# Ducted hydrokinetic turbine design optimization using DAFoam

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UNIVERSITY OF MICHIGAN

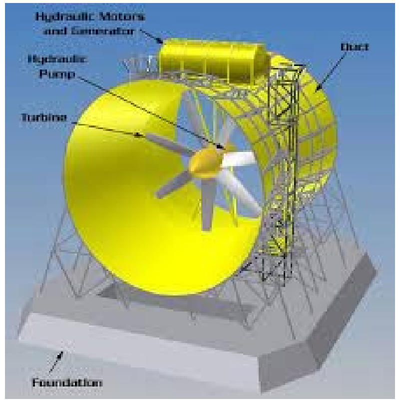
# Outline

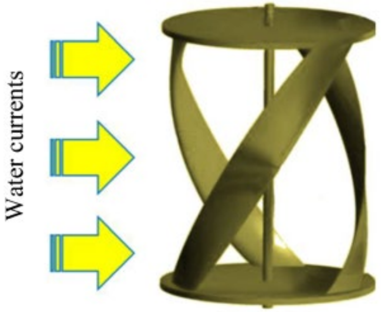
- Problem statement
- Work 1: Thin-walled ducted turbine optimization
  - Free-Form Deformation (FFD)
- Work 2: Foil-shaped ducted turbine optimization
  - Engineering Sketch Pad (ESP)

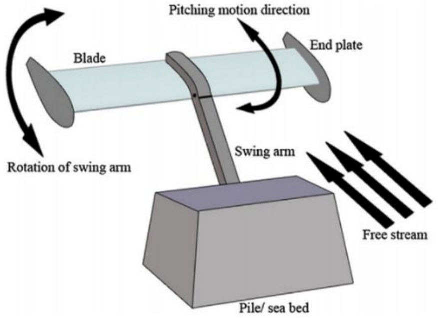
# Hydrokinetic turbine

- Device that extracts energy from natural water flows

- Various types
  - **Horizontal-axis**
    - Popular benchmark: Bahaj turbine (efficiency: 46%)
  - Vertical-axis (cross-flow)
  - Oscillating foil



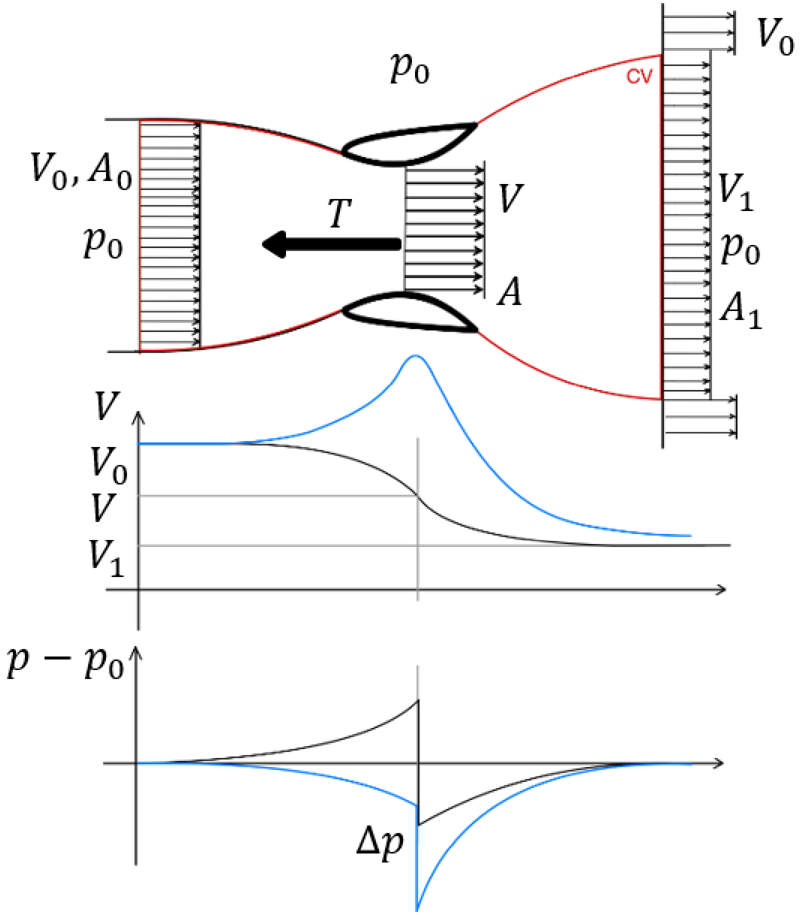




A.S. Bahaj, A.F. Molland, J.R. Chaplin, W.M.J. Batten, Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank, Renewable Energy, Volume 32, Issue 3, 2007, Pages 407-426, ISSN 0960-1481

# Improving efficiency of turbines

- Betz limit from 1D momentum theory
  - mass, momentum conservation + Bernoulli
  - Efficiency limited by 59.3%

- Introducing ‘Duct’
  - Accelerate & condition fluid flow
  - Improve overall energy extraction efficiency



# Motivation and goal

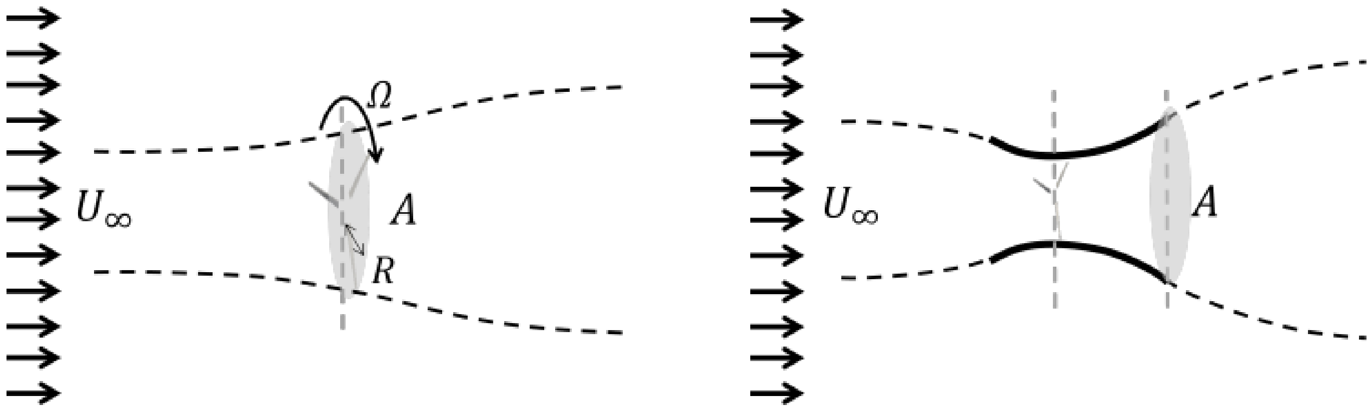
- No substantial evidence provided for the effects of ducts
- Difficult analytical explanation
  - Experimental/computational approaches are necessary
- Lack of systematic optimization with high-fidelity approach

→ Find an efficient ducted turbine design
Corroborate the benefit of using a duct

→ Design optimization using DAFoam

# Physical problem

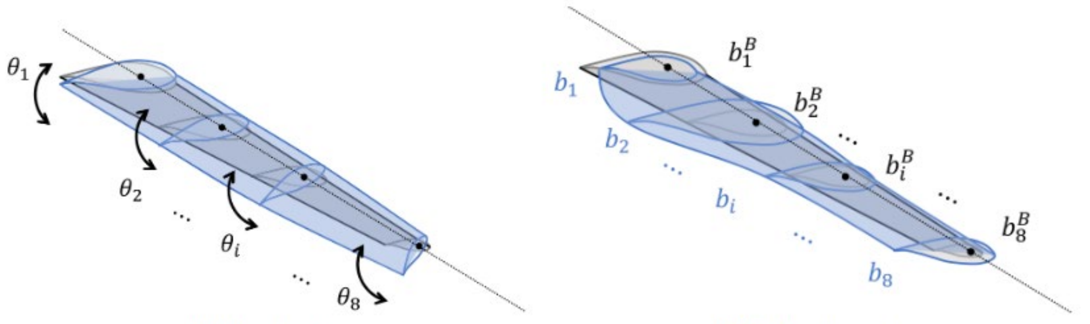
- **<u>Find efficient horizontal-axis ducted turbine design</u>**
  - Given $U_\infty$ and $\Omega$
  - measuring Power coefficient (efficiency): $C_P = \frac{\text{Extracted power}}{\text{Available power in flow}} = \frac{Q\Omega}{\frac{1}{2}\rho U_\infty^3 A}$
  - which is a function of Tip Speed Ratio: $\lambda = \frac{\Omega R}{U_\infty}$
  - Measure $C_P$ with maximum frontal area of a whole device



