Aérojoules Project: Vertical Axis Wind Turbine

EMSHIP Master's Thesis Presentation

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Nantes, February 27, 2012

Outline

1. Motivation
2. Turbine Design
3. 2-D Aerodynamic Analysis
4. 3-D Aerodynamic Analysis
5. Structural Design
6. Simplified Load Estimation
7. Conclusions and Recommendations

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   - Why VAWTs?
   - The Aérojoules Project
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General discussion

Background

- Traditionally, HAWTs dominate the large-sized turbine market
- Increased interest in the small and medium–sized range
- Impulse to new developments in VAWTs

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Advantages of VAWTs

- No special mechanisms for yawing into wind
- Generator closer to ground, simpler maintenance
- Lower operational speed: Less noise in urban installation

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Advantages of VAWTs

- No special mechanisms for yawing into wind
- Generator closer to ground, simpler maintenance
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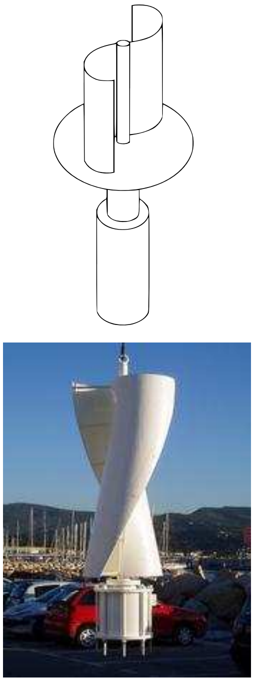
Disadvantages of VAWTs

- Less efficient than horizontal axis wind turbines
- Difficulty of modeling the wind flow accurately
- Highly dynamic loading on the blade

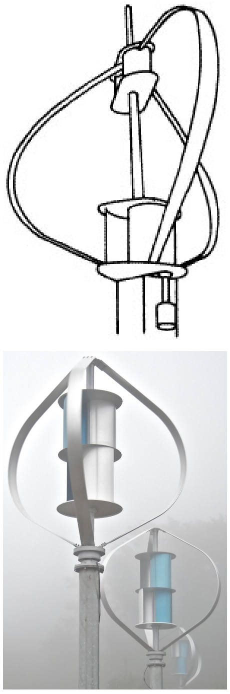
Classification of VAWTs

Drag–driven: Savonius Type



Lift–driven: Darrieus Type

Combined: Darrieus–Savonius



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Origin and Objectives

About the project

- Started by the Ocean Vital Foundation
- Model successfully tested at the Vendée Globe 2008
- Multidisciplinary project: ICAM, CSTB, Jalais, Garos, AIC
- VAWTs oriented to the Nantes region
- Three variants: 300W, 1500W and 3000W

Left: Model used for the Vendée Globe 2008

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    - Introduction to Turbine Analysis
    - Previous Works
    - Analysis and Optimization
    - Blade Support Interface
    - Airfoil Preselection
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Methods for Turbine Analysis

Aimed at obtaining the global efficiency

- Actuator Disk Method
- Double Actuator Disk Method
- Rotor Disk Method

Aimed at obtaining the flow characteristics

- Blade-Element/Momentum Theory (BEM)
- Double Multiple Streamtube Method (DMS)
- Vortex Method
- Computational Fluid Dynamics (CFD)

Methods for Turbine Analysis

Aimed at obtaining the global efficiency

- Actuator Disk Method ⇒ Maximum efficiency 59.3%
- Double Actuator Disk Method ⇒ Maximum efficiency 64%
- Rotor Disk Method ⇒ HAWT

Aimed at obtaining the flow characteristics

- Blade-Element/Momentum Theory (BEM) ⇒ HAWT
- Double Multiple Streamtube Method (DMS) ⇒ Simple flow field
- Vortex Method ⇒ Noise propagation analysis
- **Computational Fluid Dynamics (CFD)** ⇒ Efficiency & flow pattern

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Performance and main dimensions

Considered constraints

- Expected power output
- Compromise between aerodynamic and power generation aspects
- Aesthetic aspect of the turbine
- Interaction with the future manufacturer
- Search for an airfoil with the best lift to drag ratio

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Parameters set

- 2m^2 square–shape swept area: diameter $=$ height $=$ 1.4m
- Three helicoidal blades in composite materials: fiber glass – epoxy
- NACA 6412 airfoil, chord $=$ 0.2m

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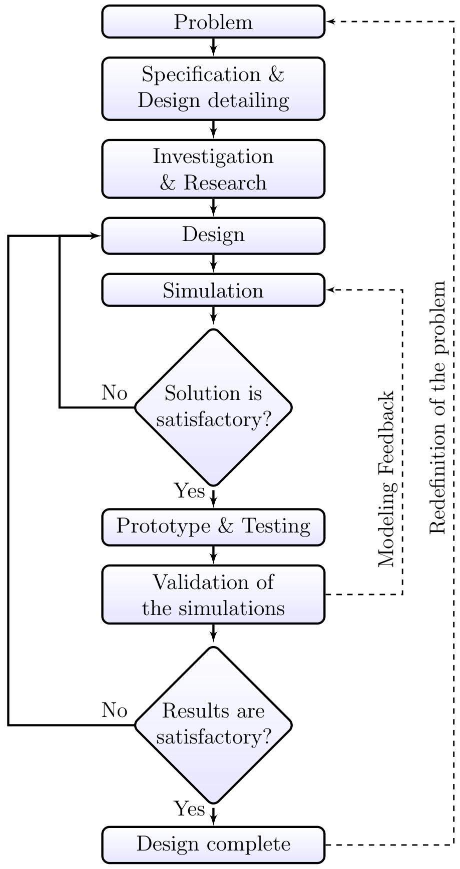
Design process



Problem

Specification & Design detailing

Investigation & Research

Design

Simulation

Solution is satisfactory?

No

Yes

Prototype & Testing

Validation of the simulations

Results are satisfactory?

No

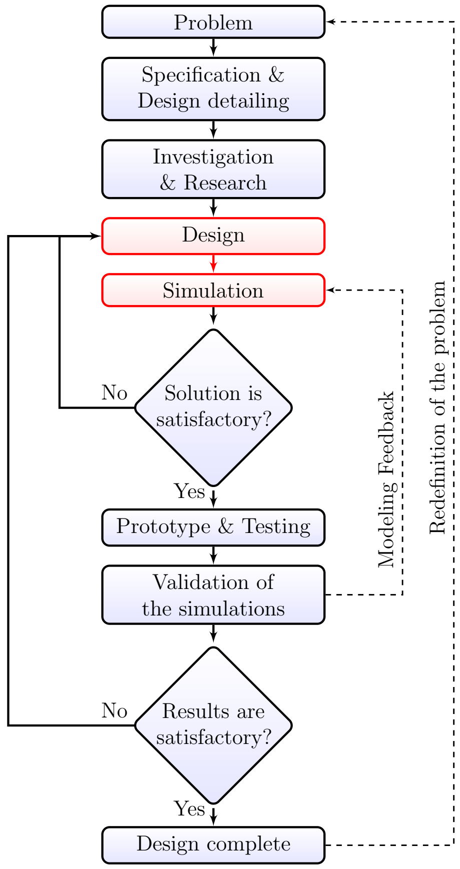
Yes

Design complete

Modeling Feedback

Redefinition of the problem

Design process



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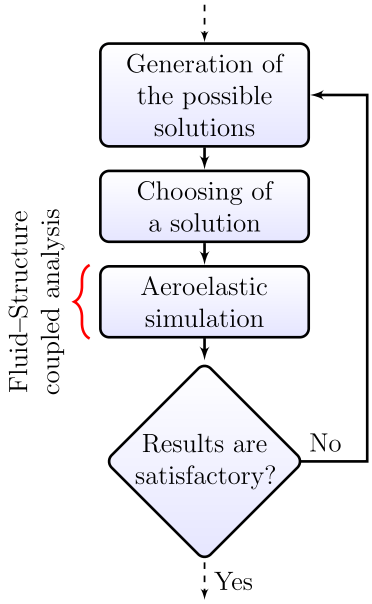


Generation of the possible solutions

Choosing of a solution

Aeroelastic simulation

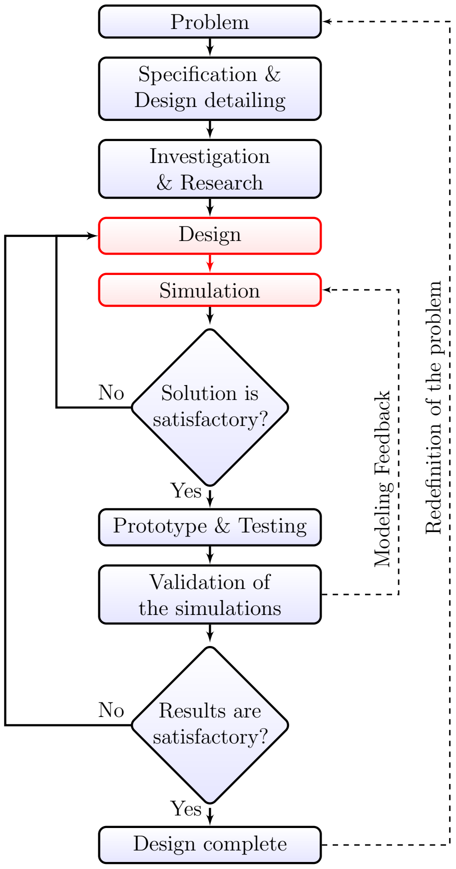
Fluid–Structure coupled analysis

Results are satisfactory?

No

Yes

Design process



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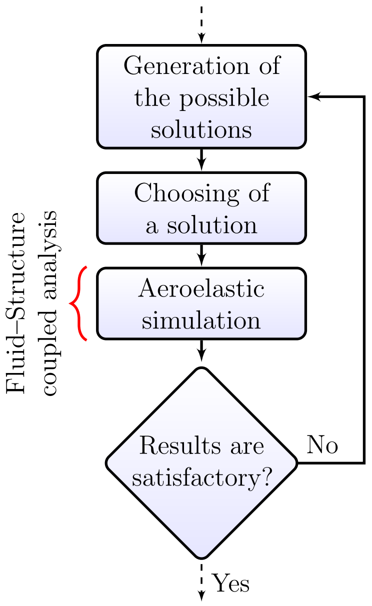
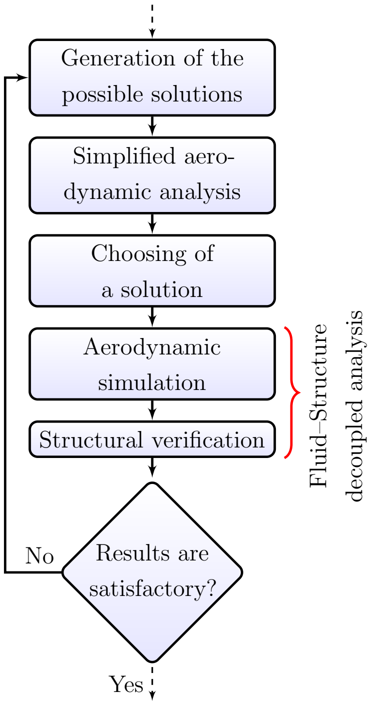


Adopted: Decoupled Analysis

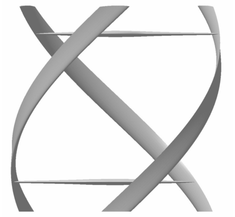


Outline

Study of design alternatives

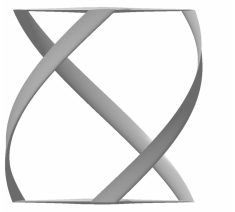
Interfaces at intermediate positions along the blades

- Concept used on a tested model
- Reduction of bending efforts at links
- Local reduction of aerodynamic forces
- Tip vortex effect not addressed



Interfaces at the blades extremities

- Allows works on tip vortex effect
- Increased solicitations at links
- Might require additional intermediate supports



▸ Designs

Outline

General discussion

Criteria for the selection

- Aerodynamic performance
- Structural strength and stiffness
- Aeroelastic behavior
- Manufacturability
- Maintainability
- Noise generation

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Available airfoil families

- Conventional Airfoils
    - Four and five digits NACA Series
    - Other non–NACA airfoils
- Laminar Airfoils
    - Six and seven digits NACA Series
- NREL Families
- VAWT Tailored Airfoils

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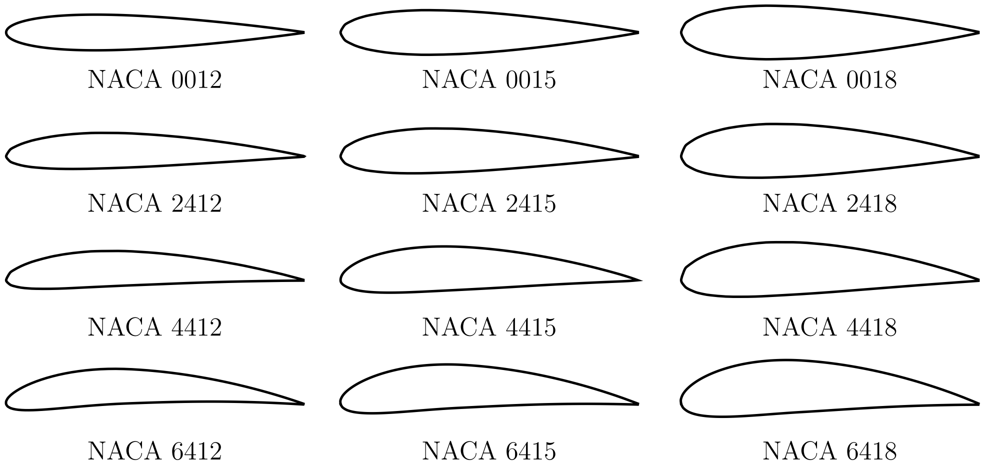
Preselected NACA four–digit airfoils



