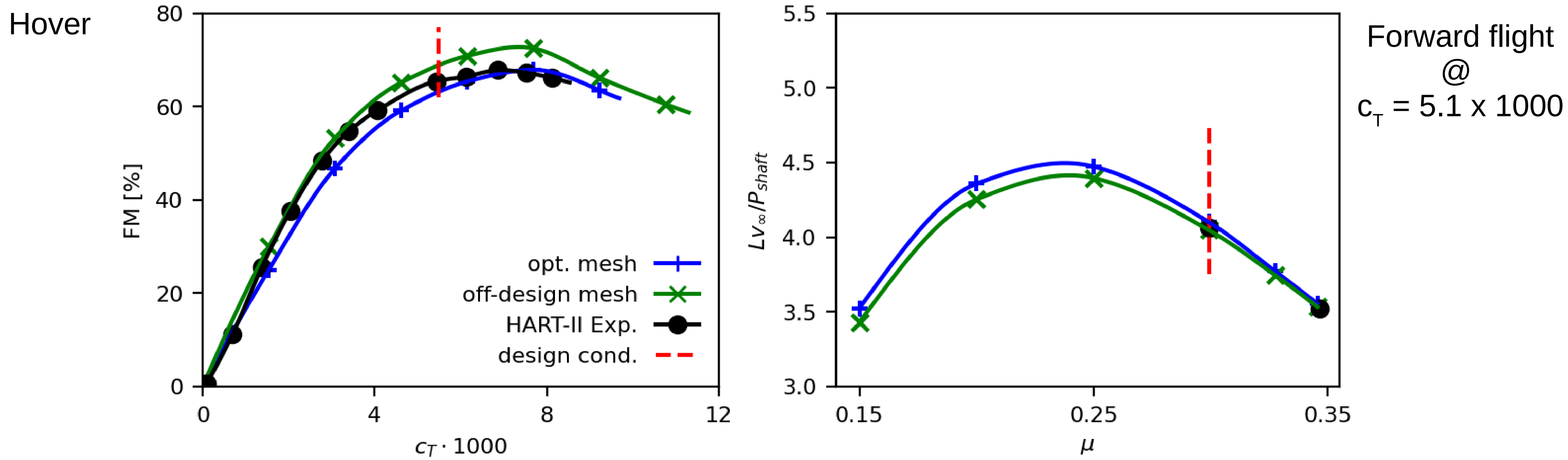


Mach 0.3



Mach 0.6

# Methodology Rotor Simulation




- Validation of CFD grids against wind tunnel test of Bo105 blade “HART-II” in the FTK campaign [40].
  - Hover meshes lack wind tunnel → lack of re-circulation → too good FM on finer mesh!
  - Forward flight matches well
- Grid study in [41]

# Design Goals

- Goal: reduction of required power in hover and forward flight
  - Explicitly used for rotor optimization
  - Flow conditions are derived for airfoils (next slide)
  - Airfoil goal is minimization of drag
- Implicit Constraints
  - Trimmed rotor
  - same lift coefficient for airfoils
- Explicit constraints
  - Peak to peak root torsion moment of rotor
  - Minimum maximum lift of airfoils on retreating side
  - Average pitching moment of airfoils in hover condition

| parameter | value | |
|---|---|---|
| no. blade | 4 | |
| radius | 2 m | |
| chord | 0.121 m | |
| tip Mach | 0.64 | |
| | hover | forward flight |
| $c_T \cdot 1000$ | 5.5 | 5.1 |
| $c_X \cdot 1000$ | 0 | 0.6 |
| $c_{mr}, c_{mp}$ | 0,0 | 0,0 |
| advance ratio $\mu$ | 0 | 0.3 |
| trim angles | $\theta_0$ | $\theta_0, \theta_c, \theta_s, \alpha_q$ |

Rotor specs & flight conditions

| 12% only | Mach | Re x $10^6$ | $c_l$ range |
|---|---|---|---|
| retreating | 0.10 | 0.1 | max |
| hover | 0.65 | 1.9 | 0.2 ... 0.6 |
| advancing | 0.75 | 2.1 | -0.2 ... 0.2 |
| 12% inboard | Mach | Re x $10^6$ | $c_l$ range |
| retreating | 0.10 | 0.1 | max |
| hover | 0.52 | 1.5 | 0.3 ... 0.6 |
| advancing | 0.75 | 2.1 | -0.1 ... 0.3 |
| 9% outboard | Mach | Re x $10^6$ | $c_l$ range |
| retreating | 0.42 | 1.2 | max |
| hover | 0.65 | 1.9 | 0.2 ... 0.4 |
| advancing | 0.88 | 2.5 | -0.2 ... 0.1 |

Airfoil flow conditions

# Design Airfoils

- For 2D airfoil design, flow conditions need to be derived
- 3D loads from CFD simulations to estimate target lift coefficient $c_l$

$$c_l = c_z cos\phi - c_x sin\phi \quad (1)$$

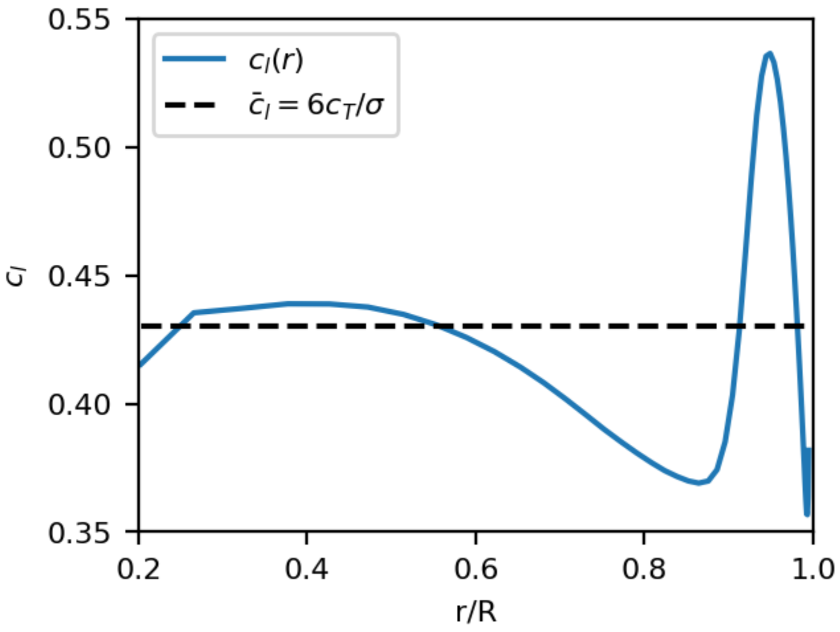
$$c_{x,z} = \frac{2}{\rho c V^2}\frac{dF_{x.z}}{dr} \quad (2)$$