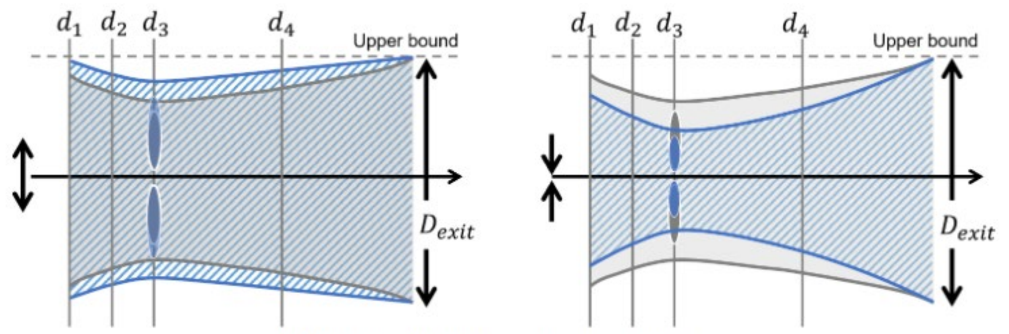
(a) Unducted turbine (b) Ducted turbine

# Optimization problem

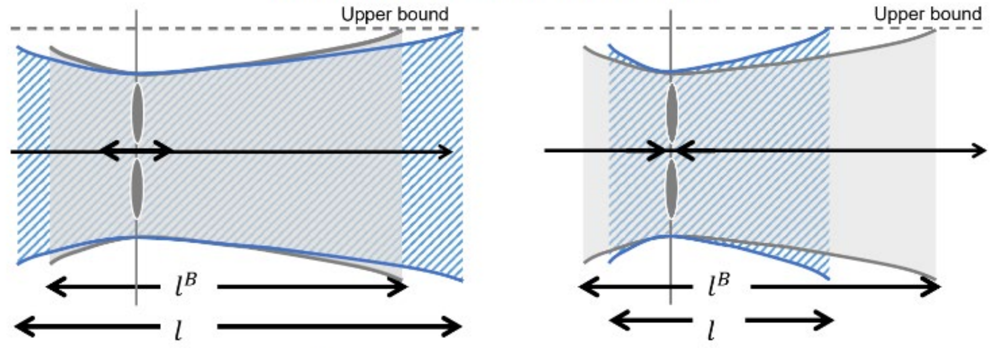
$$
\begin{aligned}
\text{maximize} \quad & C_P \\
\text{by varying} \quad & -30^\circ \leq \{\theta_i\}_{i=1}^{8} \leq 30^\circ, && \textbf{Blade twists} \\
& 0.8 \leq \left\{ \frac{b_i}{b_i^B} \right\}_{i=1}^{8} \leq 1.2, && \textbf{Blade section scales} \\
& 0 \leq d_3 \leq \{d_j\}_{j=1,2,4} \leq D_{\text{exit}}, && \textbf{Duct/blade radial scales} \\
& 0.3 \leq \frac{l}{l^B} \leq 1.5, && \textbf{Duct axial scale} \\
\text{subject to} \quad & \frac{2R}{d_3} = 0.91, && \textbf{Tip gap ratio}
\end{aligned}
$$




**(a)** Twist angles **(b)** Blade section scales




**(a)** Duct sectional radii change. Expansion and contraction



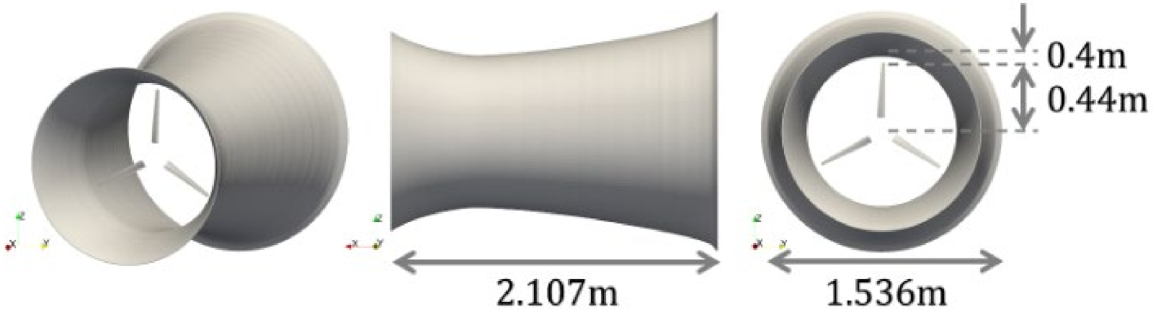

**(b)** Duct length change. Elongation and shortening

# Thin-walled ducted turbine baseline design

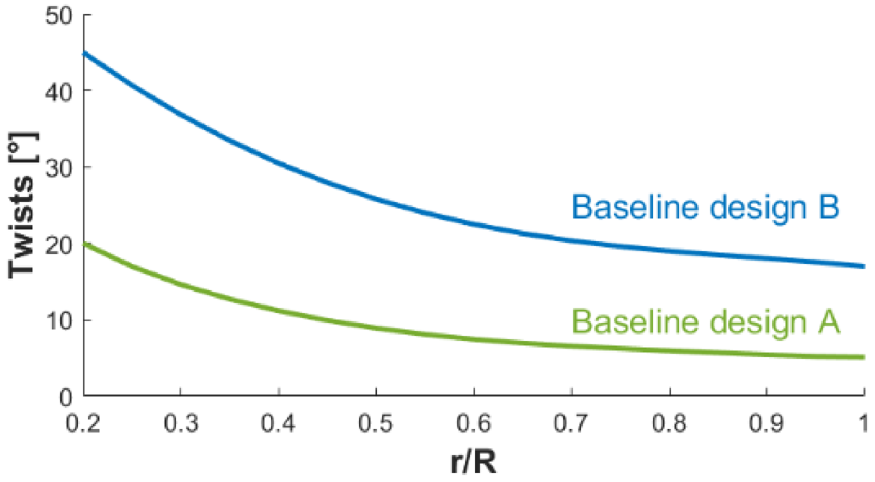
- Baseline $C_P$
  - Design A: $C_P \sim 28\%$
  - Design B: $C_P \sim 45\%$

- Blades: Bahaj et al. [2007] turbine
  - Original twist profile (Design A)
  - Modified twist profile (Design B)
  - No hub included

- Duct: Knight et al. [2018]
  - Thin wall



(a) Different views of baseline ducted turbine



(b) Twist distributions of baseline designs A and B

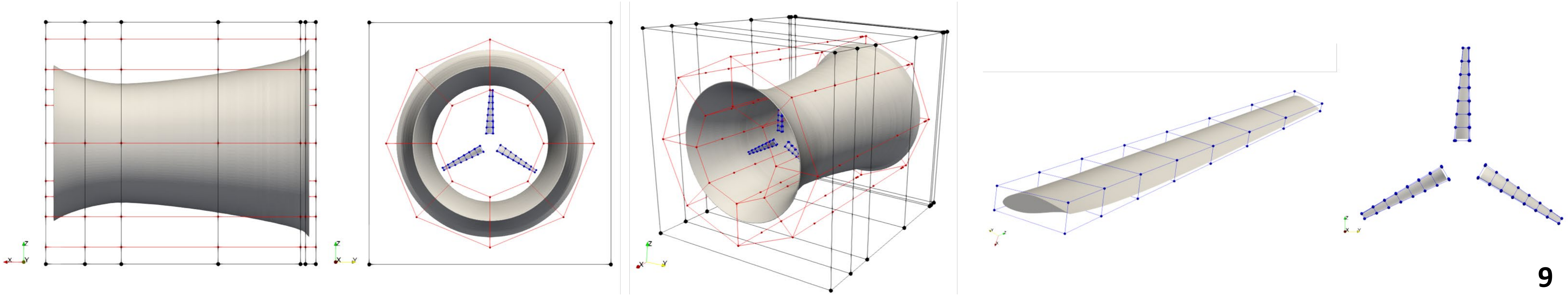
# Ducted turbine FFD setup

- 2 Layers of FFD boxes:
  - Parent box
    - FFD points control – Radial scale (black)

    → Blade and duct throat radii scales together, keeping the same tip gap ratio

    → Last 3 sections densely located at exit to fix the exit radius

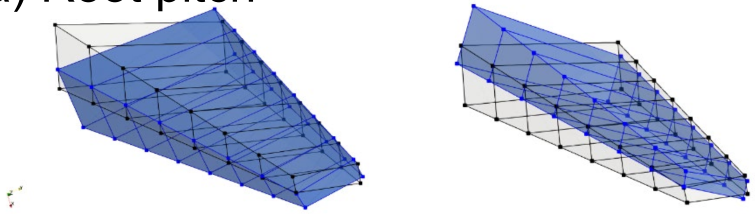
  - Children box
    - FFD points control - Duct length (red)
    - FFD points control - Blade geometry (blue)