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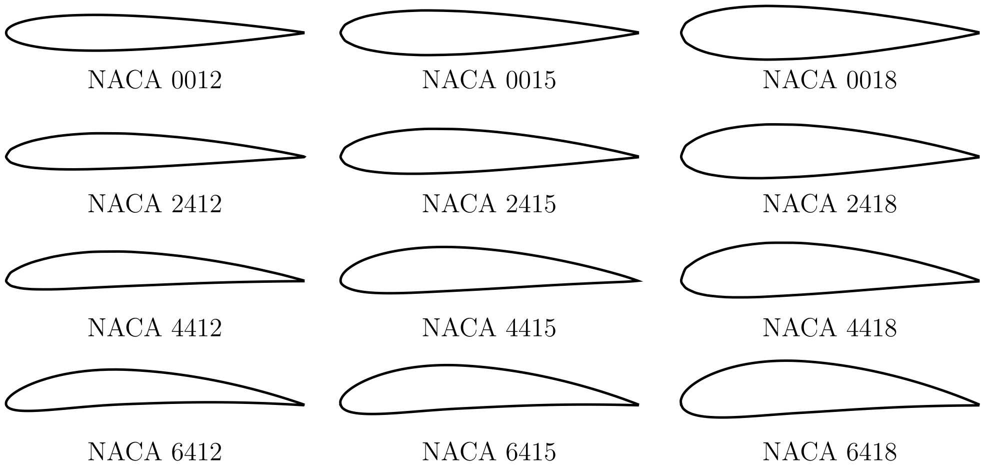
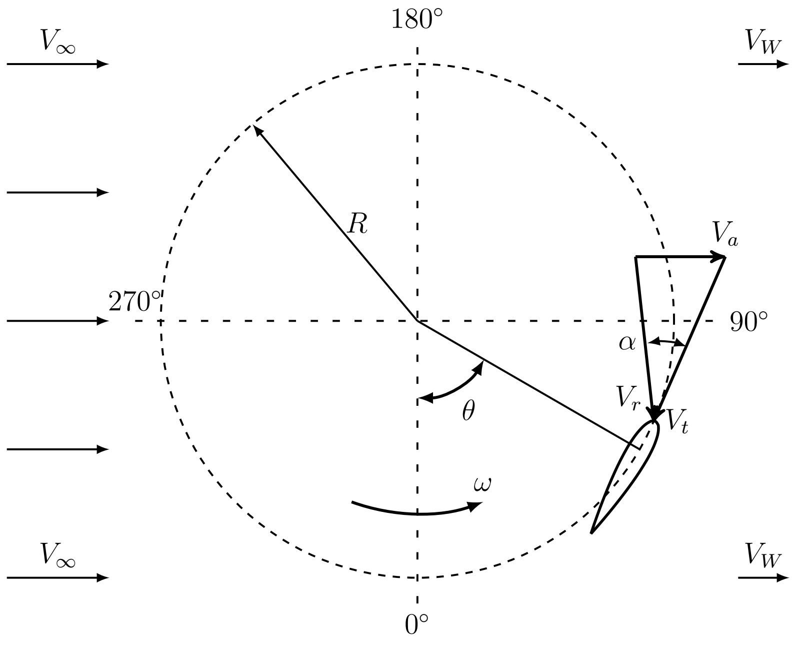


Considerations

- Manufacturing ⇒ Simple geometries
- Design & Analysis ⇒ Well documented airfoil data
- Operation & Maintenance ⇒ Low sensitivity to roughness
- Optimization ⇒ Wide range of alternative designs

Outline

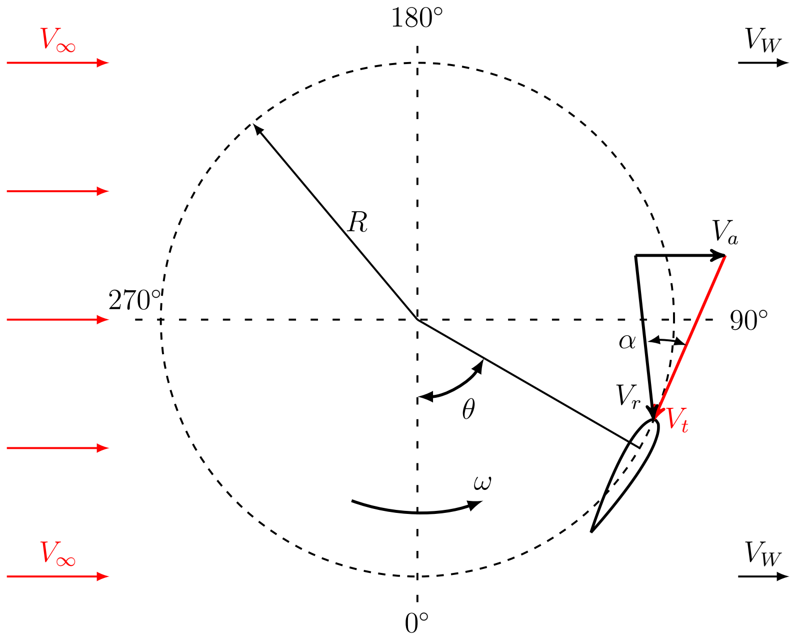
General operational parameters



Characteristics

- Simplified analysis
- Insight into the VAWT operation
- Estimation of diverse flow variables
- Background knowledge for further studies

General operational parameters



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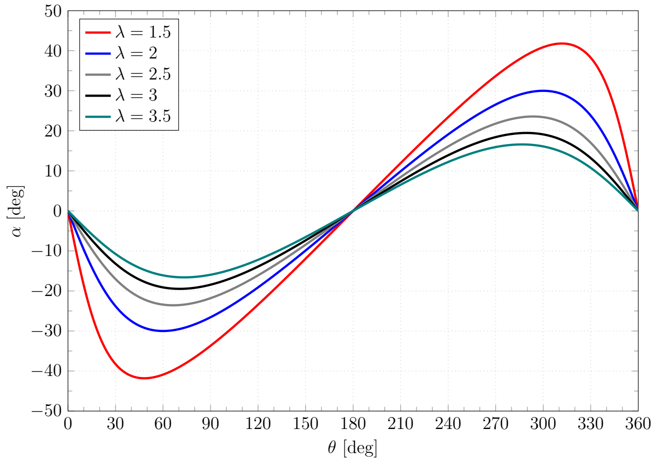
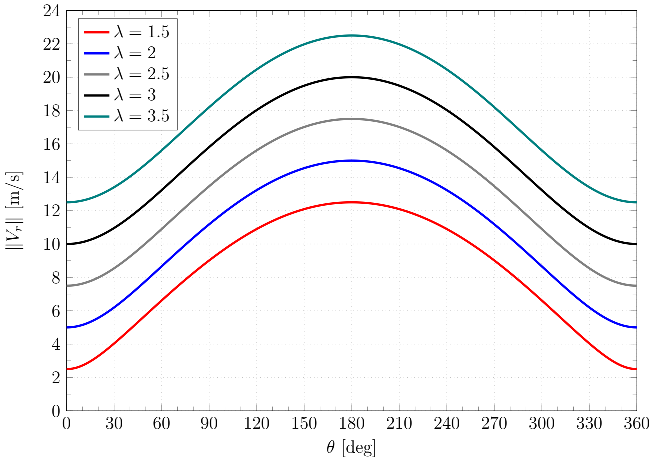
Important definition:

$$\text{Tip speed ratio: } \lambda = \frac{V_t}{V_\infty} = \frac{\text{Blade tip velocity}}{\text{Wind velocity}}$$

Study of flow variables





Incidence angle (α) vs. θ

- Decreases with λ
- Magnitude above 15°

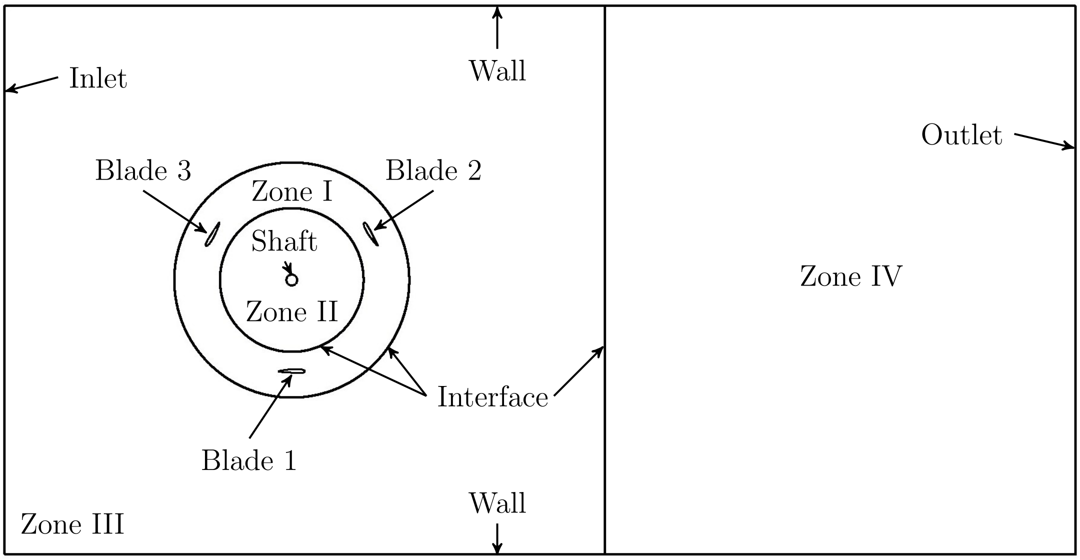
Incidence velocity (V_r) vs. θ

- Increases with λ
- Influences local Reynolds number

▸ Performance study

Outline

Models characteristics

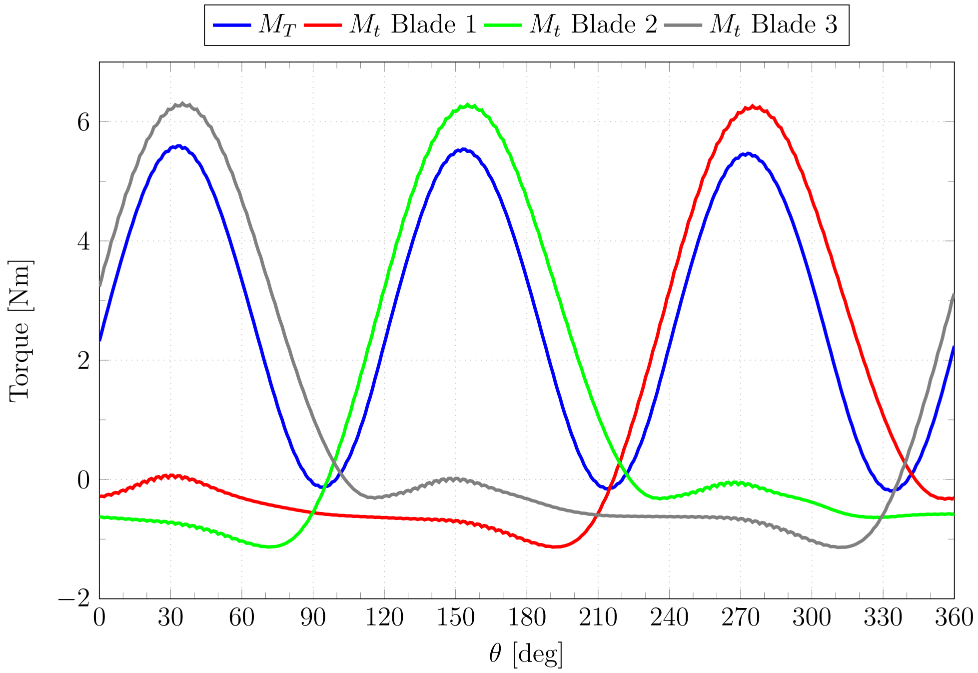


Considerations

- $V_{inlet} = 5m/s$
- RANS equations
- Realizable k–ϵ model
- Two-Layer approach
- All $y+$ wall treatment
- Six values of λ