$$\phi = \arctan(v_i/V) \quad (3)$$

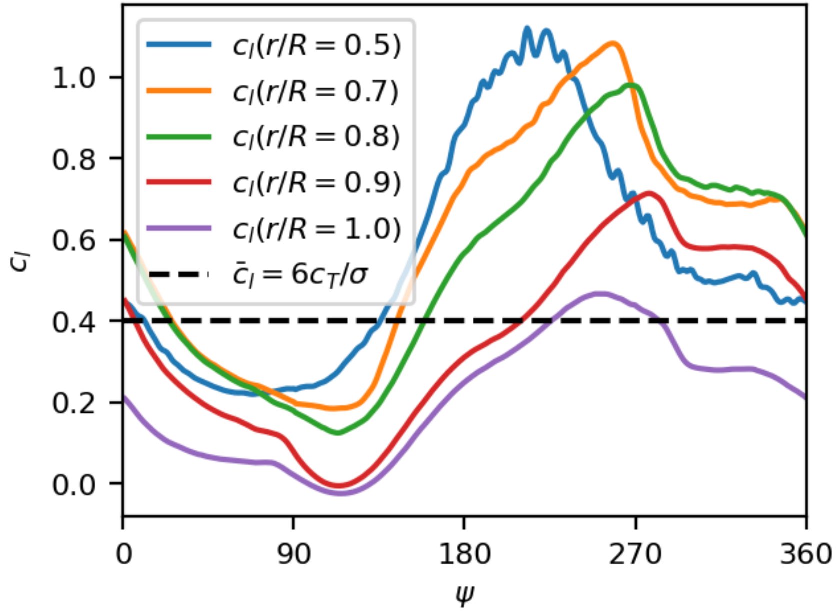
$$v_i \approx -\frac{v_\infty \sin\alpha_q}{2} \pm \sqrt{|(\frac{v_\infty \sin\alpha_q}{2})^2 + \frac{n_{blades} dF_z}{4\pi\rho_\infty r dr}|} \quad (4)$$

$$V \approx \sqrt{(\Omega r + v_\infty \cos\alpha_q sin\psi)^2 + (v_\infty \sin\psi + v_i)^2} \quad (5)$$

- Selected a range of lift coefficients for investigation of
  - Hover
  - Retreating side
  - Advancing side




Hover lift coefficient estimation

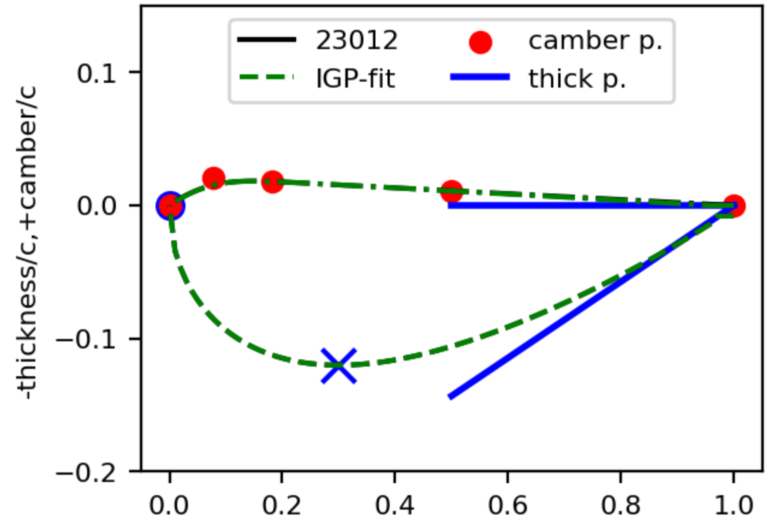



Forward flight lift coefficient estimation (μ=0.3)

# Design Parameters

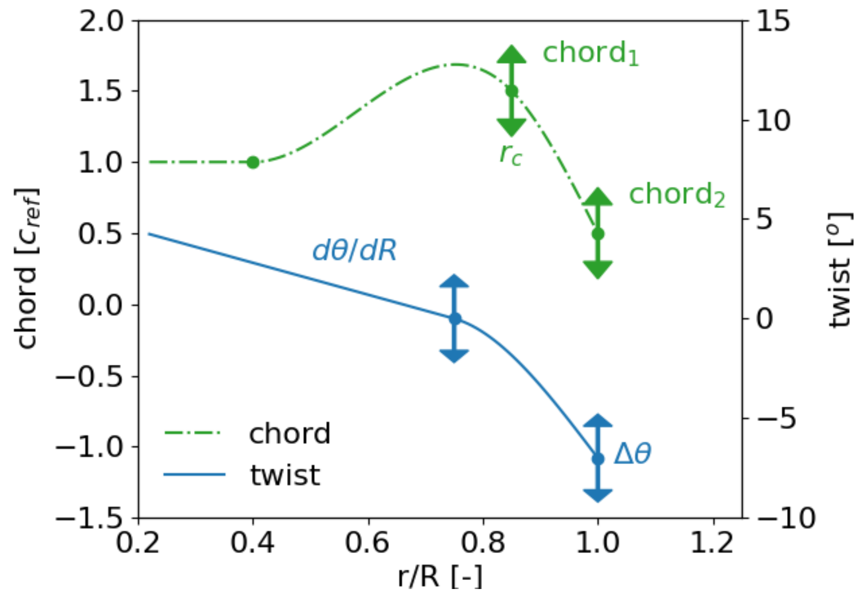
- Airfoils
  - parameterized with “Improved Geometric Parameterization” by Xiaoqiang et al. [23] (camberline & thickness distribution)
  - Added a tab function (see paper)
  - 8 design variables in total