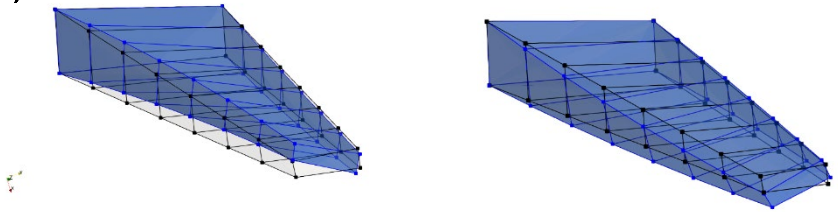
# Design variable change through FFD

- Blade

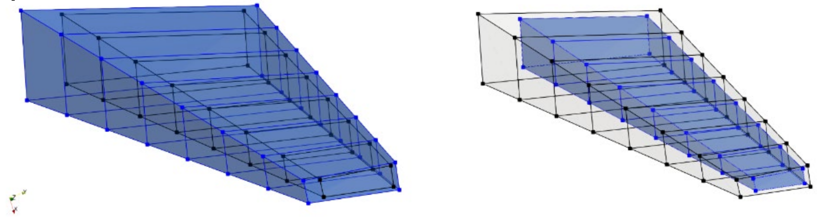
(a) Root pitch



(b) Twists

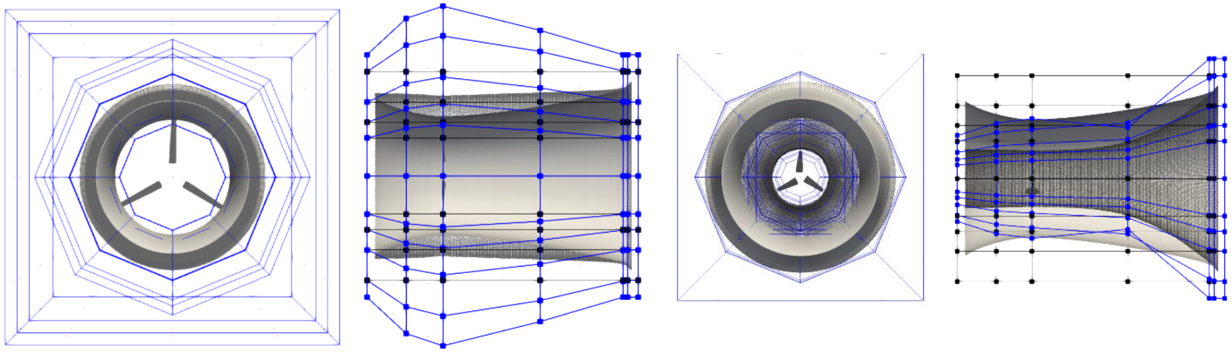


(c) Blade section scales

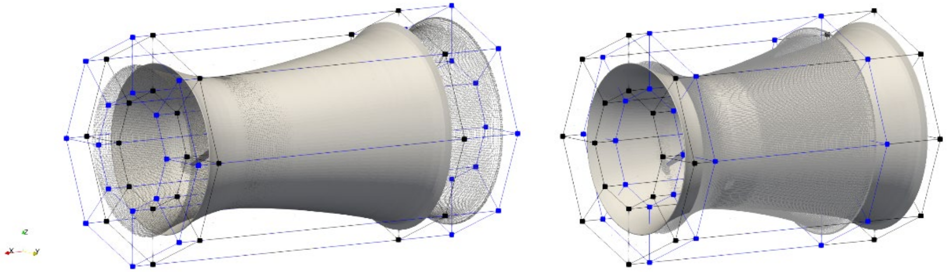


- Duct

(a) Duct radial scales. Expansion and contraction



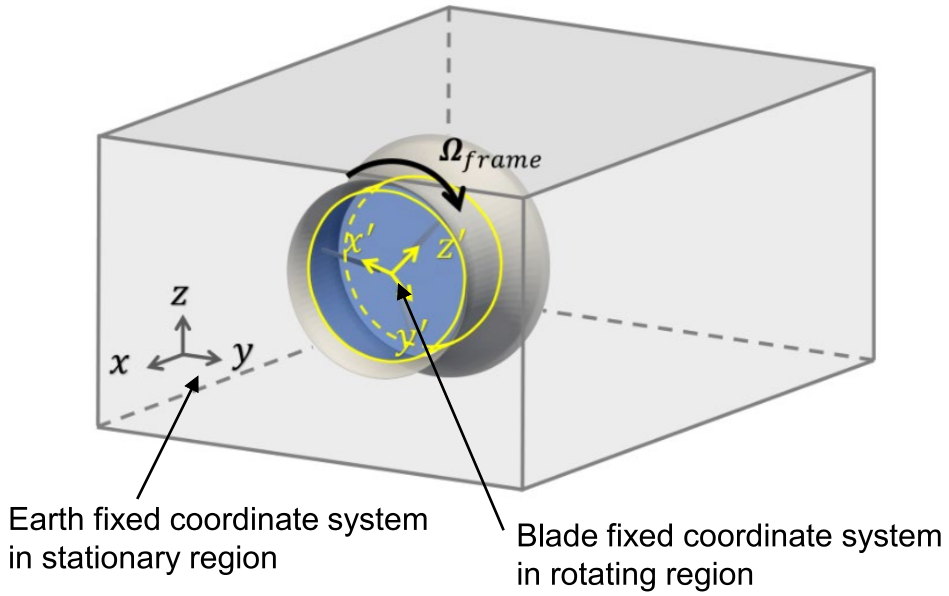
(b) Duct length scale. Elongation and shortening



# CFD simulation
# : Turbine rotation modeling

- Steady RANS + Multiple Reference Frame method (MRF)
  - Multiple coordinate systems
  - Efficient, fair accuracy
  - Low-fidelity approach

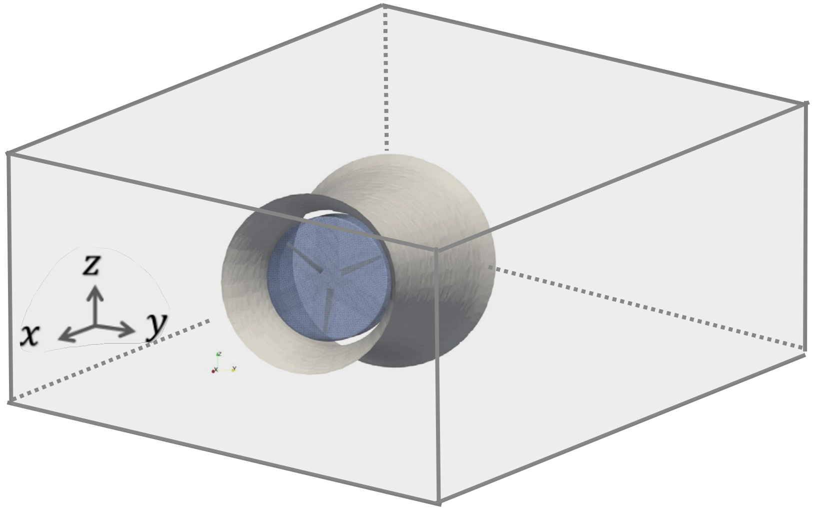
→ Optimization




<MRF method>

- Unsteady RANS + Arbitrary Mesh Interface (AMI)
  - Rotating-sliding mesh
  - Computational mesh rotation at each time step
  - Relatively accurate, expensive
  - High-fidelity approach

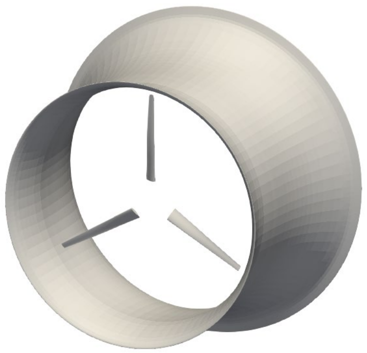
→ Re-evaluation

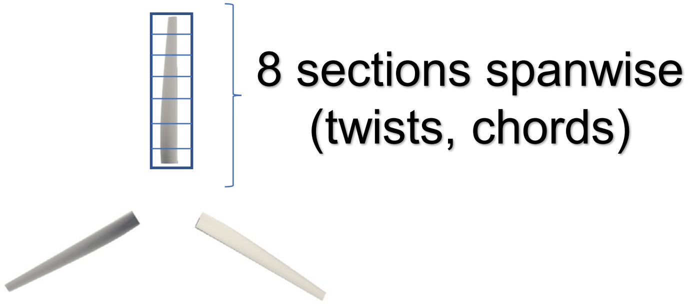


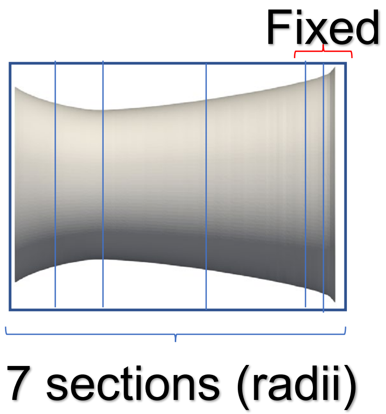

<AMI method>

# Ducted turbine optimization setup

| | | OPT A (from 28%) | OPT B (from 45%) |
|---|---|---|---|
| **Baseline Design** | **Blade** | **Original-twist Bahaj** | **Twist-modified Bahaj** |
| | **Duct** | **Thin-walled duct from Knight et al. [2018]** | |
| **Objective** | | Maximize $C_P$ @ fixed $U_\infty$ & $\Omega$ | |
| **Design variables** | **Blade** | Root pitch/ twists/ chords (16 vars) | |
| | **Duct** | Length / radii (5 vars) | |
| **Constraints** | | Fixed blade-duct gap ratio | |