▸ Mesh

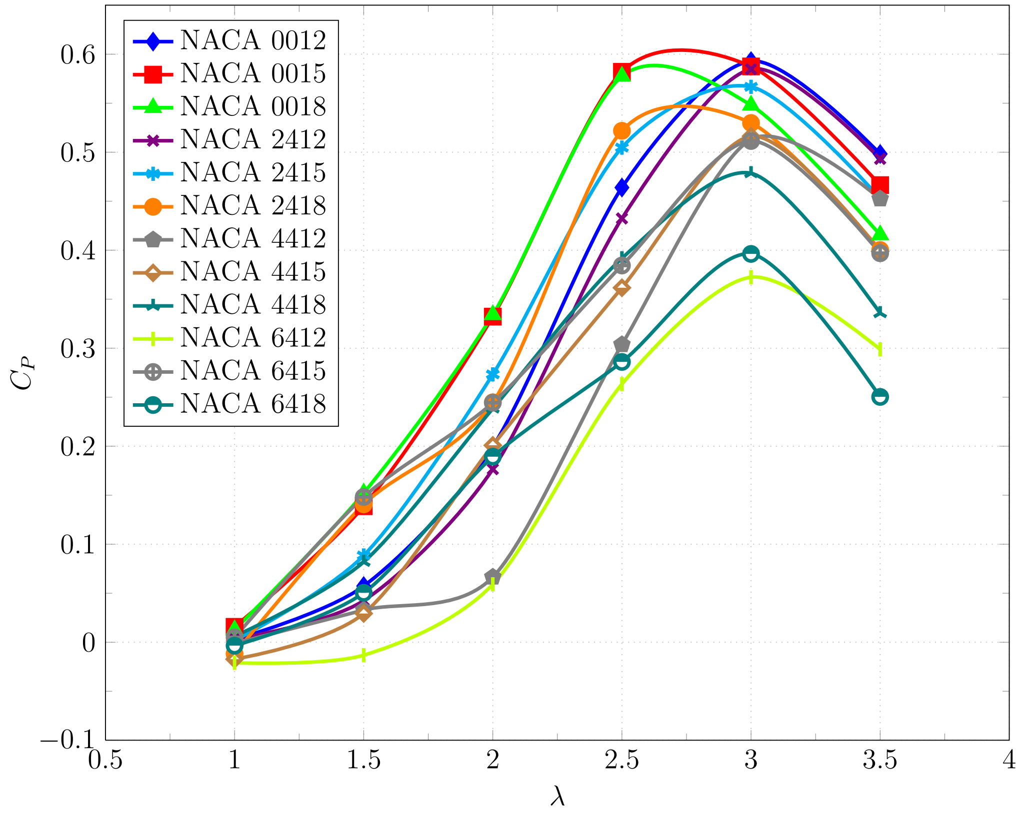
Results. Typical torque curve



NACA 2415
$\lambda = 3$

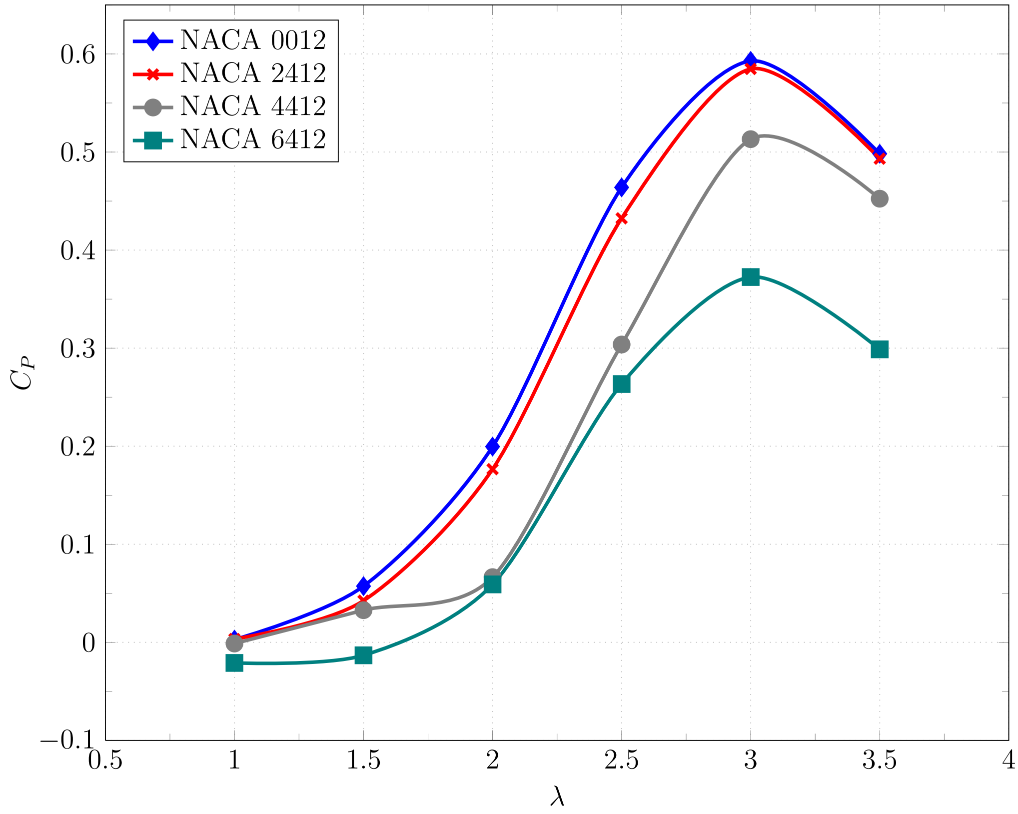
Turbine efficiency: $C_P = \frac{P_a}{P_w} = \frac{M_{Ta}\,\omega}{\frac{1}{2}\,\rho\,S\,V_\infty^3}$

Results. Comparison of efficiencies



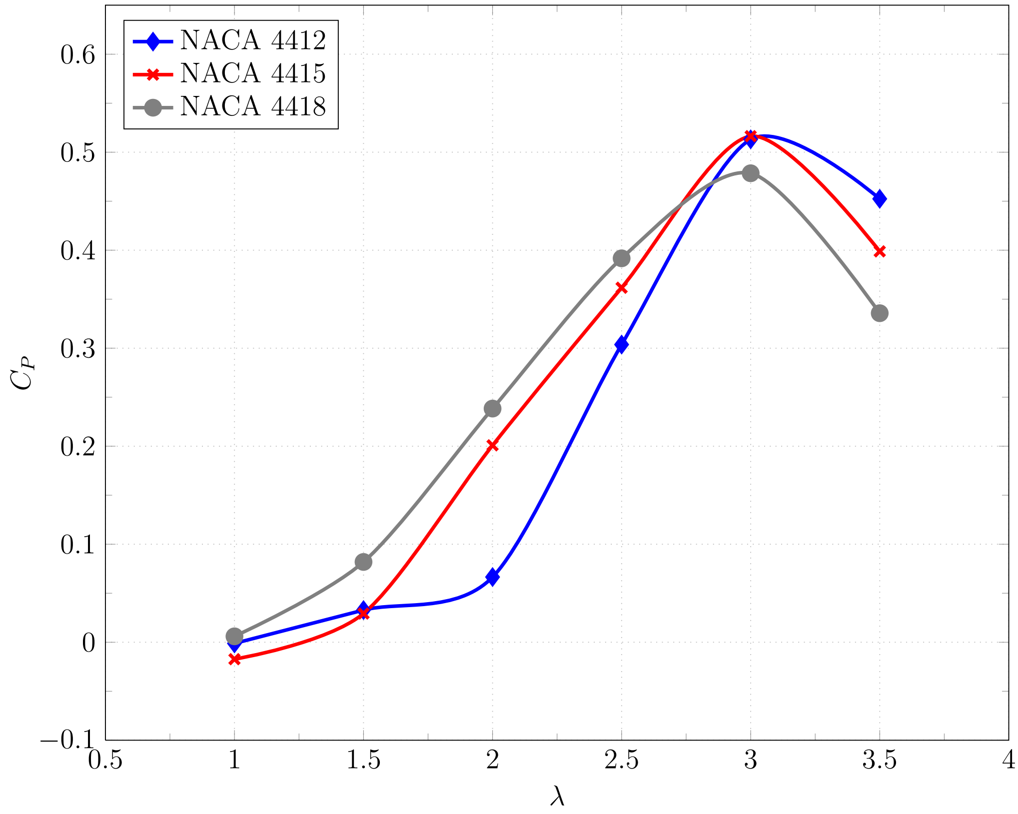
Overall view

Results. Comparison of efficiencies



Curvature effect
12% thickness

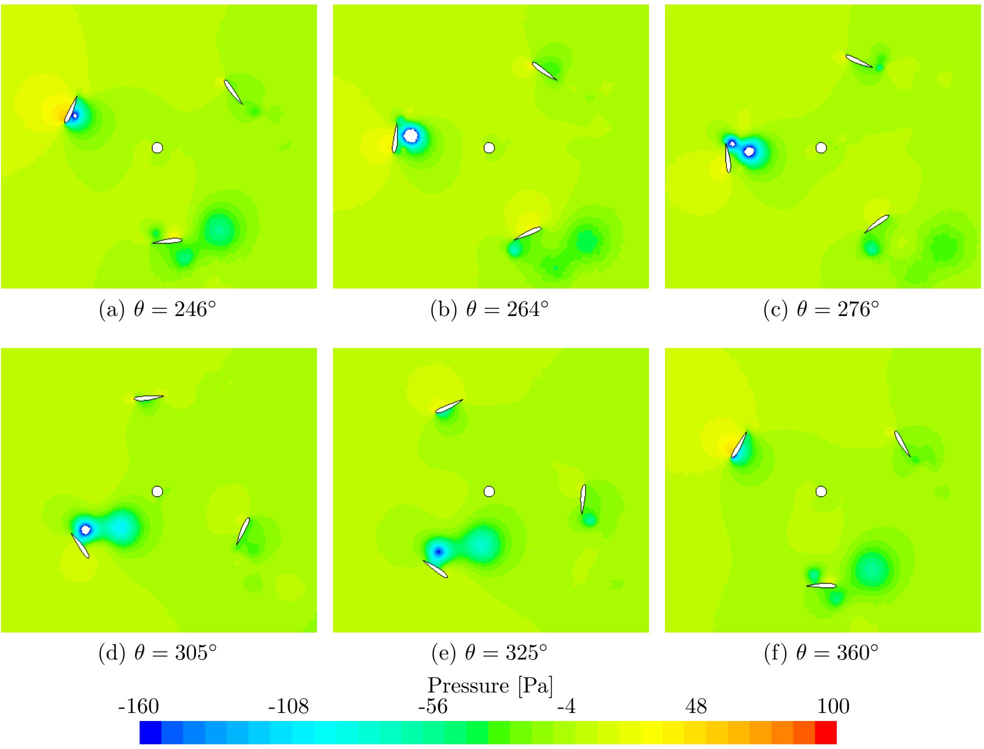
Results. Comparison of efficiencies



Thickness effect
4% curvature

▸ Complete

Flow pattern



(a) $\theta = 246°$ (b) $\theta = 264°$ (c) $\theta = 276°$

(d) $\theta = 305°$ (e) $\theta = 325°$ (f) $\theta = 360°$

NACA 2415 $\lambda = 1$

- Higher α
- Evident flow detachment
- Doublet

▸ $\lambda = 3$

Conclusion of the analysis

Effect of curvature increase

- Reduction of peak efficiency
- Self-starting characteristics not captured

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- Not clear tendency
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- Unexpected behavior: self–starting
- Possible simulation problems: dynamic stall

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- Peak value close to theoretical limit
- Results considered qualitatively for airfoil selection

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Selected airfoils for further analysis

- NACA 0015
- NACA 2415

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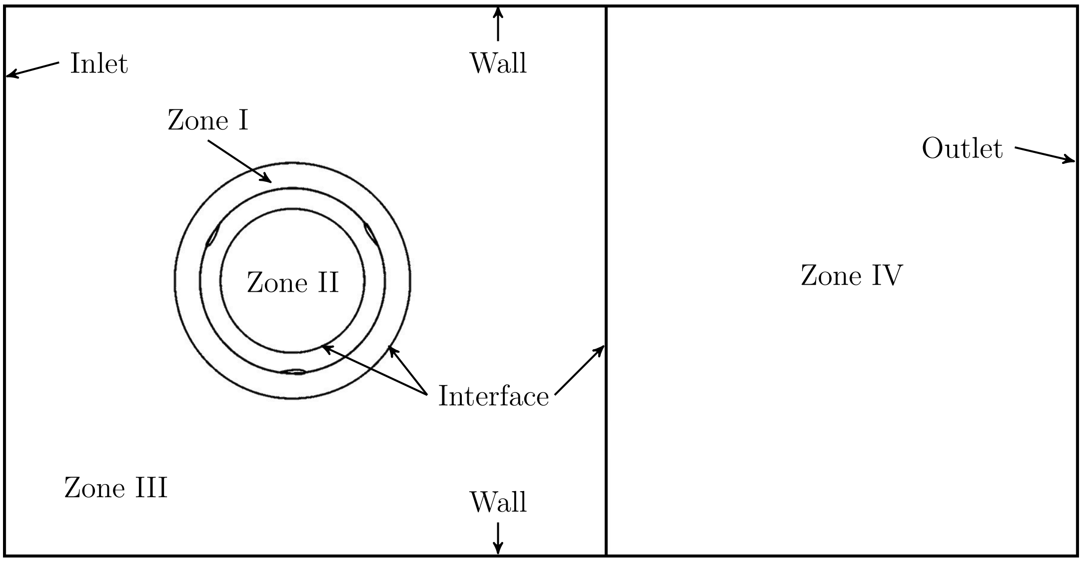
Simplified model characteristics