camberline and thickness distribution of IGP fit



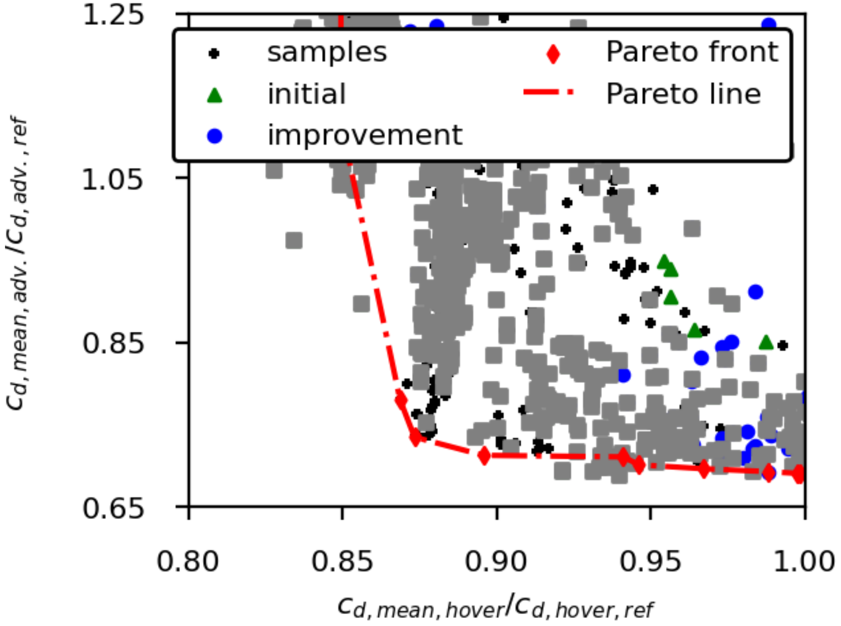

- Rotors
  - cubic spline for chord length
  - linear twist with a tip offset given through a spline
  - Total of 4 parameters

Exemplary rotor parameterization

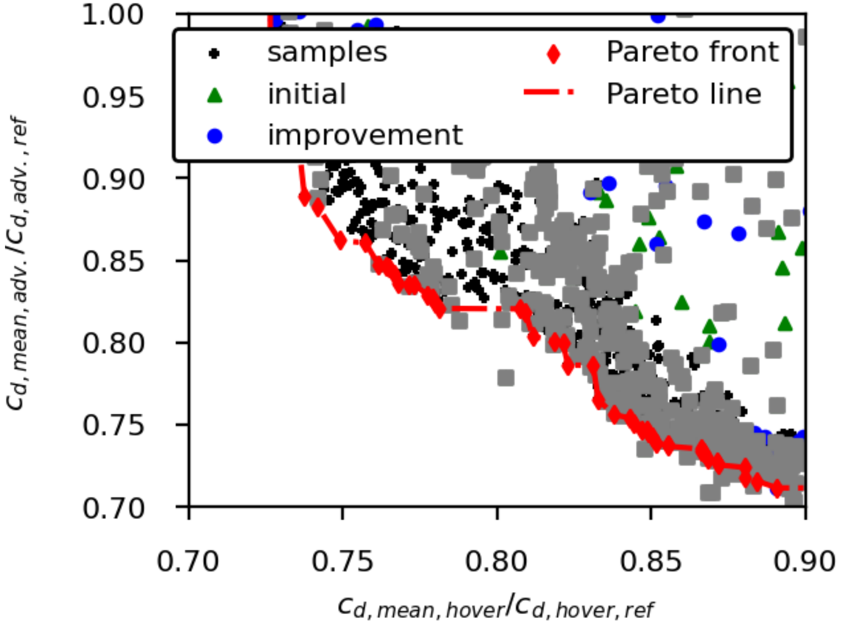


# Design Airfoils

- 1120 and 1351 simulations with 11 and 49 Pareto optimal designs for 12% and 9% airfoil optimization
- many designs violate a constraint, either they
  - miss maximum lift
  - exceed the pitching moment
- Subset of three airfoils selected
  - Best hover airfoil
  - Best advancing side airfoil
  - Balanced airfoil