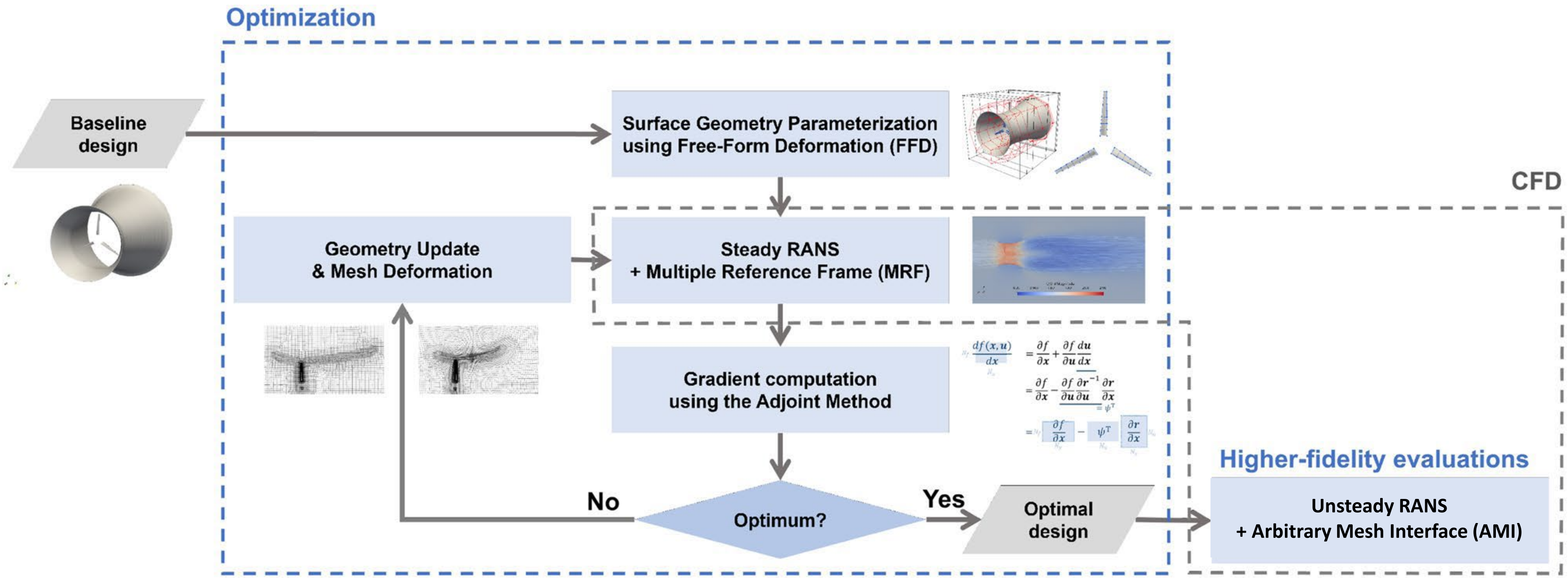


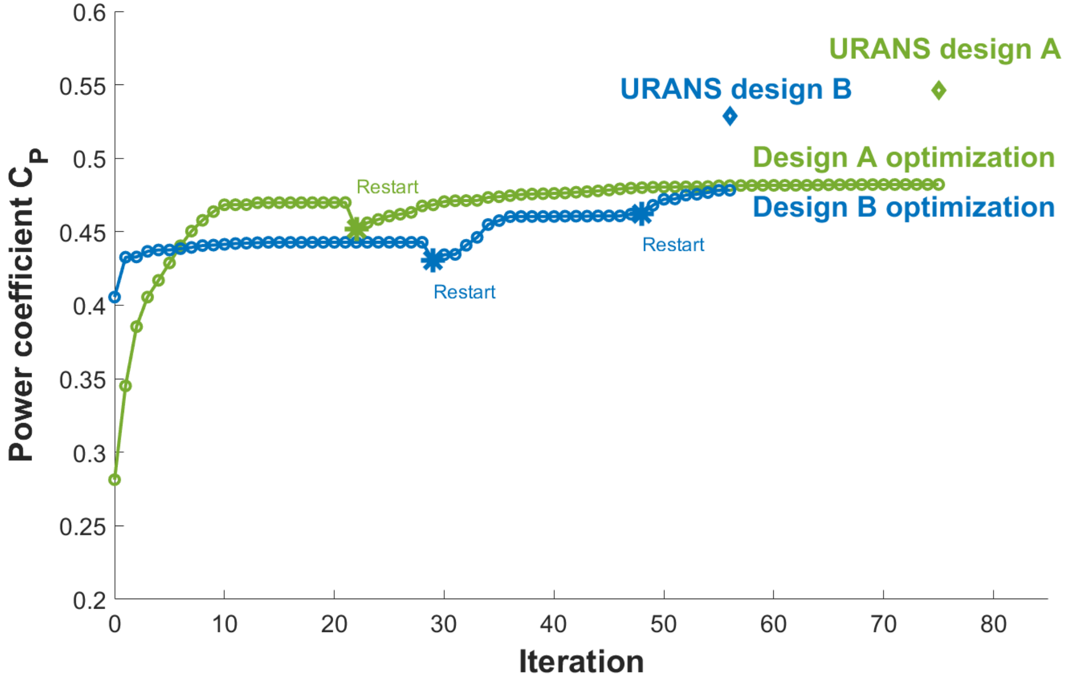

A.S. Bahaj, A.F. Molland, J.R. Chaplin, W.M.J. Batten, Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank, Renewable Energy, Volume 32, Issue 3, 2007, Pages 407-426, ISSN 0960-1481

Knight B, Freda R, Young YL, Maki K. Coupling Numerical Methods and Analytical Models for Ducted Turbines to Evaluate Designs. *Journal of Marine Science and Engineering*. 2018; 6(2):43. https://doi.org/10.3390/jmse6020043

# Optimization process



# Optimization results: $C_P$




**Optimization (steady RANS + MRF) + SA model**

**Design A**

| | Num of cells | $y^+$ Blade | $y^+$ Duct | $C_P$ |
|---|---|---|---|---|
| **M0** | 2,741,276 | 47.75 | 200.2 | 0.5462 |
| **M1** | 4,697,325 | 40.82 | 191.1 | 0.5511 |
| **M2** | 7,280,862 | 33.30 | 147.7 | 0.5381 |

**Design B**

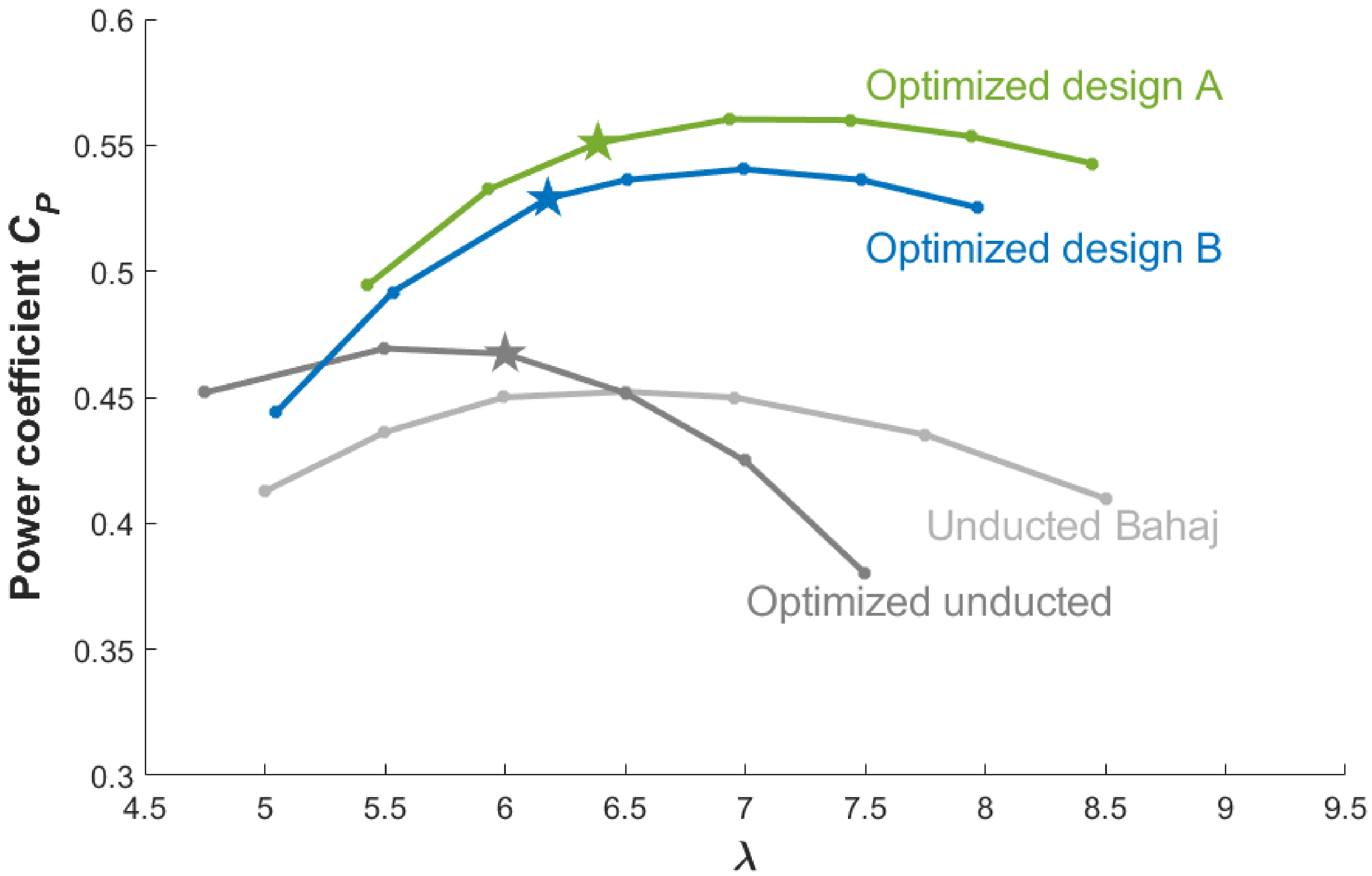
| | Num of cells | $y^+$ Blade | $y^+$ Duct | $C_P$ |
|---|---|---|---|---|
| **M0** | 3,066,956 | 49.32 | 221.1 | 0.5287 |
| **M1** | 5,358,847 | 40.81 | 173.5 | 0.5335 |
| **M2** | 8,453,165 | 34.33 | 155.4 | 0.5337 |

**Re-evaluation (URANS + AMI) + $k-\omega$ SST**

- Optimizations started from different starting points converge to very similar $C_P$
- Re-evaluation
  - Optimization A: $0.2759\ (\lambda = 5.5) \rightarrow 0.5381\ (\lambda = 6.39)$
  - Optimization B: $0.4508\ (\lambda = 5.5) \rightarrow 0.5337\ (\lambda = 6.18)$