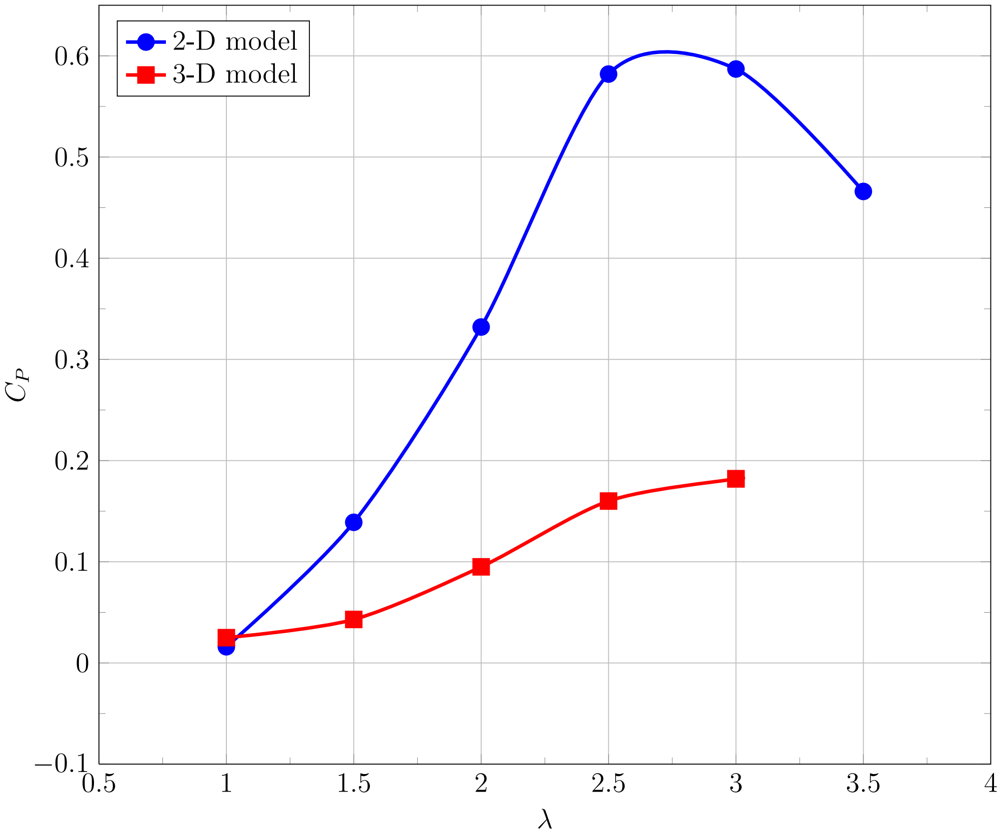


Considerations

- Equivalent to 2-D models
- Four mesh sizes

▸ Mesh

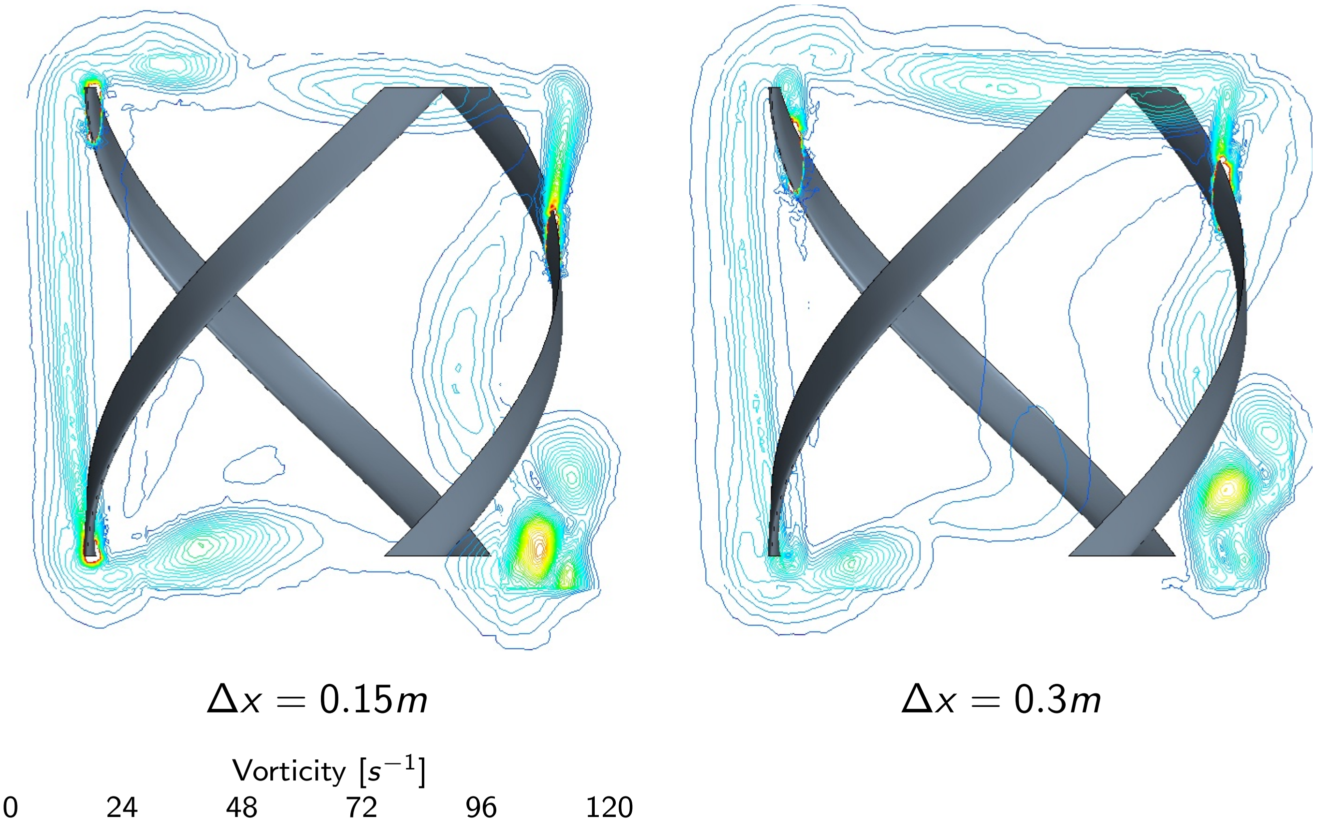
Results. Efficiency



NACA 0015

- Lower peak
- Unrealistic at low λ

Tip vortex visualization



$\Delta x = 0.15m$

$\Delta x = 0.3m$

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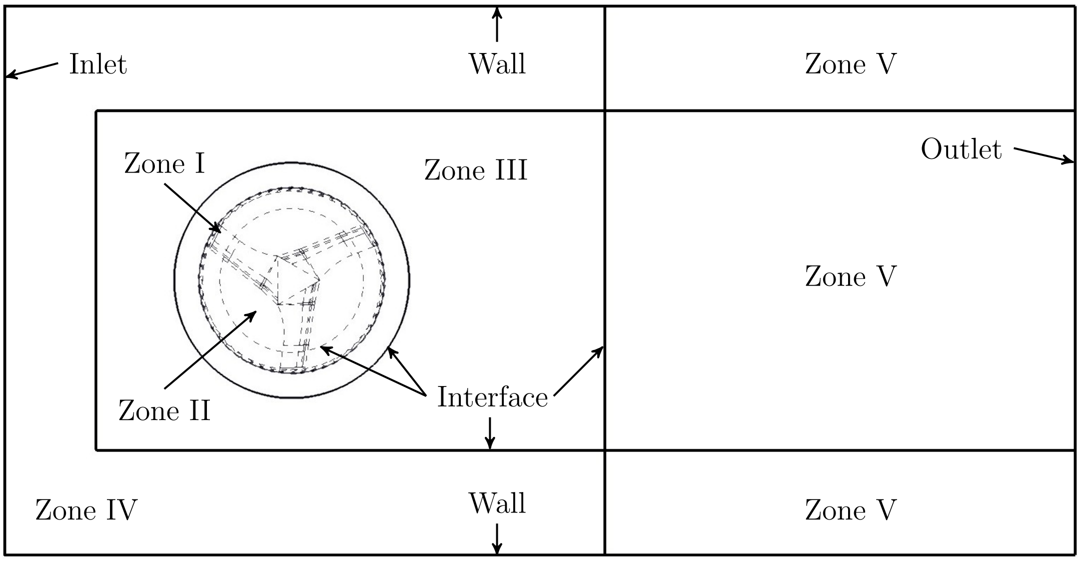
Detailed model characteristics



Considerations

- Equivalent to 3-D Simplified
- Five mesh sizes

▸ Mesh

Results. Inconveniences

Problems

- Solution does not converge
- Divergence of flow variables

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Possible causes

- Complex geometries
- Turbulence model
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- Alternative designs for the interface
- Increase mesh density
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- Last stages of involvement

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Constraint

- Last stages of involvement ⇒ Task continued based on this experience

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Origin of loads

Aerodynamic loads

- Operational: oscillatory pressure loads, friction loads
- Non–operational: pressure loads while braked, friction loads

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Inertial loads

- Operational: rotation, gravity
- Non–operational: gravity, installation and transportation

Origin of loads

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- Operational: oscillatory pressure loads, friction loads
- Non–operational: pressure loads while braked, friction loads

Inertial loads

- Operational: rotation, gravity
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Accidental loads

- Impact of foreign objects
- Installation and transportation

Outline

Diverse considerations

Previous work

- Composite materials selected: glass fiber – epoxy
- Isotropic behavior for the analysis

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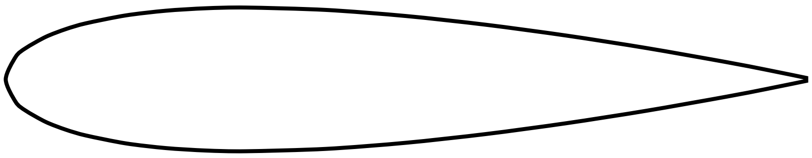
Efforts on the blades

- Global bending along the main axis
- Global bending along the secondary axis
- Torsion
- Local effects

Layout optimization



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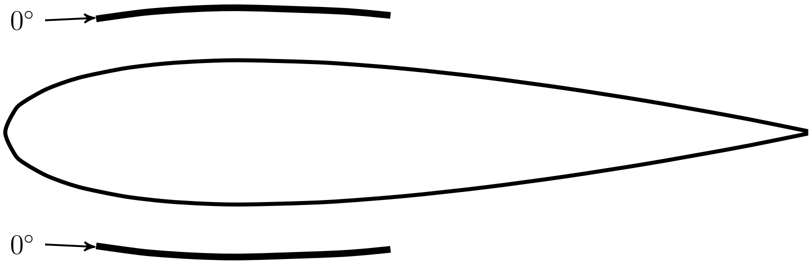

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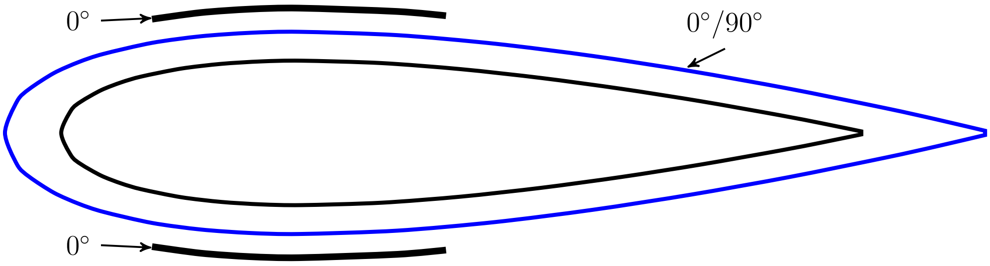

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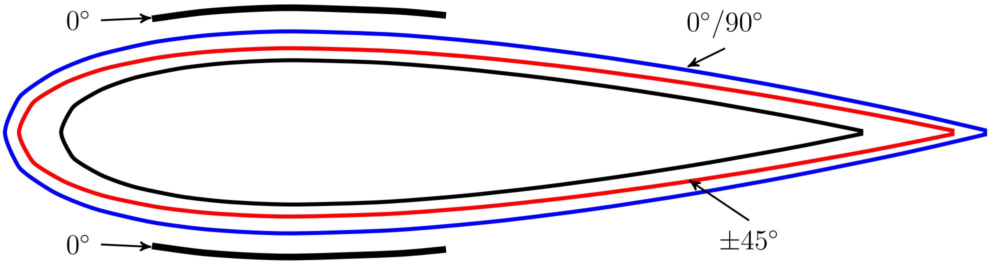

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- Global bending along the main axis
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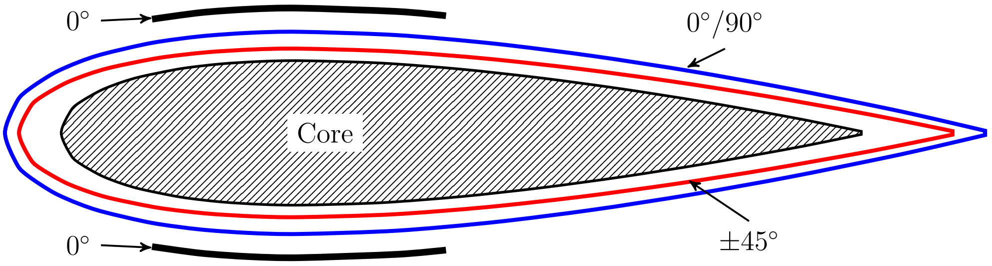
- Torsion
- Local effects

Layout optimization



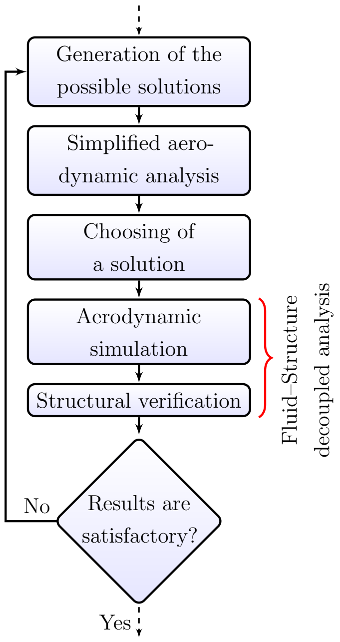
Outline

1. Motivation
2. Turbine Design
3. 2-D Aerodynamic Analysis
4. 3-D Aerodynamic Analysis
5. Structural Design
6. Simplified Load Estimation
    - Motivation
    - Implementation
    - Application
7. Conclusions and Recommendations

Motivation

Considerations

- Decoupled analysis
- Early structural optimization
- Need for aerodynamic loads
- 3-D CFD: time consuming
- Need for alternative solution



Generation of the possible solutions

Simplified aero-dynamic analysis

Choosing of a solution

Aerodynamic simulation

Structural verification

Fluid–Structure decoupled analysis

Results are satisfactory?