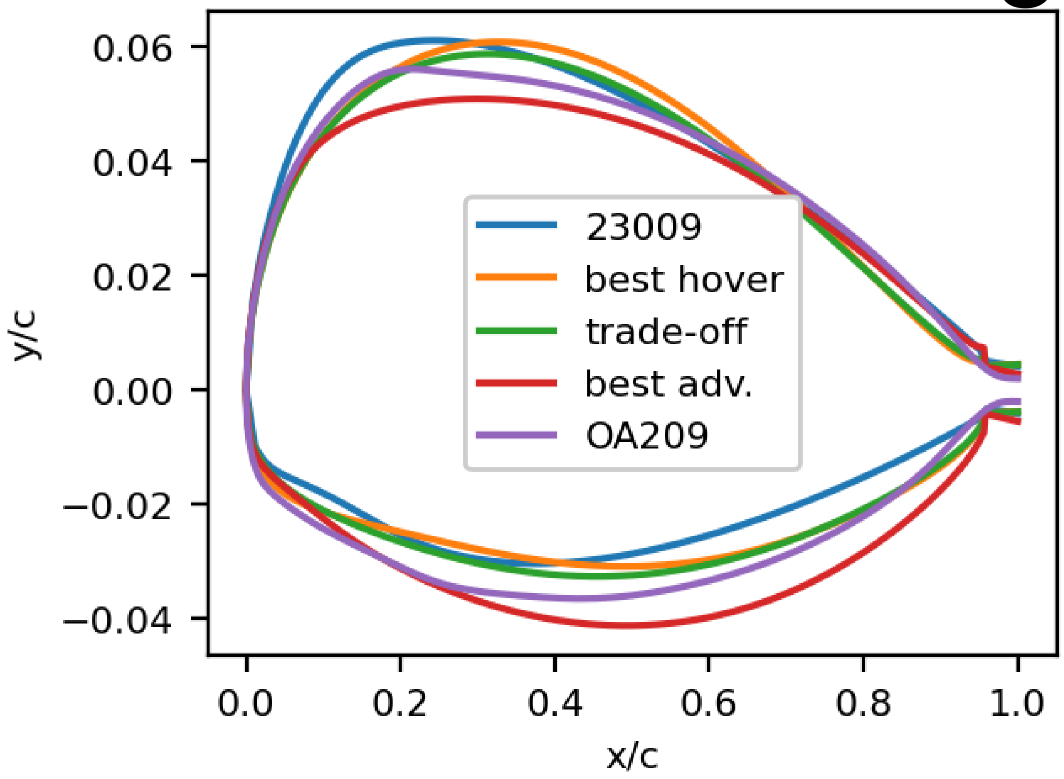

12% inboard optimization

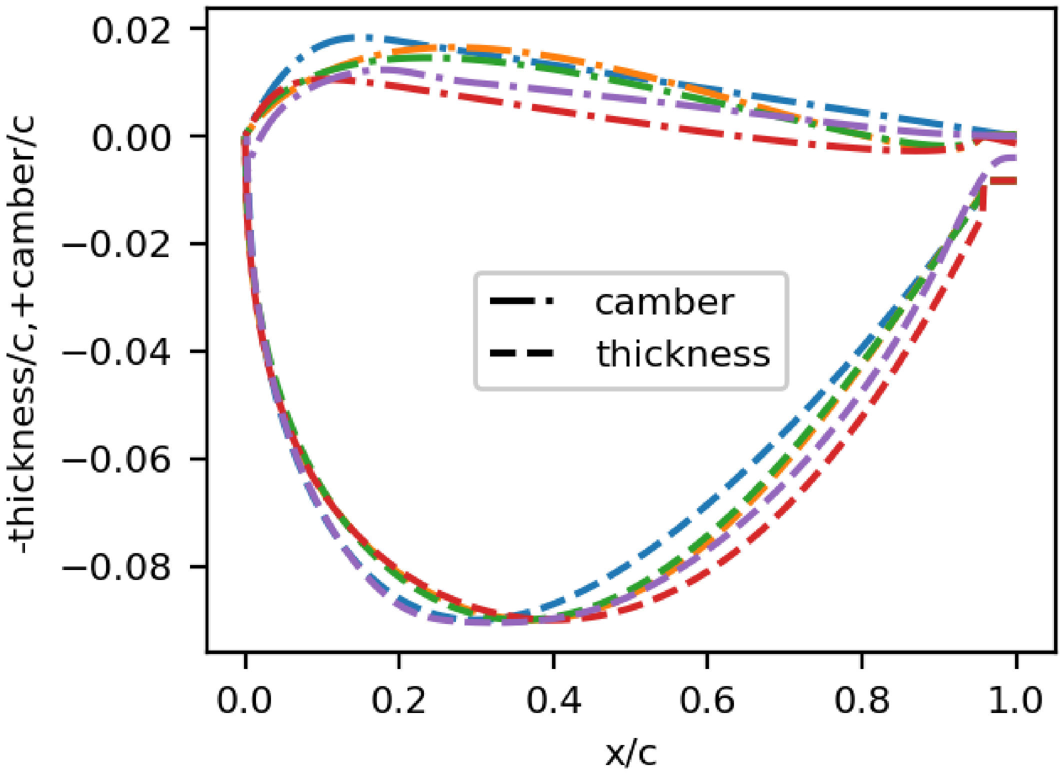



9% outboard optimization

For brevity, only 9% airfoil presented on the next slides

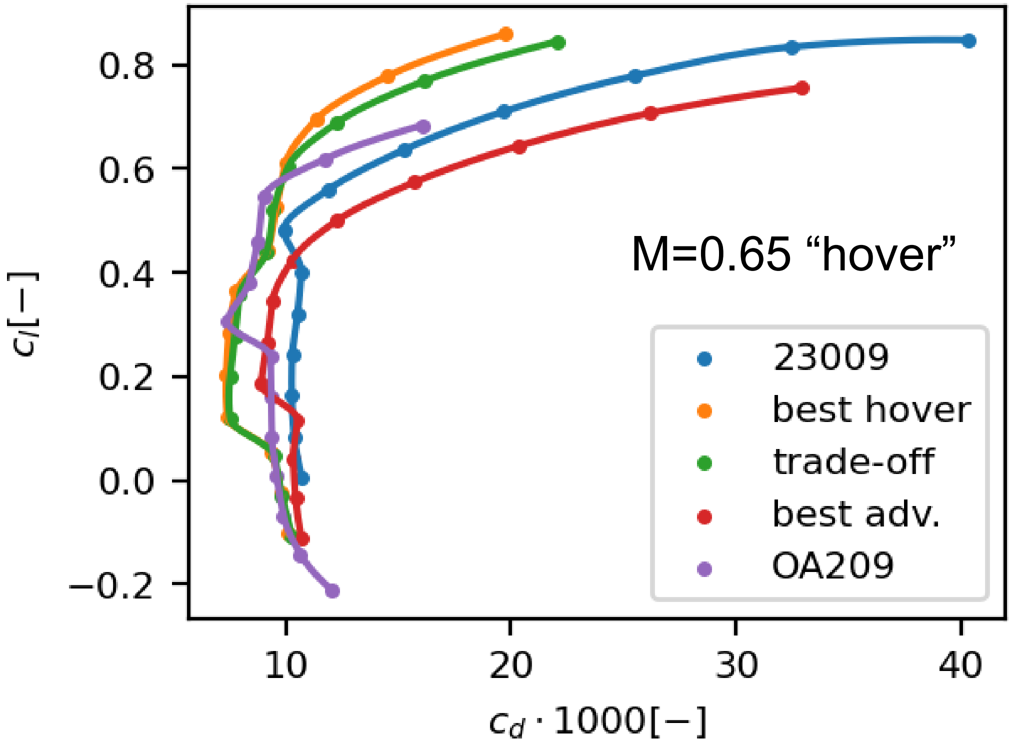
# Design Airfoils

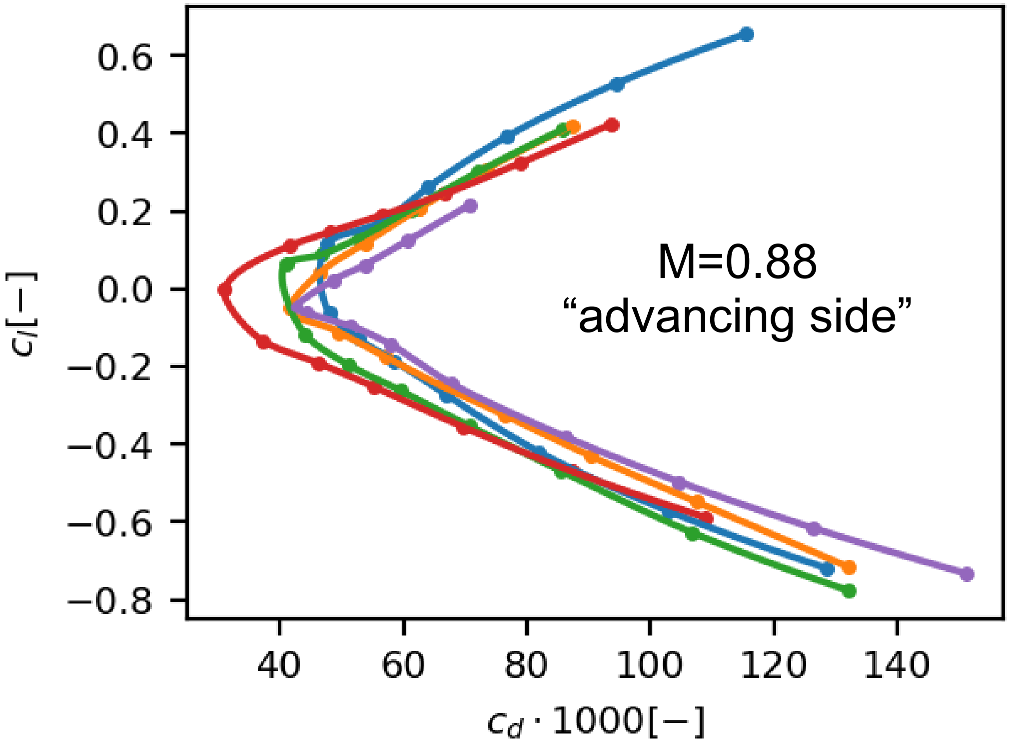



- Maximum thickness and camber shifted back from 23009