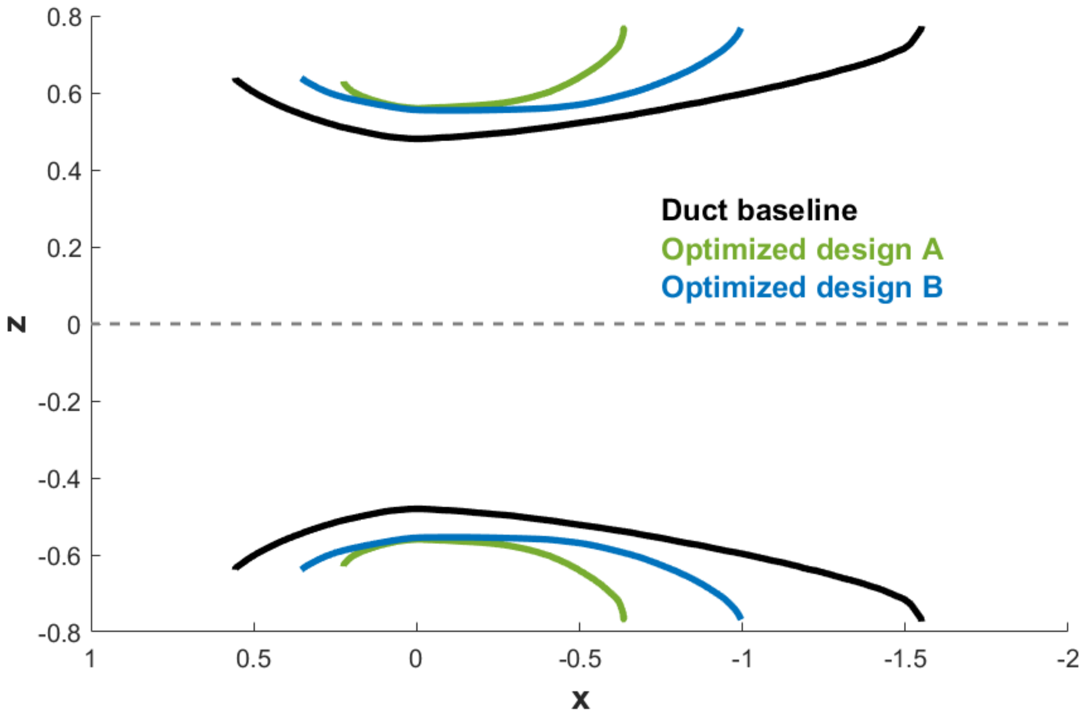
# Optimization results
# : comparison with unducted turbines

- Ducted turbines can outperform unducted turbines for a range of TSRs

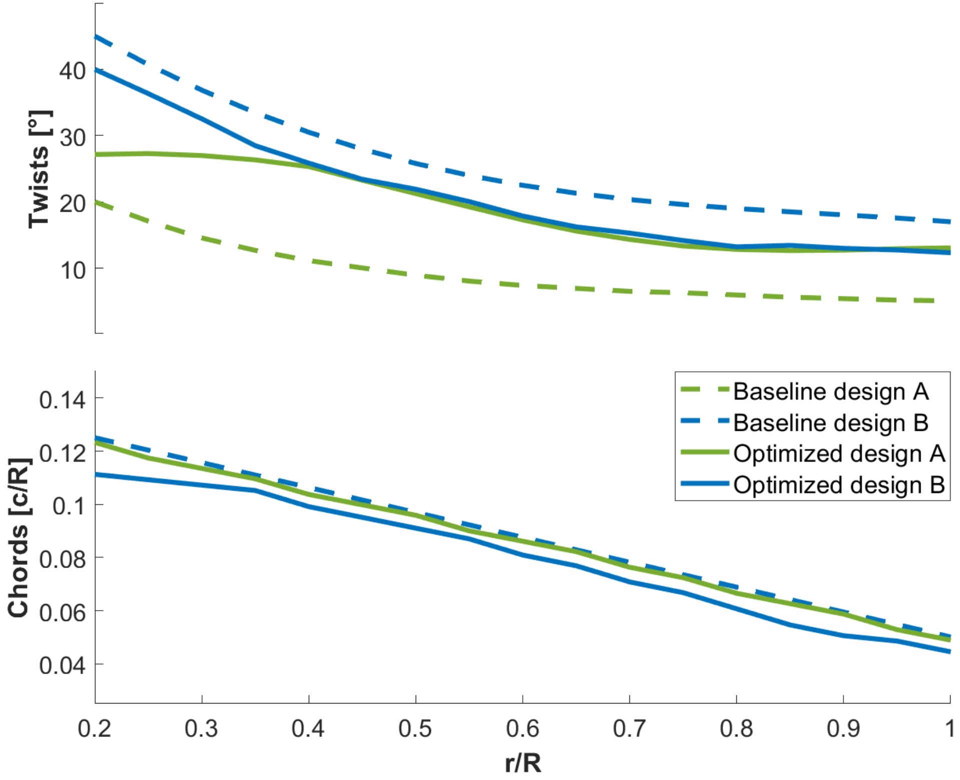


# Optimization results: geometry

- Duct
  - $C_P$ is more sensitive to the throat radius
  - Opt A) $0.409L, \quad 1.165R_{throat}$
  - Opt B) $0.641L, \quad 1.155R_{throat}$




- Blades
  - Radii are scaled with the throat radii
  - Converge to the same twist profile $(> 0.35R)$



# Summary of work 1

- Design optimization of thin-walled ducted hydrokinetic turbines is conducted

- Optimizations from different baselines converge to similar result
  - $C_P \sim 54\%$ (URANS solver)
  - Similar geometrical features: duct throat area, blade twist profile $(> 0.35R)$

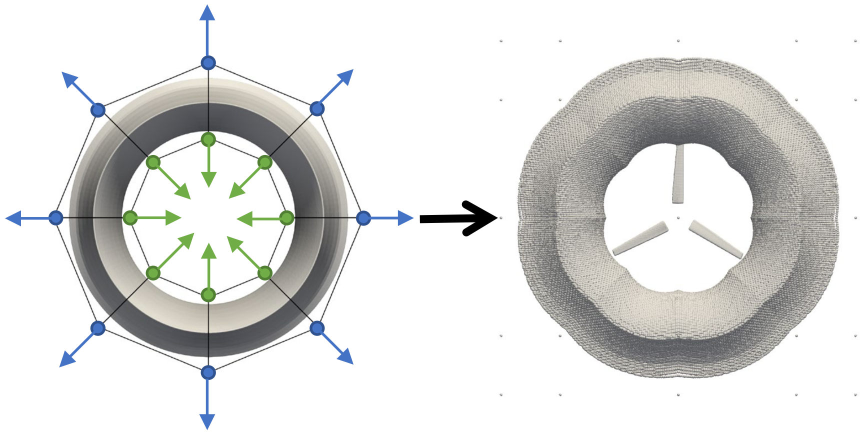
- Ducted turbine can outperform unducted turbine for a given area
  - Ducted $C_P \sim 54\%$ vs. unducted $C_P \sim 47\%$

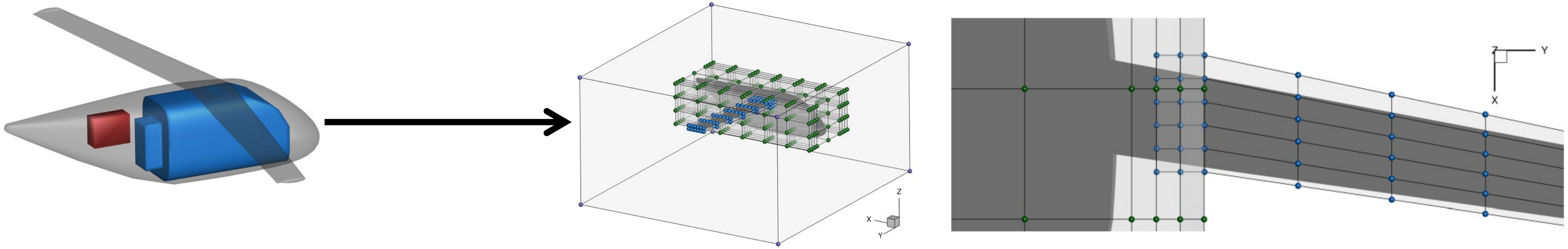
- Further improvement is needed

# Further improvement is needed

- Thin-walled duct
  - Difficult to maintain a circular and axisymmetric shape

- No hub included
  - Complex setup is needed (Hajdik et al. 2023)

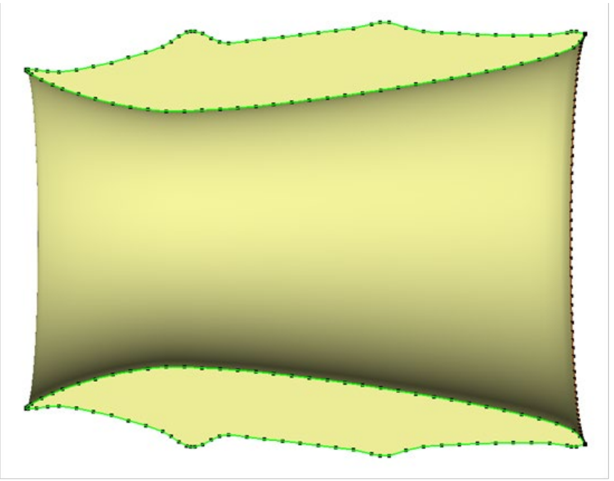




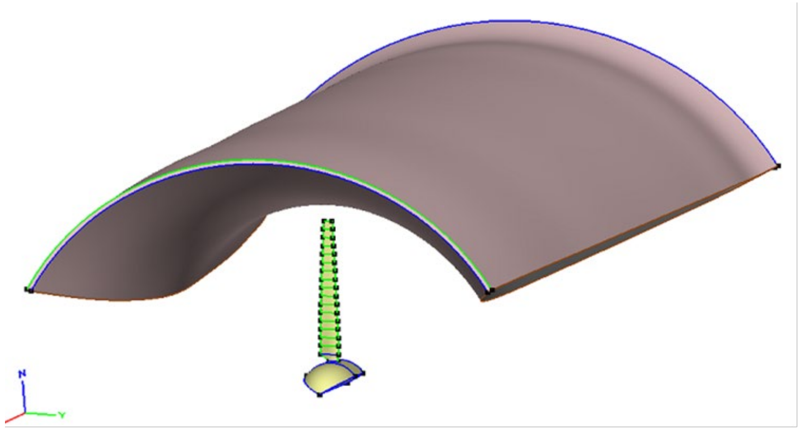
Hajdik, Hannah, Bernardo Pacini, Anil Yildirim, Benjamin J. Brelje, and Joaquim R. Martins. "Combined systems packaging and aerodynamic shape optimization of a full aircraft configuration." I
n *AIAA AVIATION 2023 Forum*, p. 3589. 2023.