No

Yes

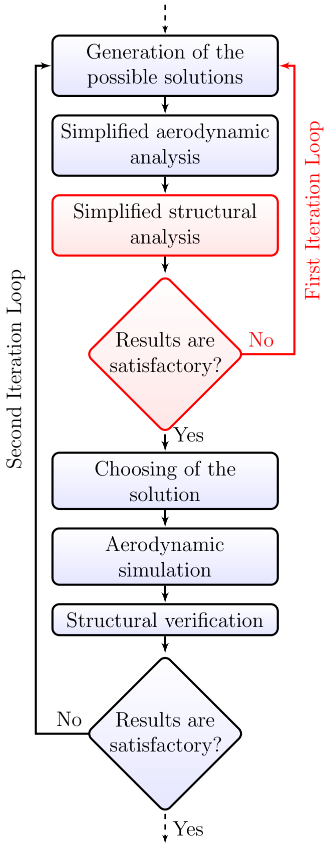
Motivation

Considerations

- Decoupled analysis
- Early structural optimization
- Need for aerodynamic loads
- 3-D CFD: time consuming
- Need for alternative solution

Proposal

- Preliminary load assessment based on 2-D CFD
- Early structural analysis
- Two iteration loops



Generation of the possible solutions

Simplified aerodynamic analysis

Simplified structural analysis

Results are satisfactory?

No

First Iteration Loop

Yes

Choosing of the solution

Aerodynamic simulation

Structural verification

Results are satisfactory?

No

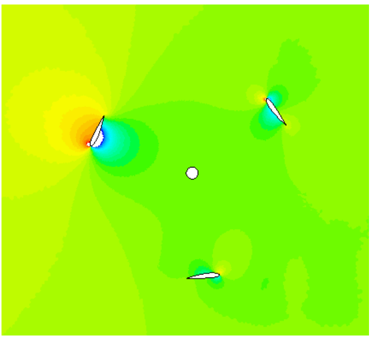
Second Iteration Loop

Yes

Outline

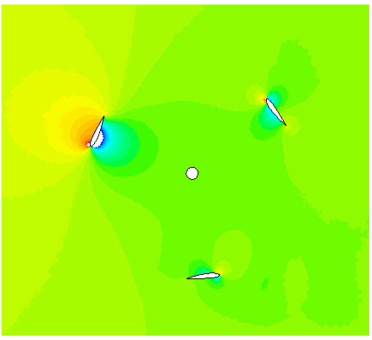
General description

2-D pressure distribution



General description

2-D pressure distribution

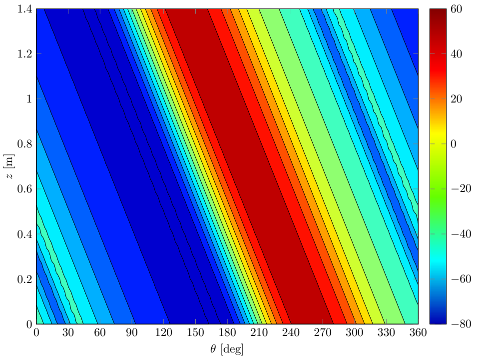


$\theta \Longleftrightarrow z$

$\longrightarrow$

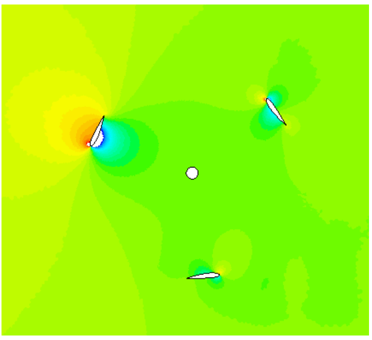
Data conditioning

3-D simplified distribution



General description

2-D pressure distribution



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Data conditioning

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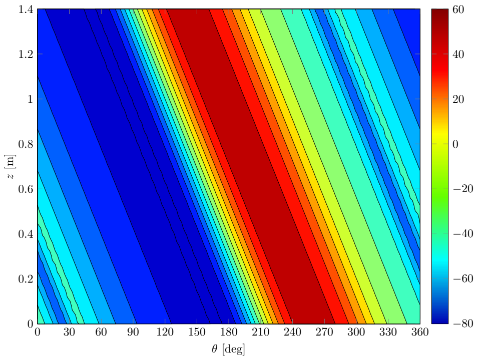
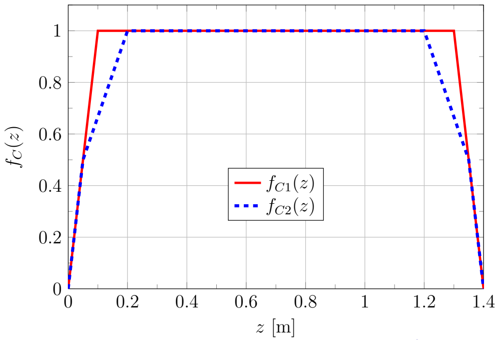
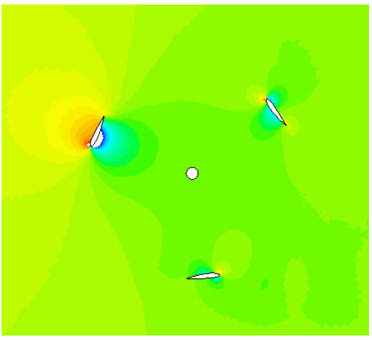


$\downarrow$ Shape function



General description

2-D pressure distribution



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$\longrightarrow$

Data conditioning

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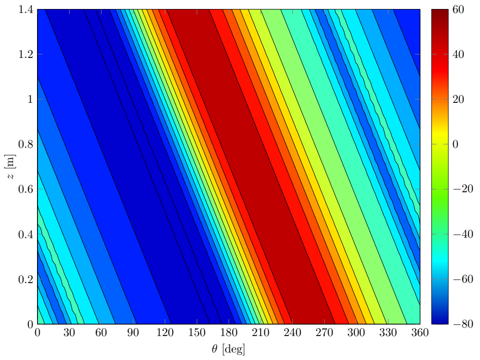
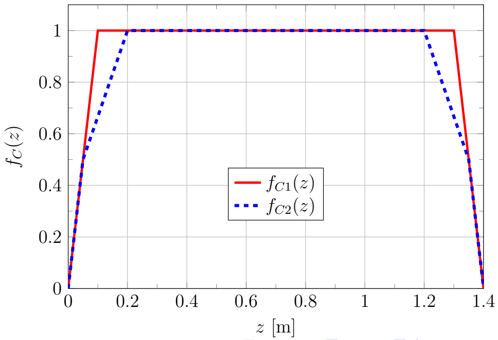
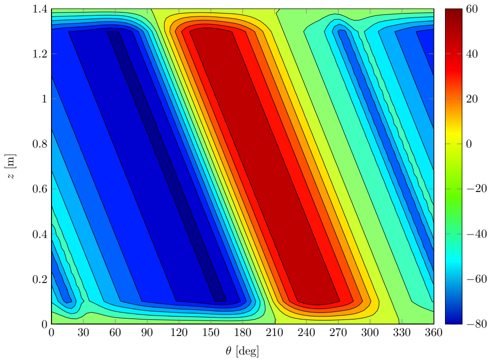


$\downarrow$ Shape function



3-D corrected distribution



Final estimation

$\longleftarrow$

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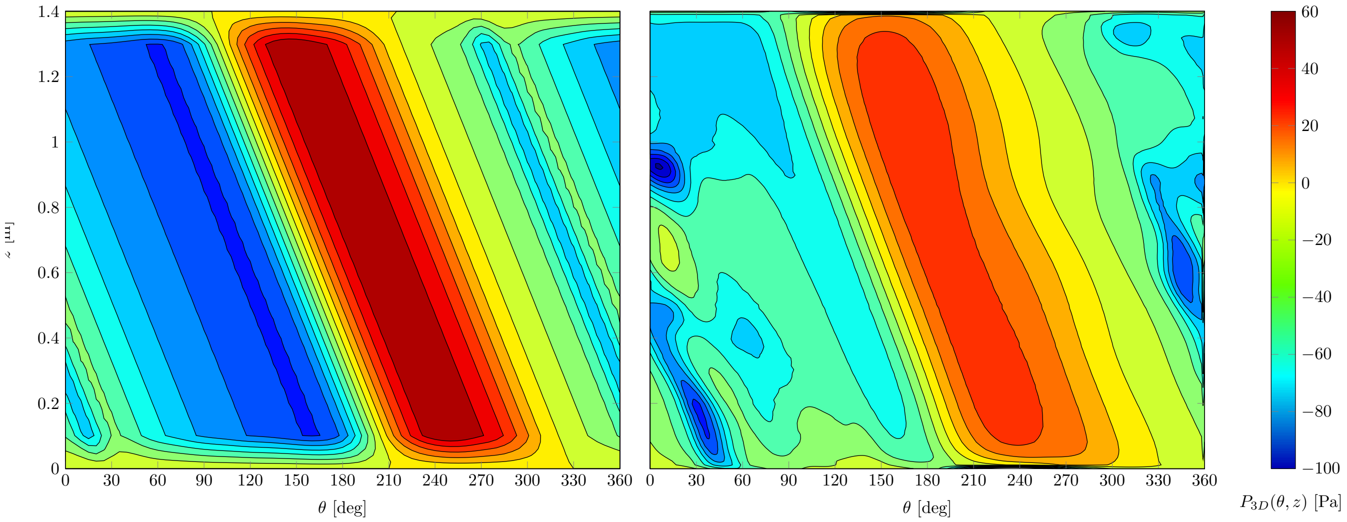
Preliminary evaluation



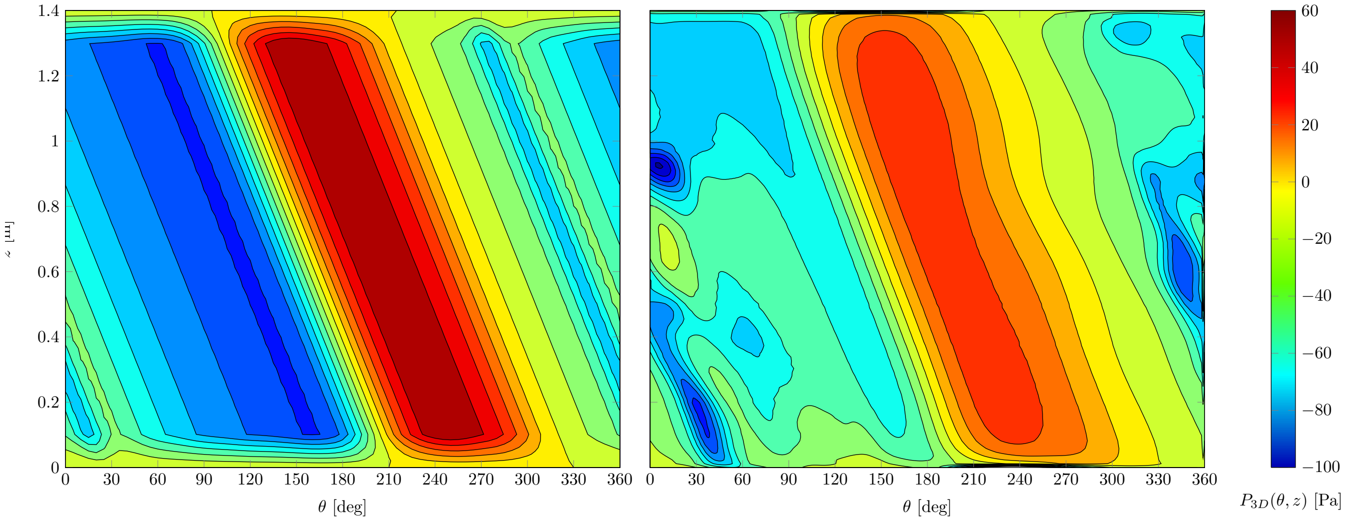
Approximation

3-D CFD simplified model

Preliminary evaluation

Approximation

3-D CFD simplified model



Observations

- Good general shape correlation
- Blunt pressure reduction at tips
- Higher peak values
- Less oscillatory

Outline

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    - Summary
    - Limitations and Future Work

Summary I

Turbine Design

- Several work flows proposed
    - Flexibility to adapt to the analysis methodology
- Blade support at extremities
    - Continuity in forces, better efficiency
    - Designs to reduce negative tip vortex effects
- Three alternative designs proposed for the blade–support interface
    - Efficiencies to be evaluated

Summary I

Turbine Design

- Several work flows proposed
    - Flexibility to adapt to the analysis methodology
- Blade support at extremities
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    - Designs to reduce negative tip vortex effects
- Three alternative designs proposed for the blade–support interface
    - Efficiencies to be evaluated

Aerodynamic analysis

- Wide study with 2-D CFD analysis
    - Selection of two candidate airfoils
- Further studies started with 3-D CFD analysis.
    - Simplified models captured the tip vortices
    - More realistic efficiency curve

Summary II

Structural analysis

- Load assessment
    - Description of the loads affecting the turbine
- Material optimization
    - Proposal for material use according to solicitations
- Development of a simplified method for preliminary studies
    - 3-D pressure distributions estimated from 2-D CFD models
    - Preliminary trials result promising

Outline

Limitations and future work

Inconveniences detected and proposed solutions

- CFD models with unsatisfactory results
    - Improvement of mesh quality
    - Assessment of the effect of turbulence model and grid–sensitivity
    - Simplification of the domain under study
    - Efficiency analysis based on alternative methods
- Incomplete structural analysis
    - Proceed with detailed analysis of the material layup

Limitations and future work

Inconveniences detected and proposed solutions

- CFD models with unsatisfactory results
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    - Assessment of the effect of turbulence model and grid–sensitivity
    - Simplification of the domain under study
    - Efficiency analysis based on alternative methods
- Incomplete structural analysis
    - Proceed with detailed analysis of the material layup