- Best advancing side airfoil has least camber, best hover airfoil the most

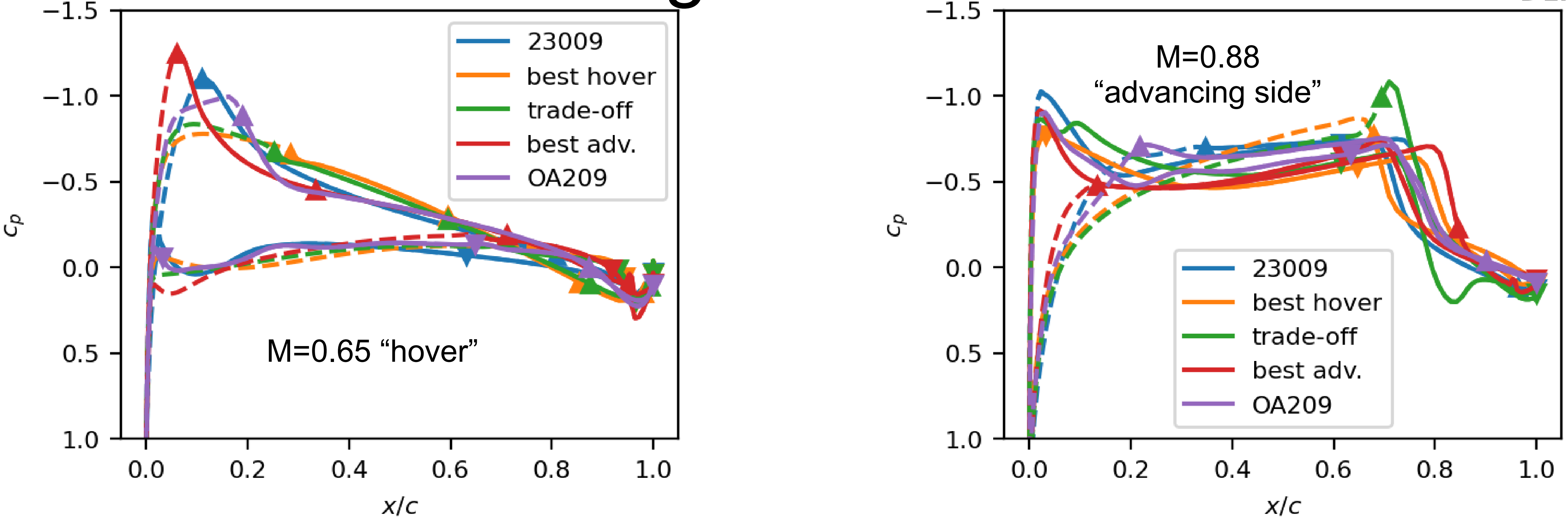
# Design Airfoil



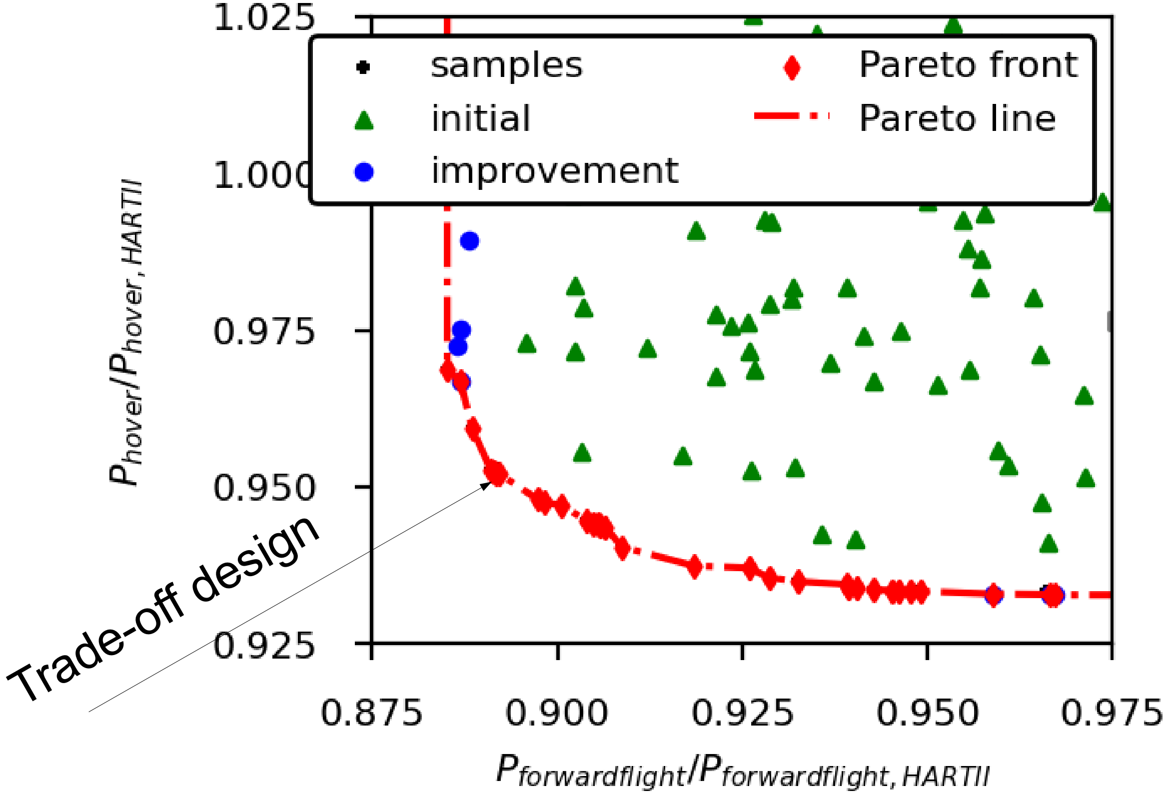

- In hover, all airfoils have a good "drag bucket"
- On the advancing side, only trade-off and best advancing side design prevail