# Engineering Sketch Pad (ESP)

- CAD-based geometry creation and manipulation system
- Geometry parameters can be directly used as design variables
  - Example of parametric design



Design variables: Points locations
(duct shape is a cubic spline curve)



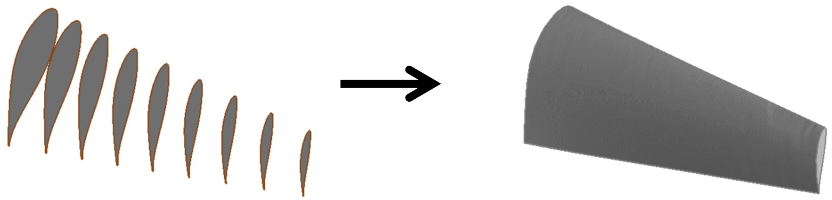
Design variables:
NACA foil thickness, camber, chord length,
blade radius, hub radius, tip gap, etc.



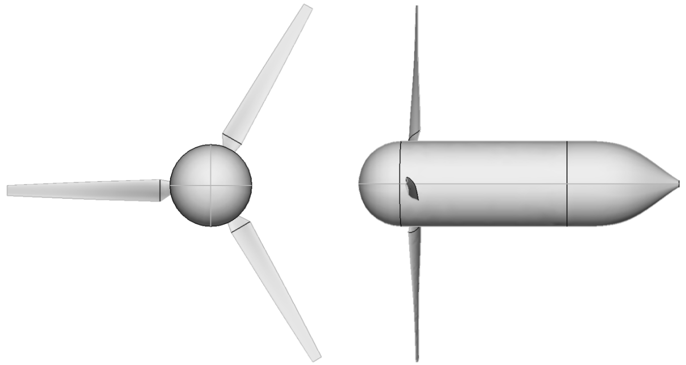
Haimes, Robert, and John Dannenhoffer. "The engineering sketch pad: A solid-modeling, feature-based, web-enabled system for building parametric geometry." In *21st AIAA Computational Flu id Dynamics Conference*, p. 3073. 2013.

# Baseline ducted turbine design

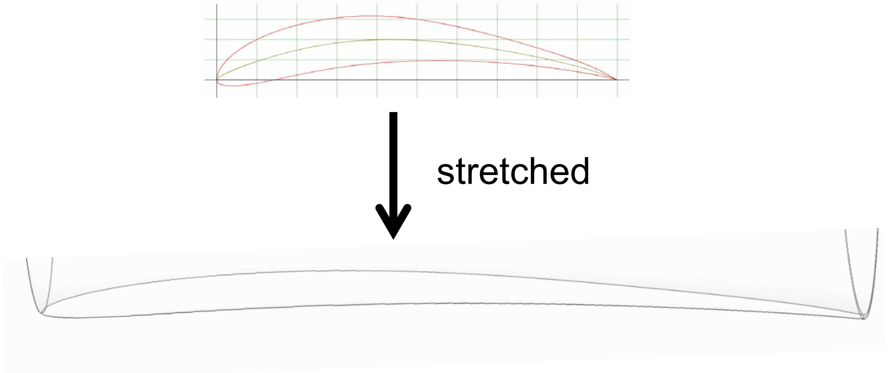
- Blade geometry
  - Twist/chord from previous optimization
  - 9 spanwise sections – Class-Shape function Transformation (CST)

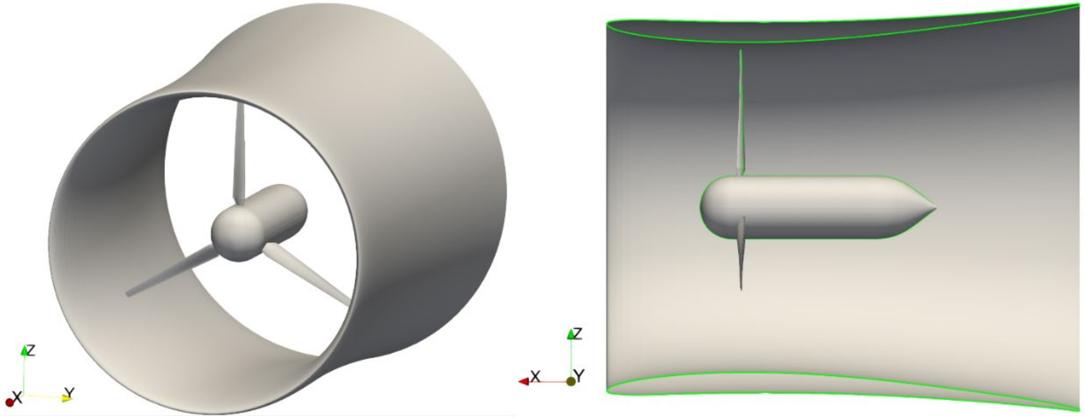


- Hub geometry
  - Cylinder + Sphere + Cone with slight modification



- Duct geometry
  - Stretched E423 foil
  - CST parametrization

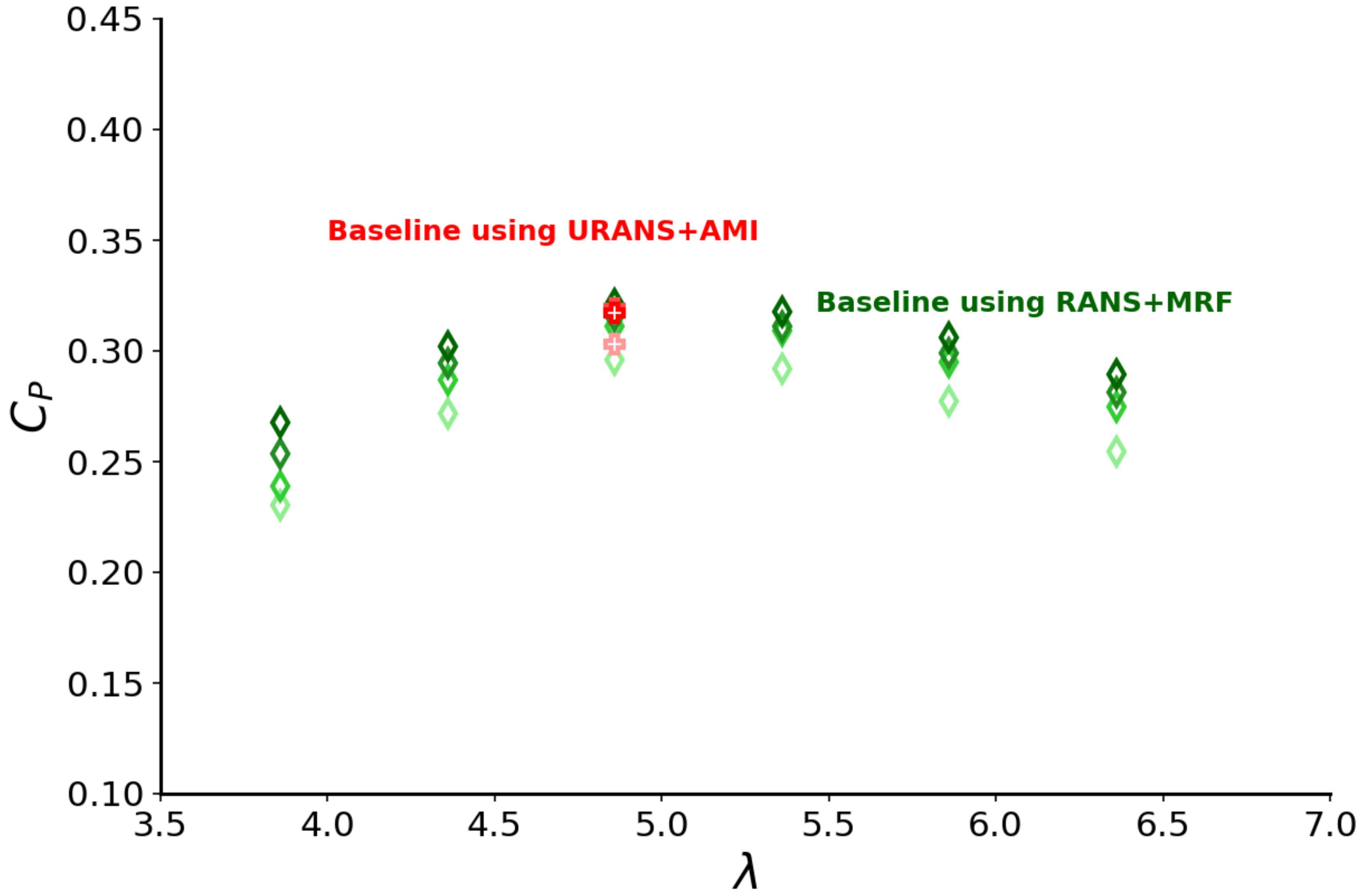




Kulfan, Brenda, and John Bussoletti. "" Fundamental" parameteric geometry representations for aircraft component shapes." In *11th AIAA/ISSMO multidisciplinary analysis and optimization conference*, p. 6948. 2006.