Recommended tasks

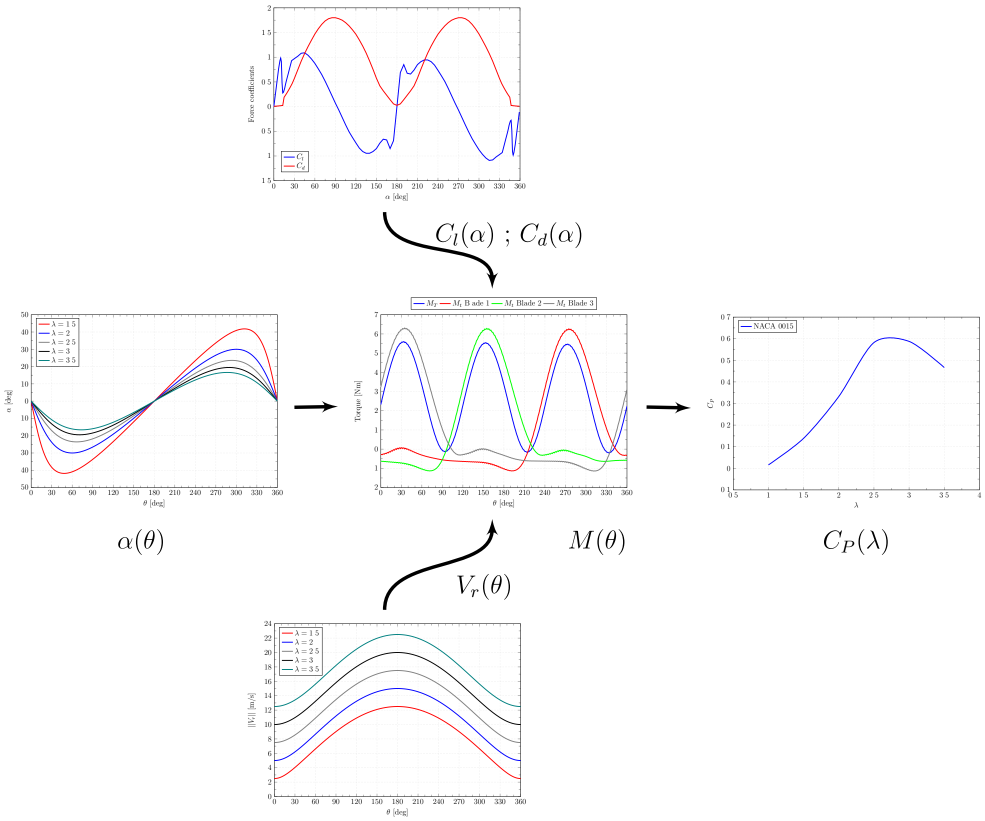
- Wind tunnel testing
    - Proceed with model validation and feedback
- Material testing
    - Characterization of unidirectional specimens to improve structural design
- Preliminary pressure loads estimation
    - Continue with the validation and development of the methodology

Thank you for your attention.

Questions?

Back up slides

A method to estimate the performance



$C_l(\alpha)$; $C_d(\alpha)$

$\alpha(\theta)$

$M(\theta)$

$C_P(\lambda)$

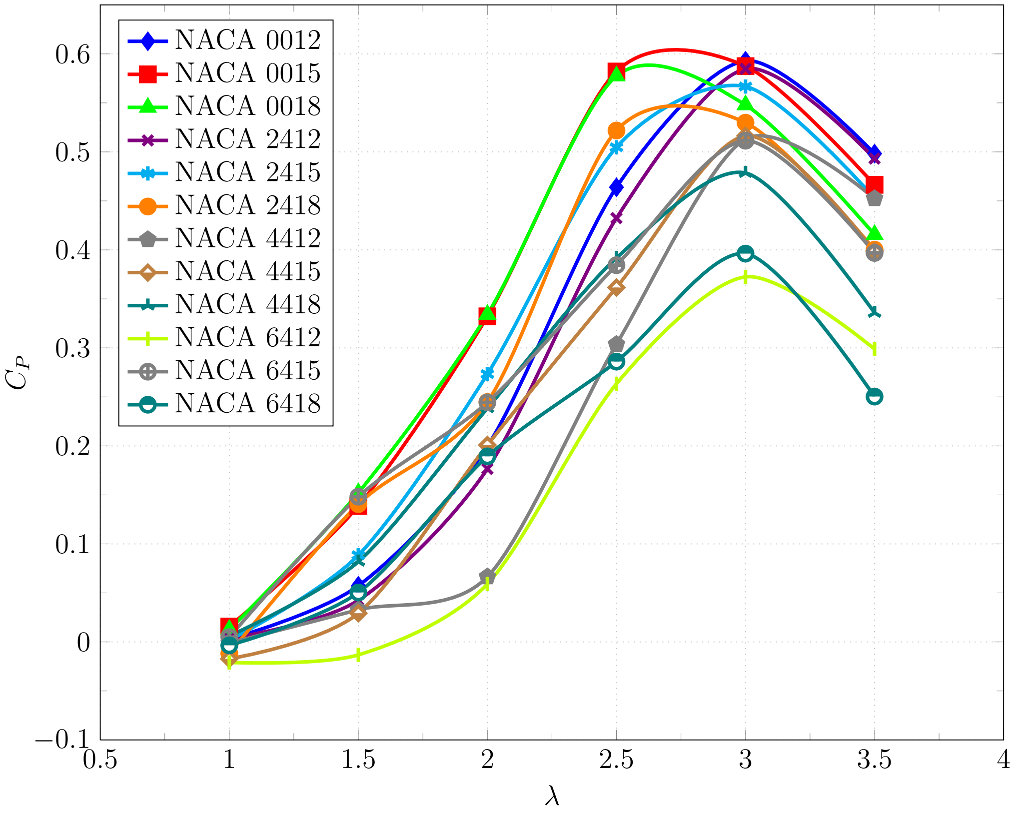
$V_r(\theta)$

Main aspects

- Based on airfoil data
- Disregards interference
- Dependent on quality of data
- Questionable results
- Unknown flow characteristics