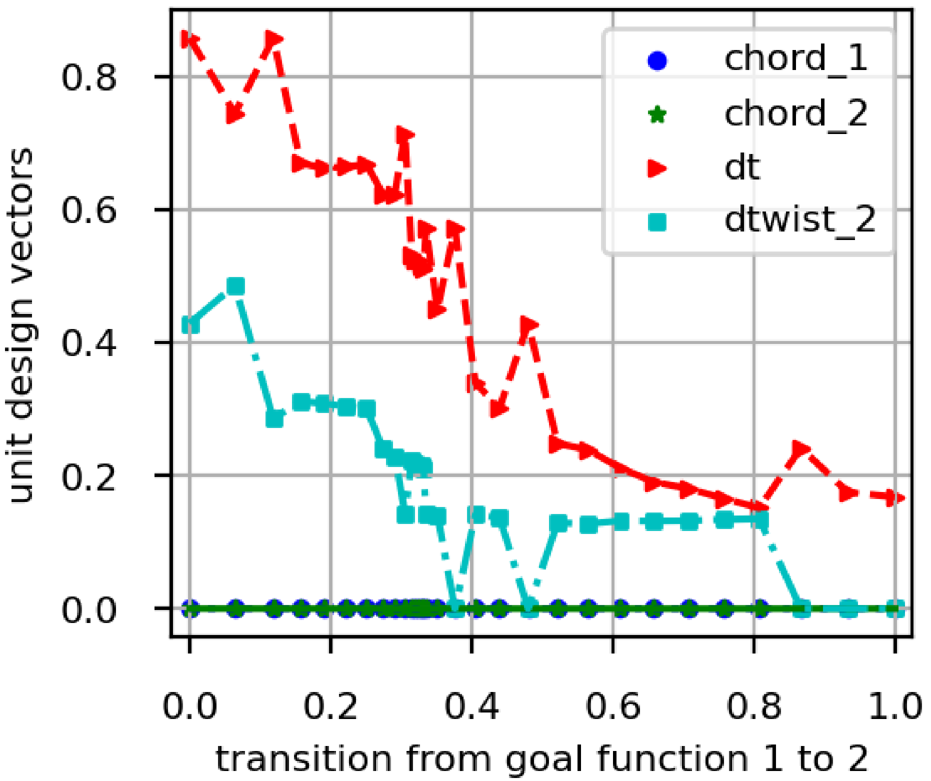
# Design Airfoil




- Hover conditions benefits from smoothed suction peak → more laminar flow trough later maximum thickness
- Advancing side benefits reduced shock → more gradual aft airfoil section