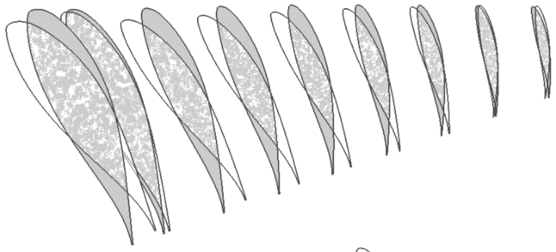
# Baseline ducted turbine design



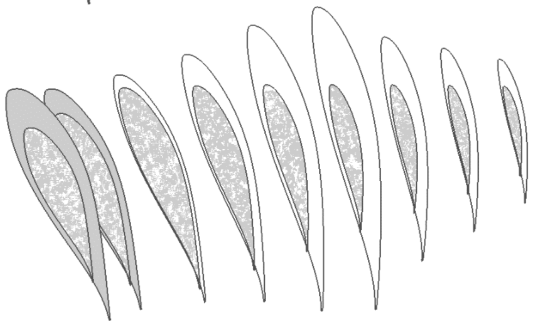
# Design variable change through ESP

- Blade

(a) Twists

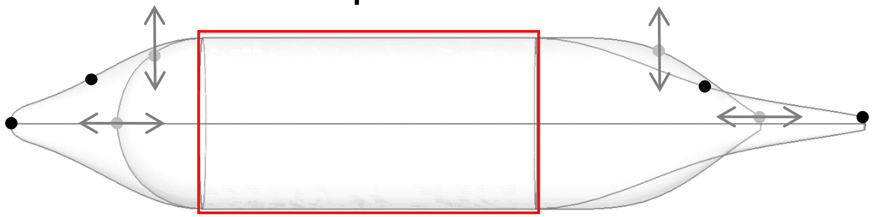


(b) Chords



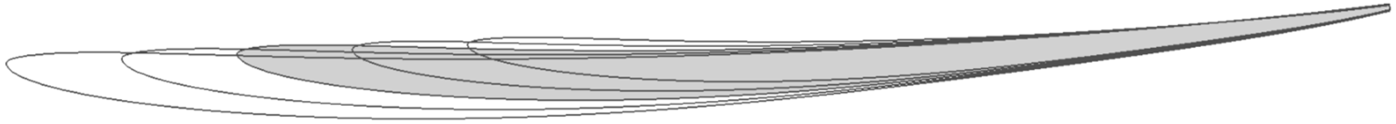
- Hub

(a) Translations of 4 points

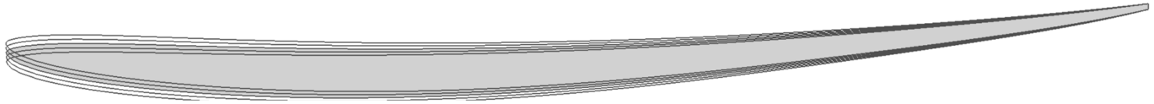


- Duct

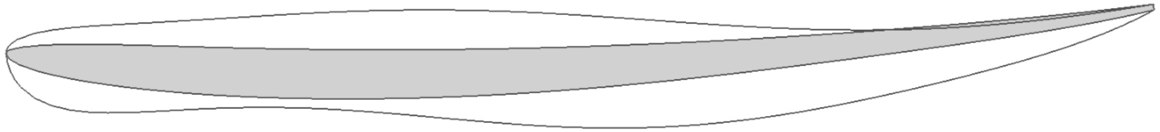
(a) Duct scale



(b) Angle of attack

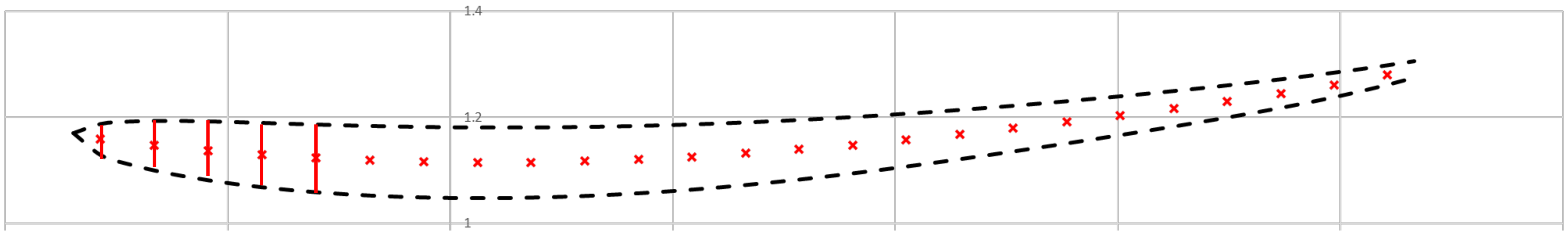


(C) Duct shape

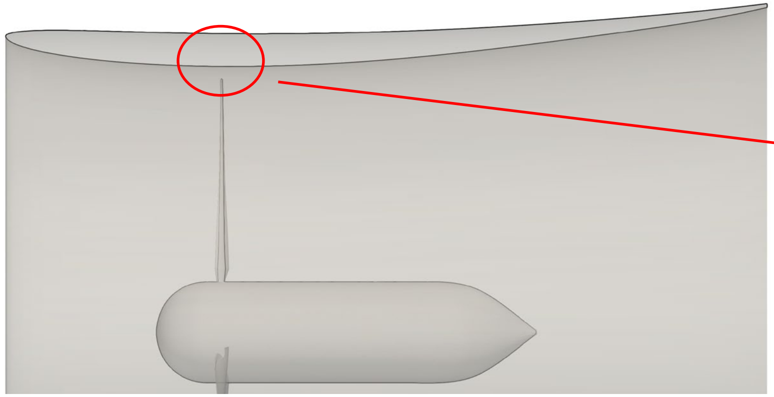


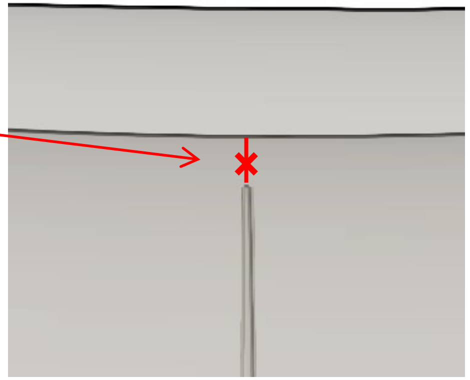
# Constraints

- Duct thickness: 1D thickness constraint



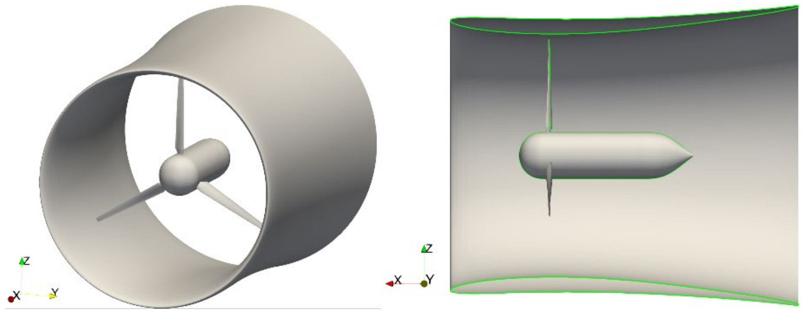

- Tip gap: proximity constraint



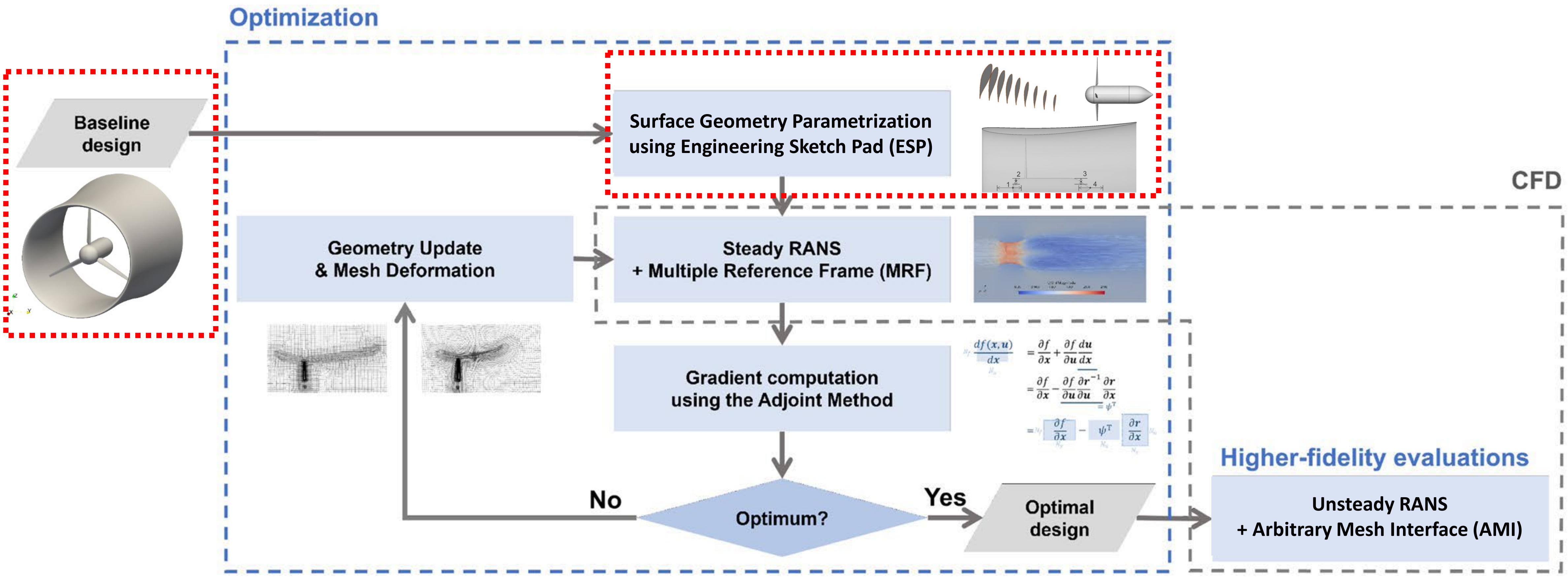


- Duct exit radius
- Duct LE curvature
- Hub cylindrical part

# Optimization setup

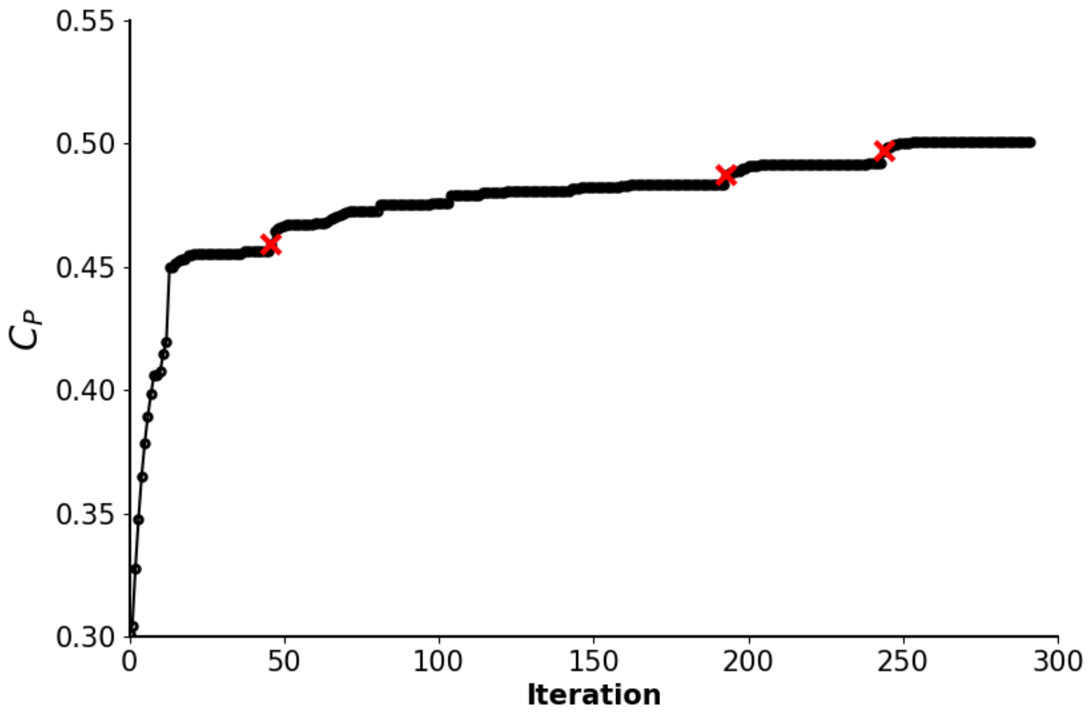
| | | |
|---|---|---|
| **Baseline design** | |  |
| **Objective** | | Maximize $C_P$ @ fixed $U_\infty$ & $\Omega$ |