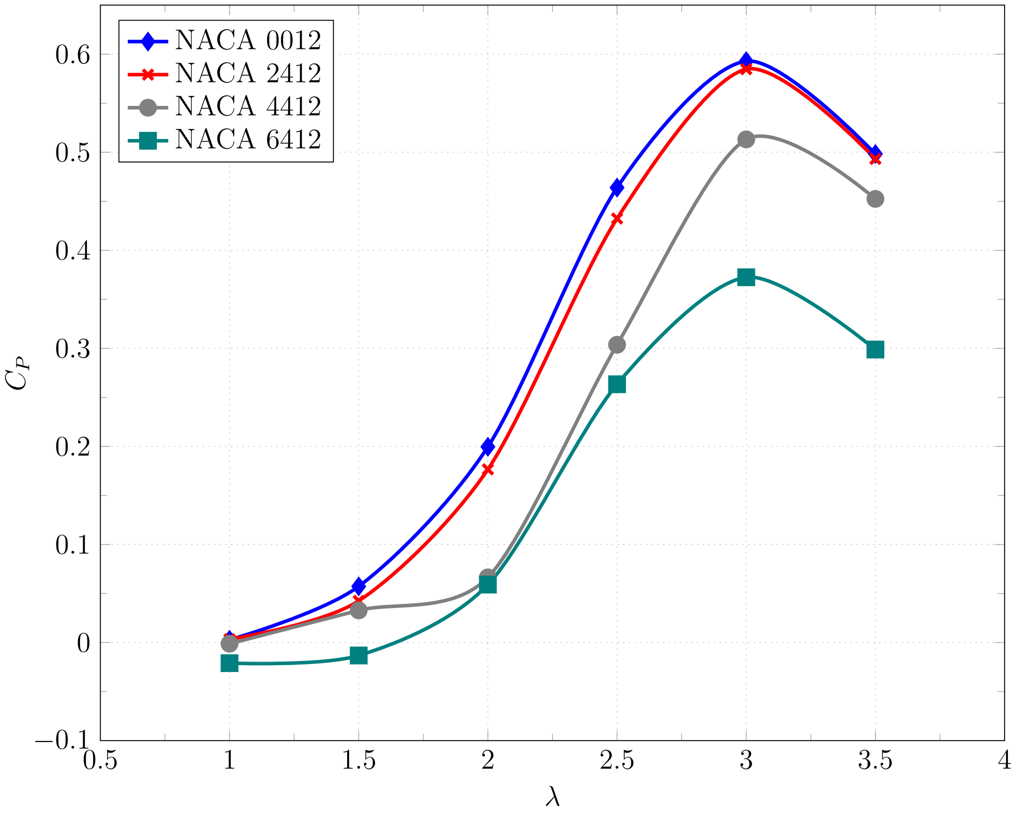
◂ Preliminary 2D Analysis

2-D. Efficiencies. Complete results



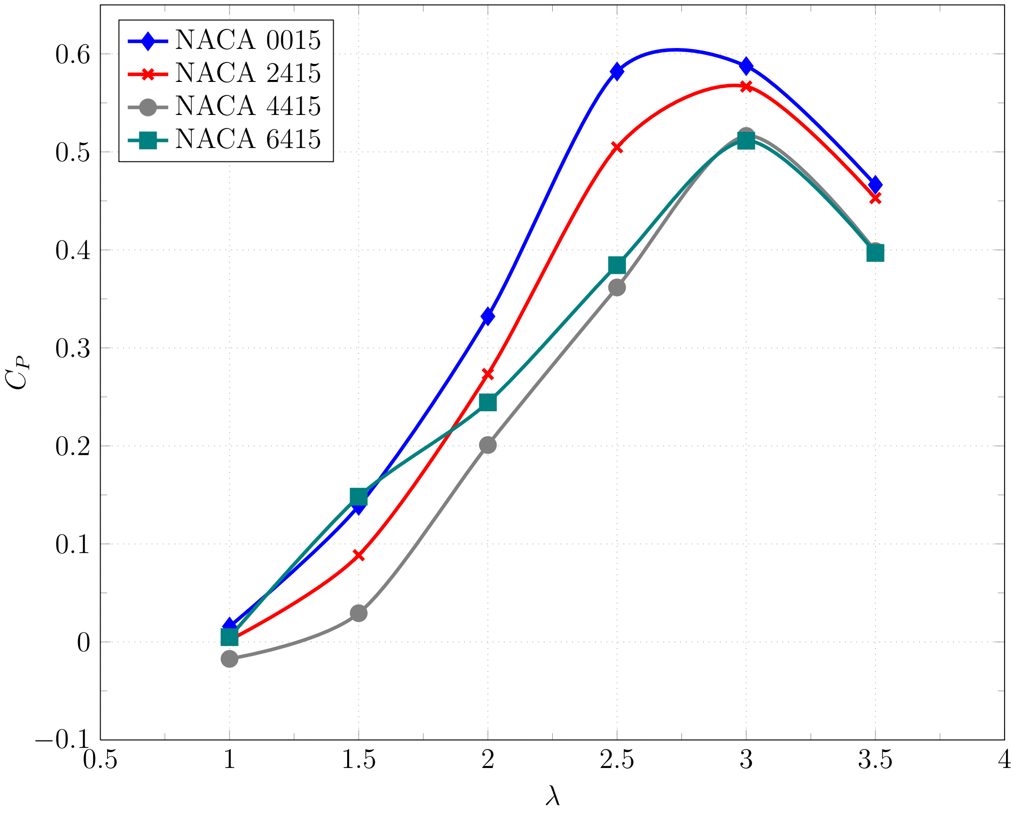
Overall view

2-D. Efficiencies. Complete results



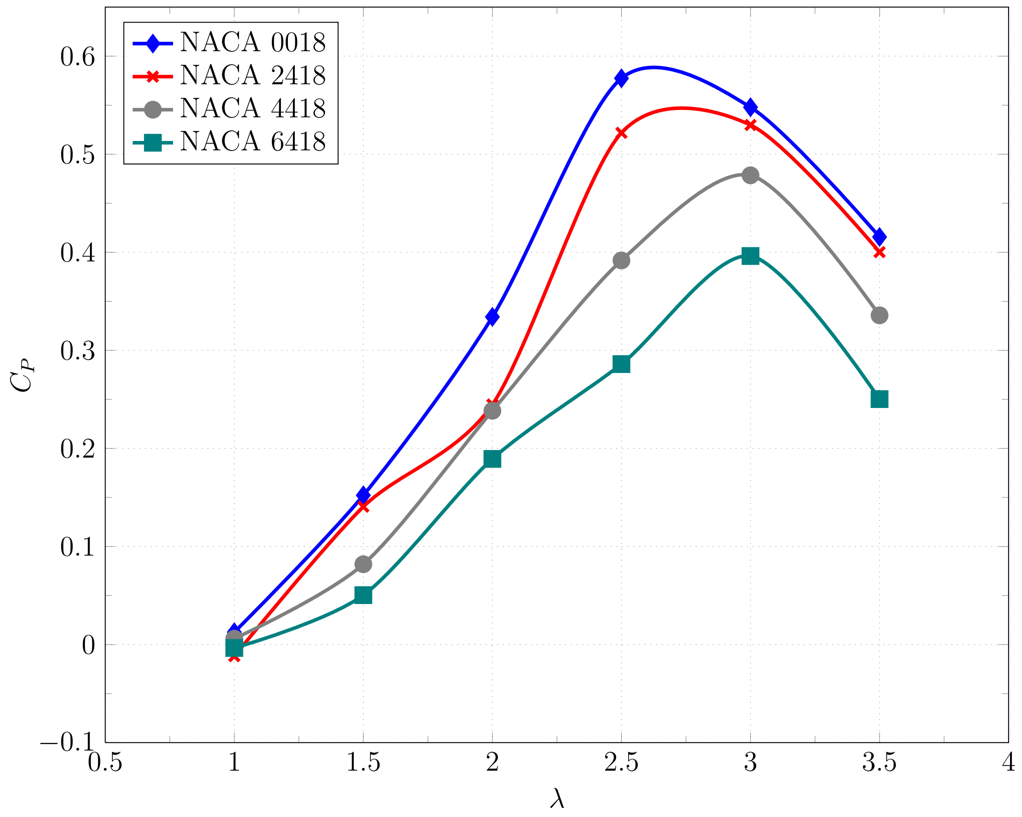
Curvature effect
12% thickness

2-D. Efficiencies. Complete results



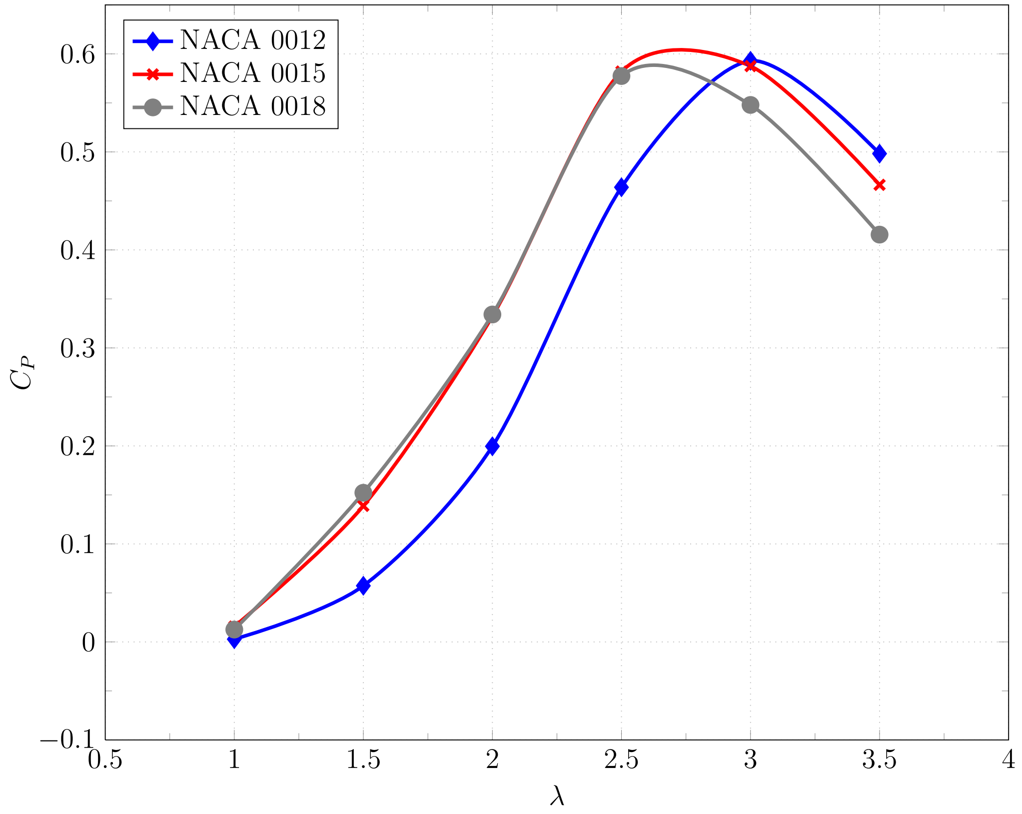
Curvature effect
15% thickness

2-D. Efficiencies. Complete results



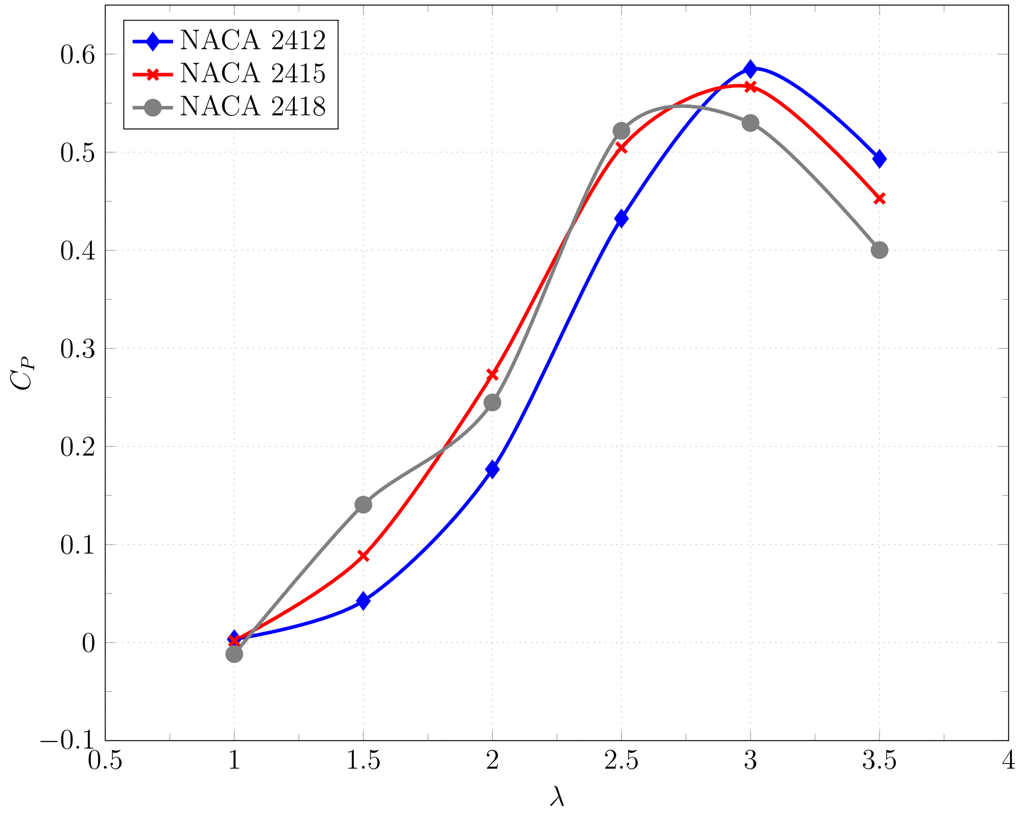
Curvature effect
18% thickness

2-D. Efficiencies. Complete results



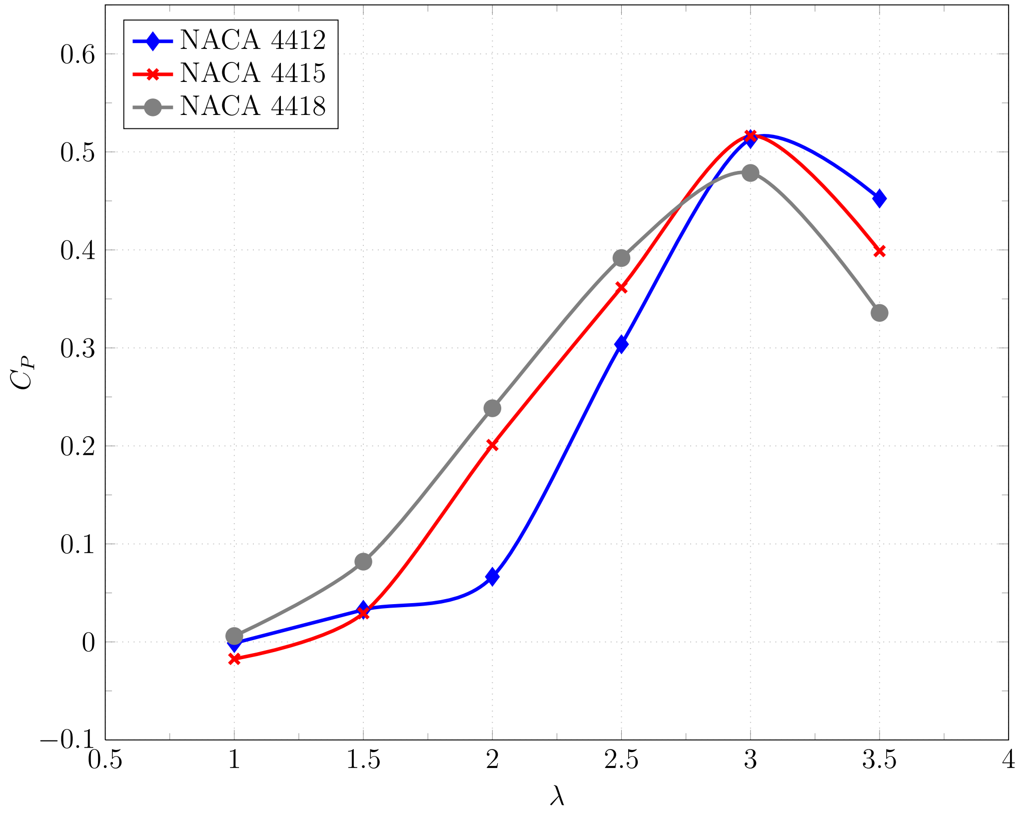
Thickness effect
0% curvature

2-D. Efficiencies. Complete results



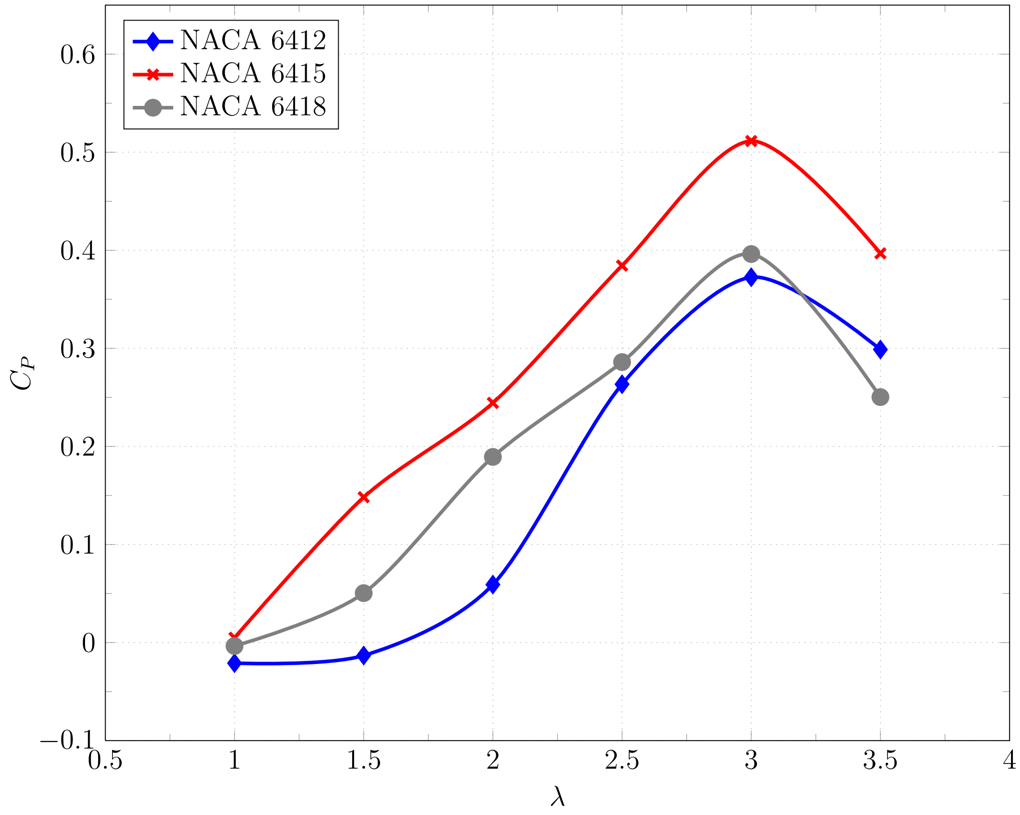
Thickness effect
2% curvature

2-D. Efficiencies. Complete results



Thickness effect
4% curvature

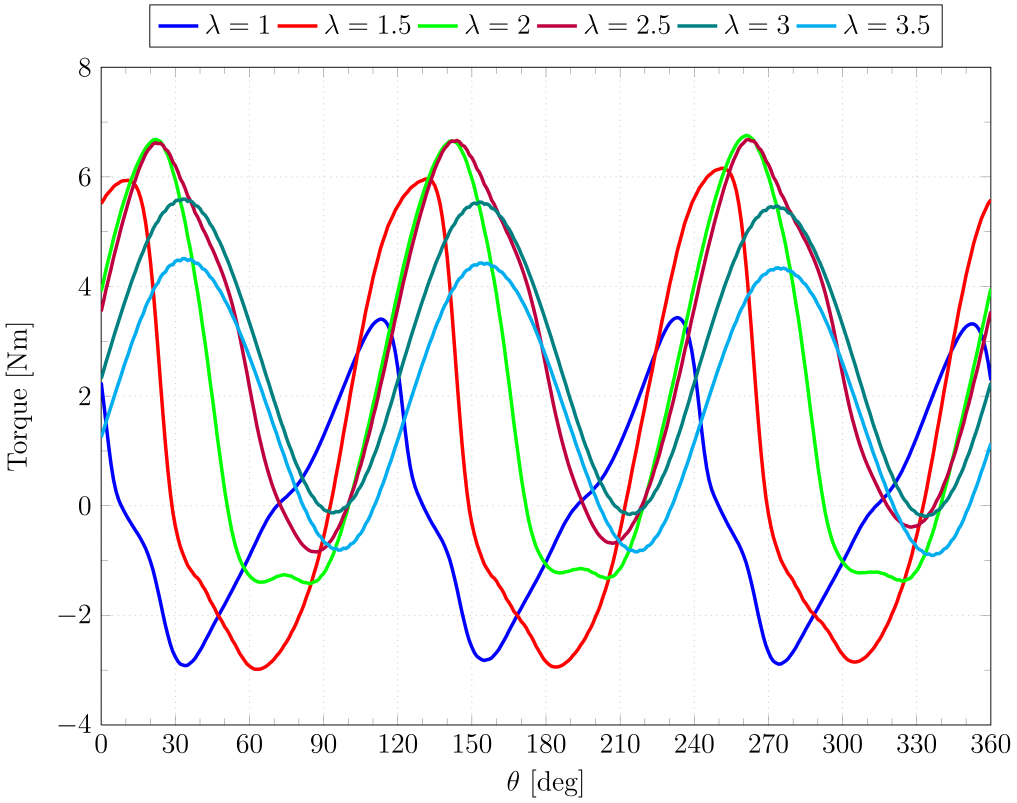