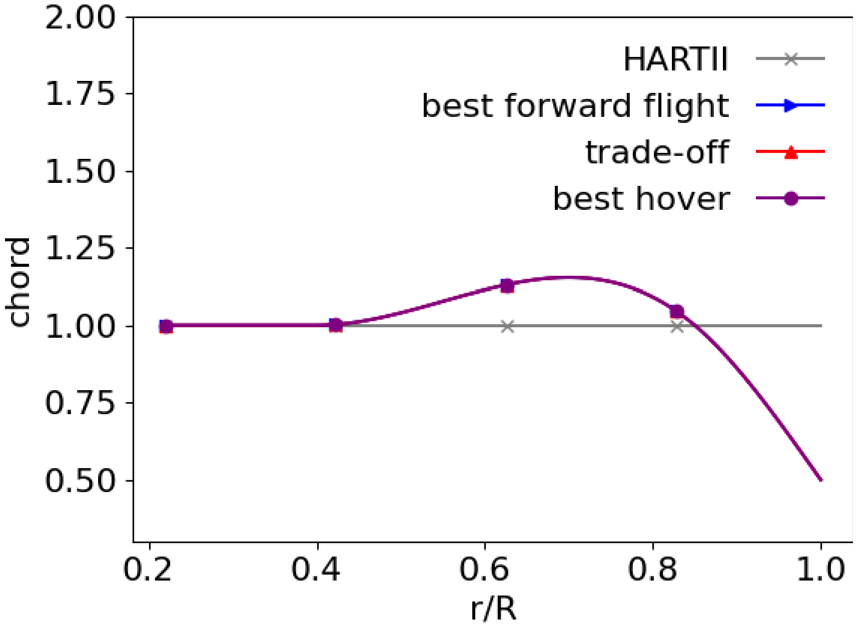
# Design Planform & Twist

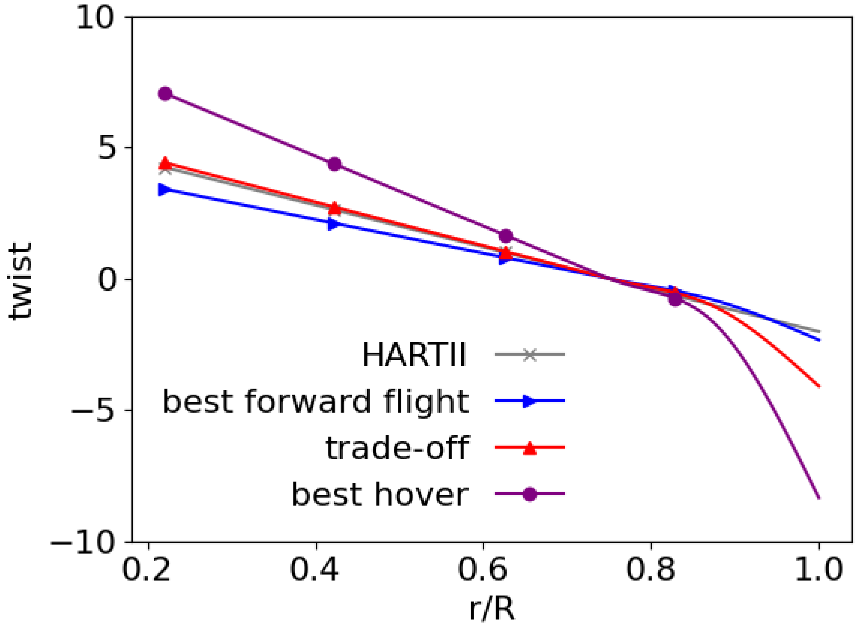


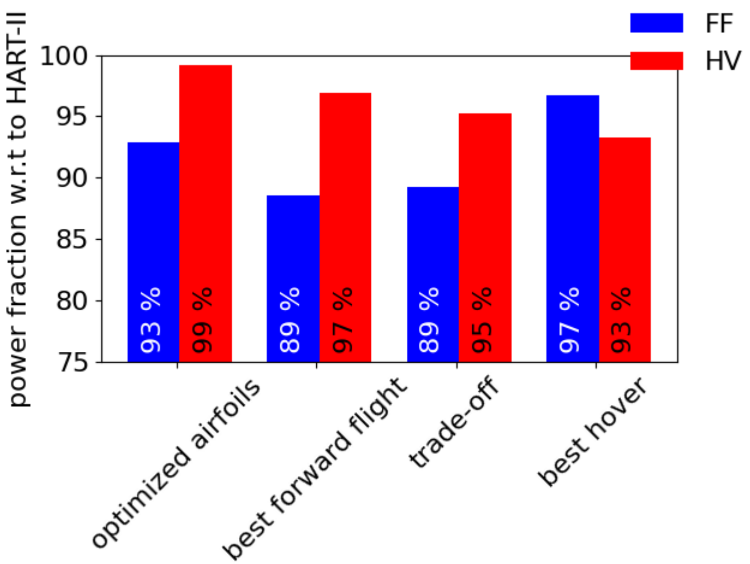




- New trade-off airfoils have been employed before hand
- 199 rotors evaluated in 2 flight conditions, 60 constraint violators, 31 Pareto optimal – turn around ~ 1 week
- General preference of tapered blade, from forward flight to hover the twist is increased

# Design Planform & Twist



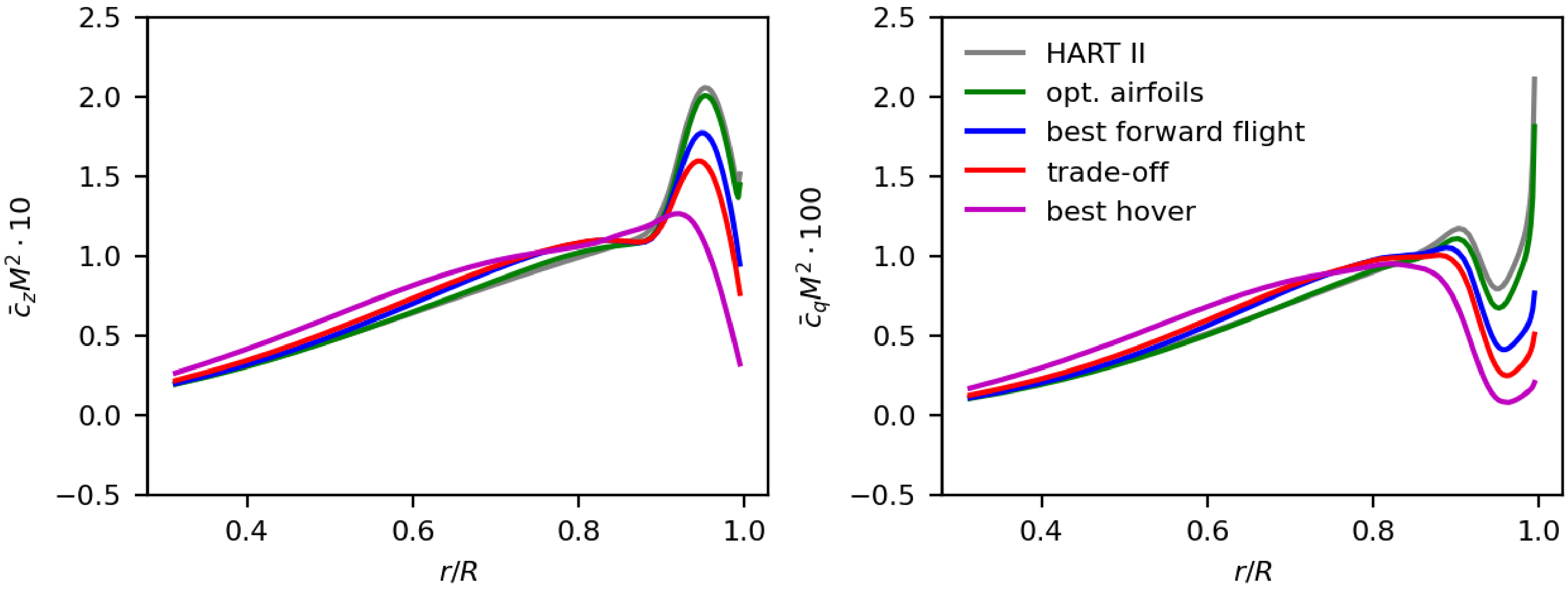




Optimization setup results

- Chord distribution is the same, an overshoot of the cubic spline is noted
- Airfoils bring greatest gain in forward flight
- Twist brings hover performance