| **Design variables** | **Turbine** | Radius/ Chords/ Twists/ Hub shape (13 vars) |
| | **Duct** | Duct shape, Duct scale, Angle of attack (13 vars) |
| **Constraints** | | Duct thickness<br>Tip gap |

# Optimization setup

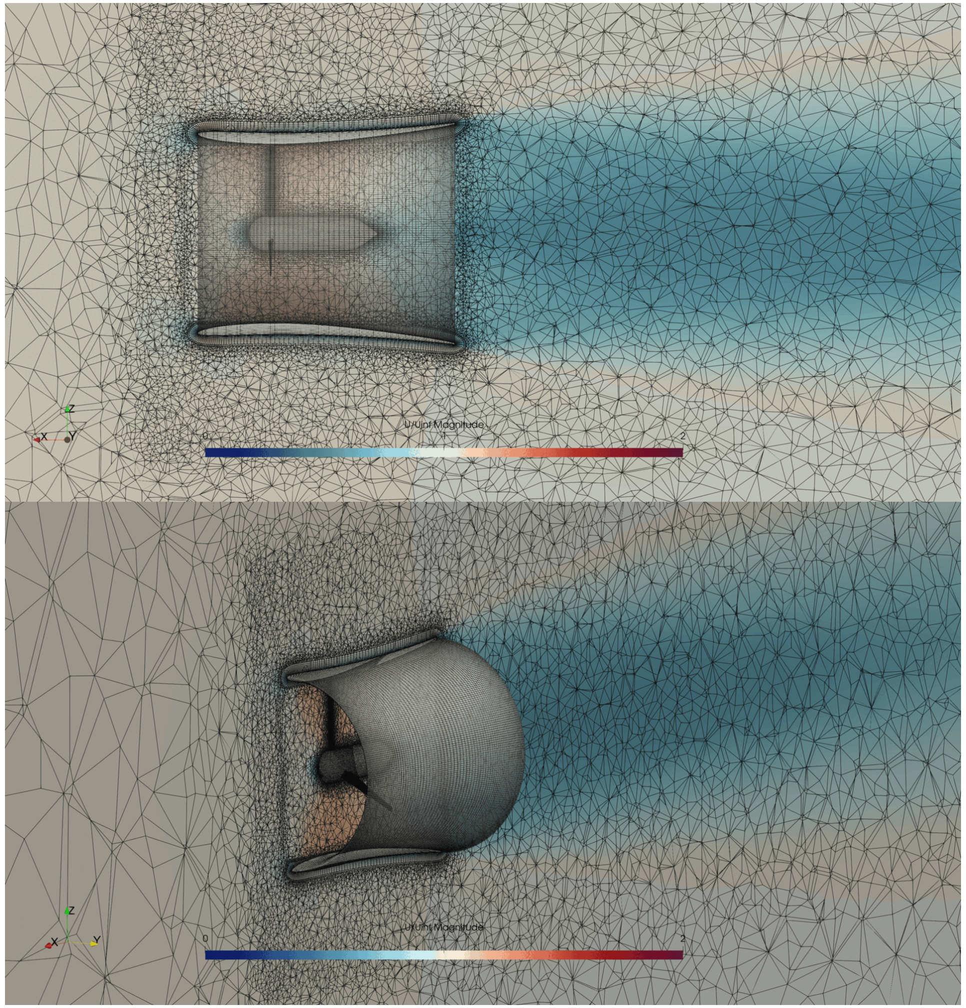


# Optimization results: $C_P$

- Optimization: $0.3011\ (\lambda = 4.86) \rightarrow 0.5009\ (\lambda = 4.65)$
- Plan to run re-evaluation using URANS-AMI

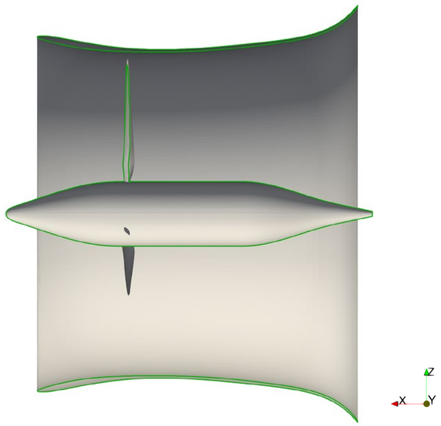


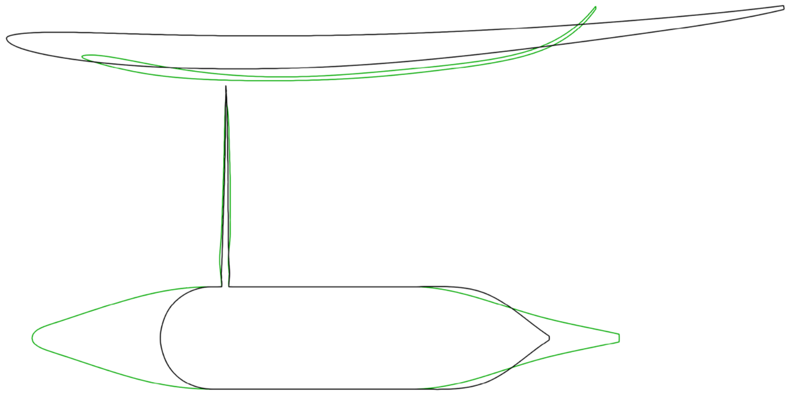

**Optimization (steady RANS + MRF)**
**+ SA model**

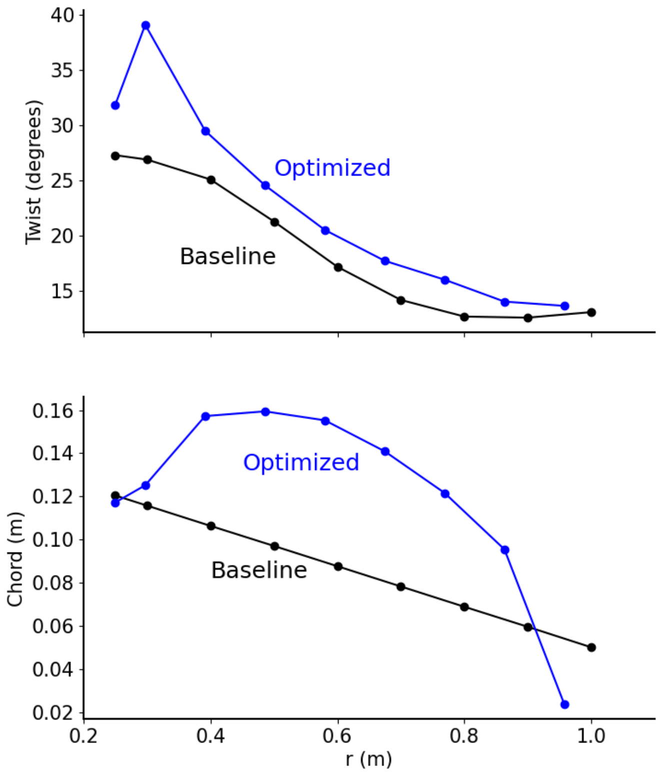


# Optimization result

- Duct
  - Shorter
  - Thin and cambered
- Hub
  - Longer
  - Protruded
  - Bigger chords
- Blade
  - Smaller radius
  - Bigger chords







# Summary of work 2

- Design optimization of a ducted turbine featuring a foil-shaped duct and a bulky hub is conducted
  - Geometry is parametrized using ESP

- Obtained ducted turbine has roughly 50% efficiency with unique geometrical features

- Further re-evaluation is needed

# Q&A