2-D. Efficiencies. Complete results



Thickness effect
6% curvature

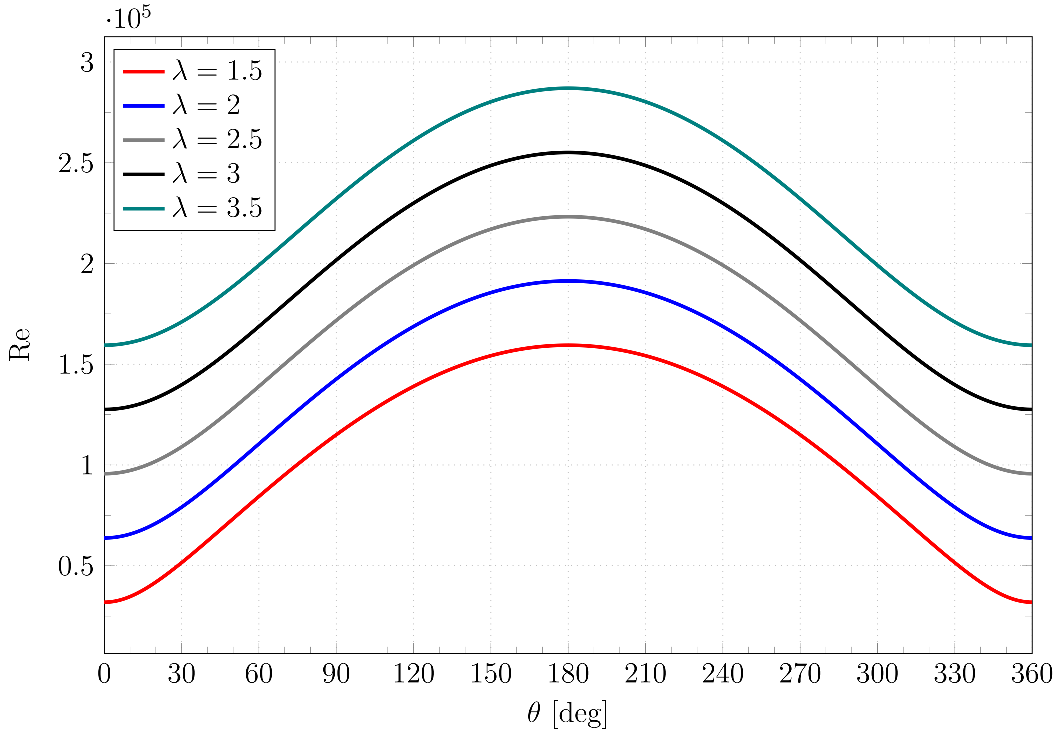
◂ 2D Analysis

2-D. Torque variation with λ.



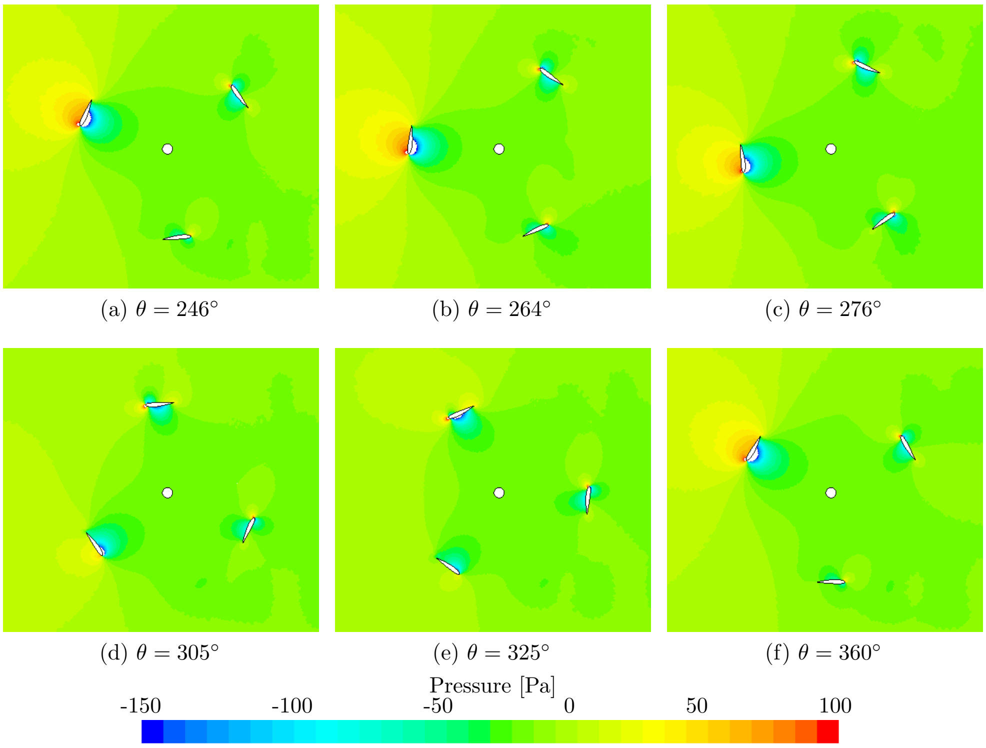
NACA 2415

2-D. Reynolds number variation with λ.



Flow variables

Flow pattern



(a) $\theta = 246°$ (b) $\theta = 264°$ (c) $\theta = 276°$

(d) $\theta = 305°$ (e) $\theta = 325°$ (f) $\theta = 360°$

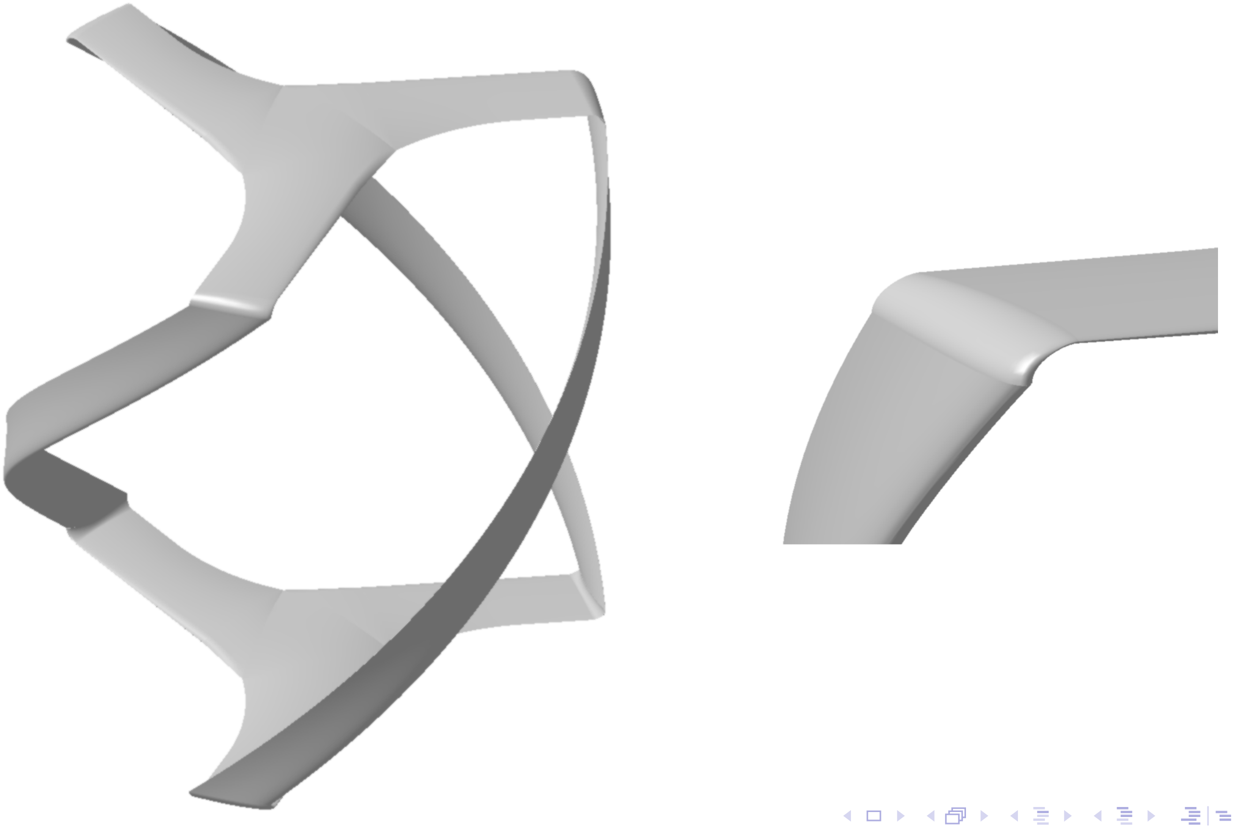
NACA 2415 $\lambda = 3$

- Lower α
- Lower intensity vortices

$\lambda = 1$

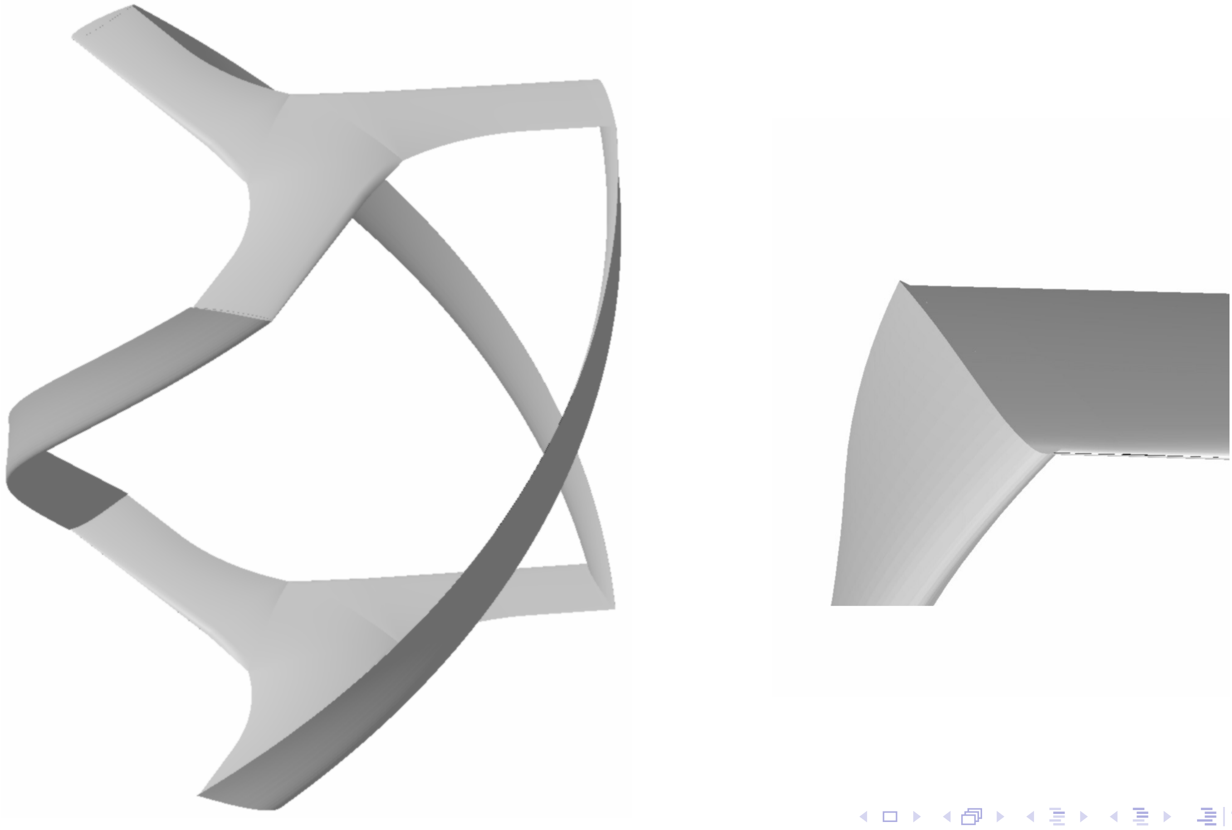
Blade support design.

Alternative 1, transition element.



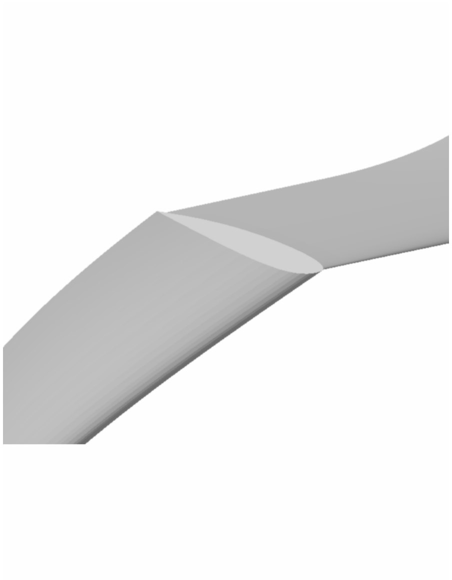
Blade support design.

Alternative 2, smoothed joint.



Blade support design.

Alternative 3, chamfered edge.



Turbine design

2-D model. Mesh general view.