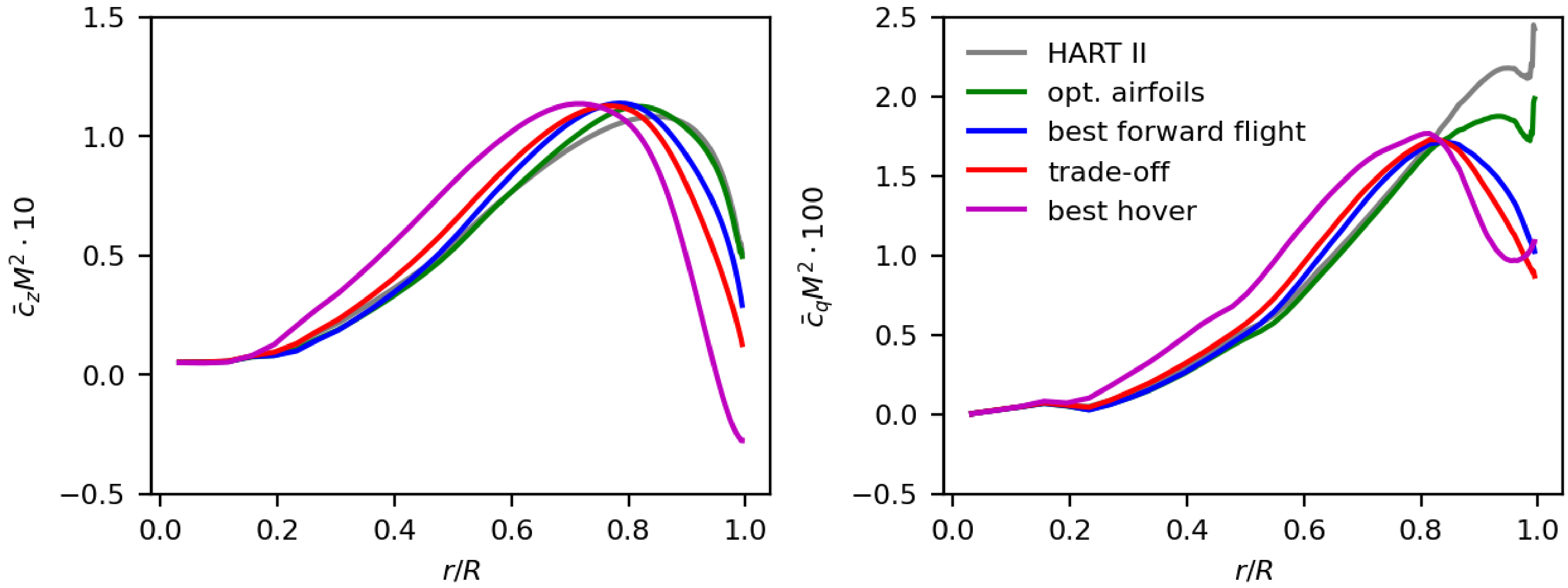
# Design Planform & Twist Hover




loads at design thrust in hover

- Airfoils have little impact on hover
- Twist offset particularly well suited to offload vortex induced lift peak

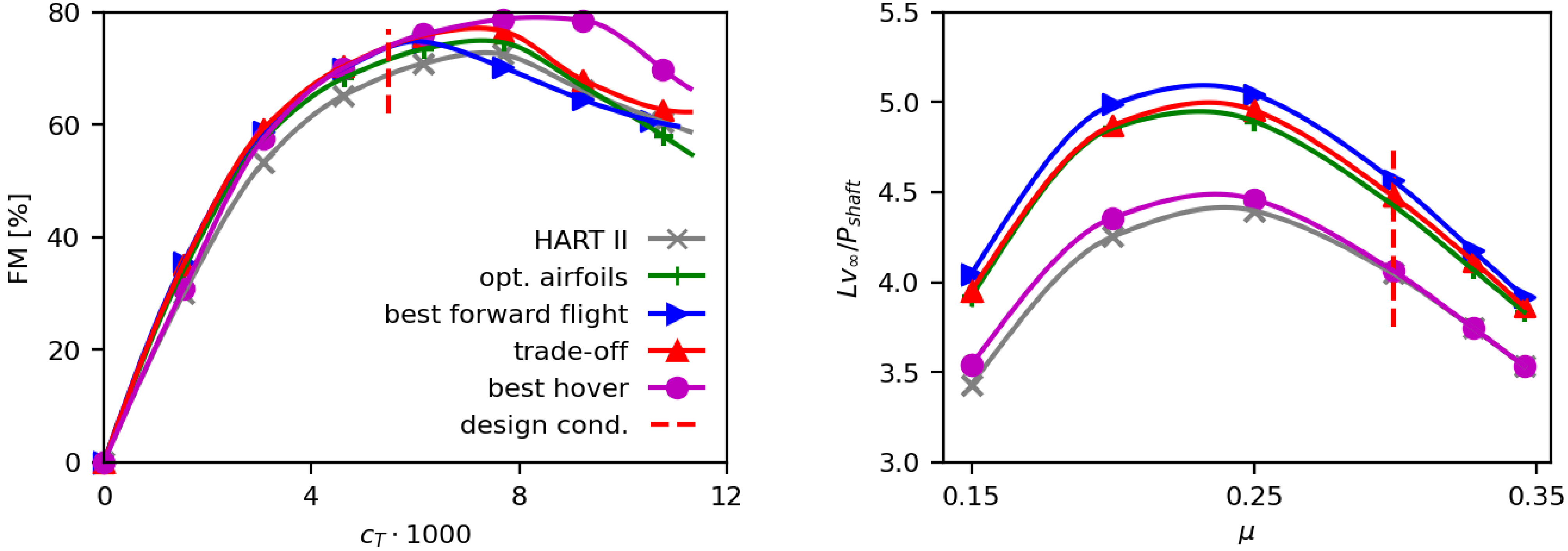
# Design Planform & Twist Forward Flight




<u>averaged</u> loads at design forward flight

- 9% airfoil helps with compressibility effects
- Too much twist leads to strong downforce on advancing side → the thust need to be bought somewhere else!

# Off-Design Analysis




- Improved airfoils raise the Figure of Merit from 69% to 72% and improve the $L/D_q$ from 4.1 to 4.4 in the design condition
- The selected blades bring these numbers to forward flight blade=(73%, 4.6), trade-off=(74%, 4.5) and hover (74%, 4.1) – best forward flight blade does not reach the same thrust level anymore in hover as the other blades
- A nondisclosed commercial design performs similar to the forward flight blade (based on the off-design simulation!)

# Summary & Outlook

- Numerical optimization used with ‘classical’ design approach – airfoils, planform & twist separated
- Through a feasible abstraction of flow conditions and goal functions, reasonable airfoil shapes could be produced
- Exchanging these on the reference rotor and optimizing its planform and twist allowed to further extend the potential
  - Airfoils helped most in forward flight, more twist in hover. Tip taper always welcomed!
- The current designs are
  - likely on par with current industrial design w.r.t. to the aerodynamic performance, but not superior
  - Acoustic and structural dynamic design need to be included and therefore will require to use more airfoils and parameters to offset limitations
- Next steps for the rotor design within DLR’s UrbanRescue/FutureRescue project
  - Perform the aerodynamic optimization with more airfoils and planform & twist parameters, but also more off-design conditions (likely delivers slightly more performance ~ 2-3% more over current design)
  - Include remaining disciplines, aero-acoustics, vibrations, structural dynamics, manufacturing

    (likely take away the 2-3% achieved from the further improved aerodynamic design)
- <u>Numerical optimization allows to tailor blades to specific requirements in exchange for weakening some design constraints</u>

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