Vertical axis wind turbines

Aerodynamic challenges to be tackled

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Institut PPRIME – Université de Poitiers

10th EAWE PhD Seminar on Wind Energy in Europe
October 28-31, 2014 in Orléans, France

Outline

- Aerodynamic obstacles to the design of a VAWT
  - How a VAWT works
  - Questioning about the ideal geometry
  - Why it is difficult to study
- Flow curvature
  - What it is
  - What it causes
- Dynamic stall
  - Why it is specific
  - Experimental study of the phenomenon and its consequences
  - Usual numerical models for dynamic stall

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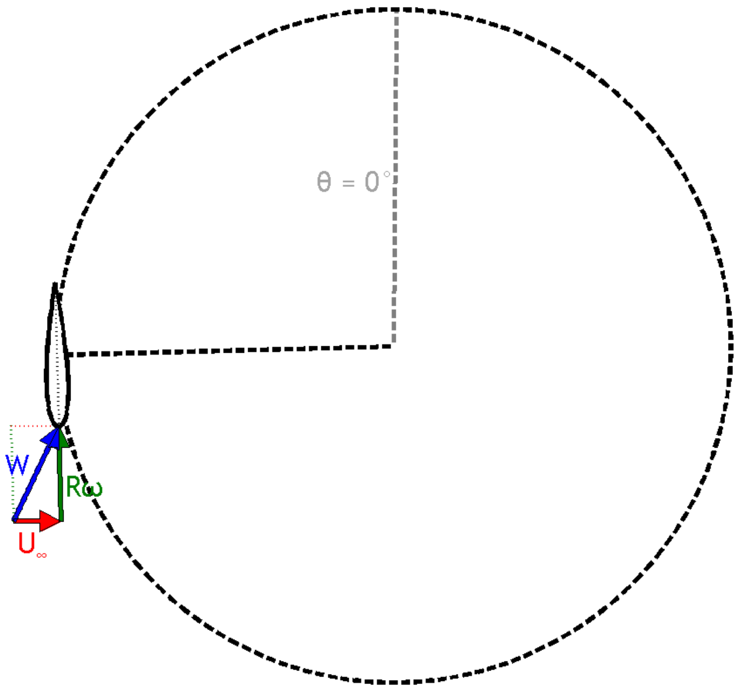
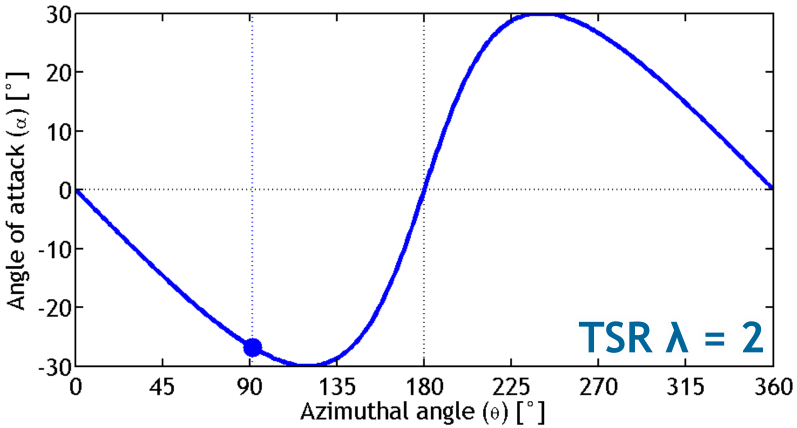
Aerodynamic obstacles to the design of a VAWT

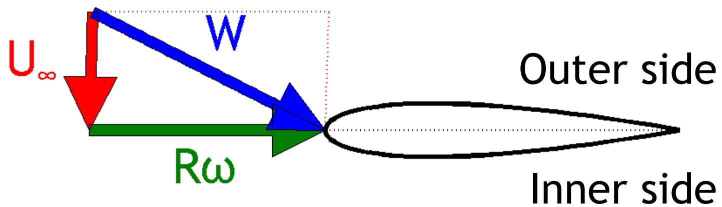
How does it work?

- Cyclic variation of the angle of attack (α)



Sectional view



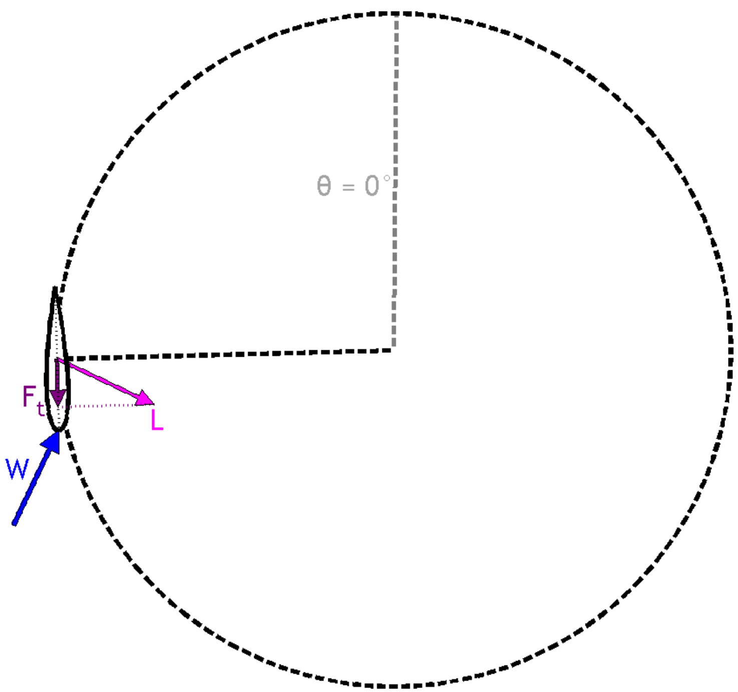


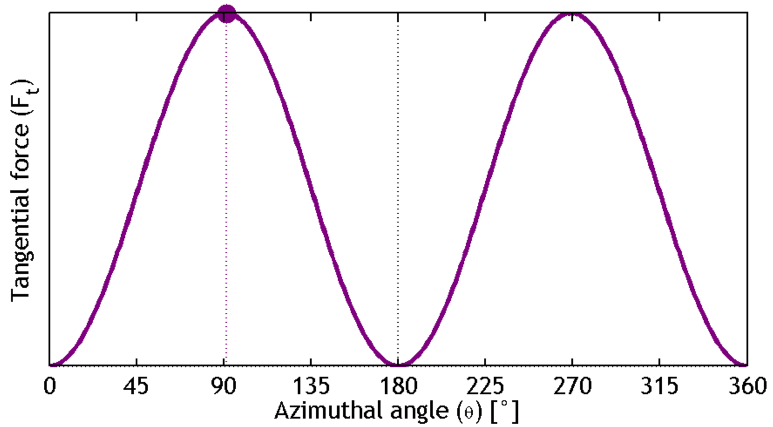
Airfoil's reference frame

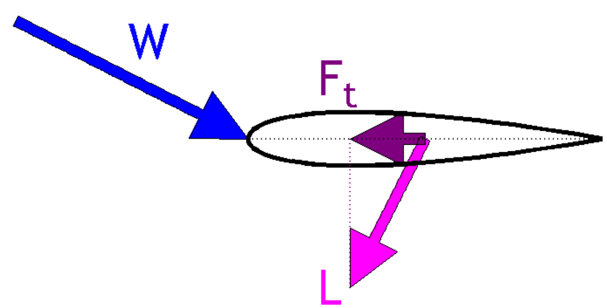
Freestream velocity
Rotational velocity
Relative velocity

How does it work?

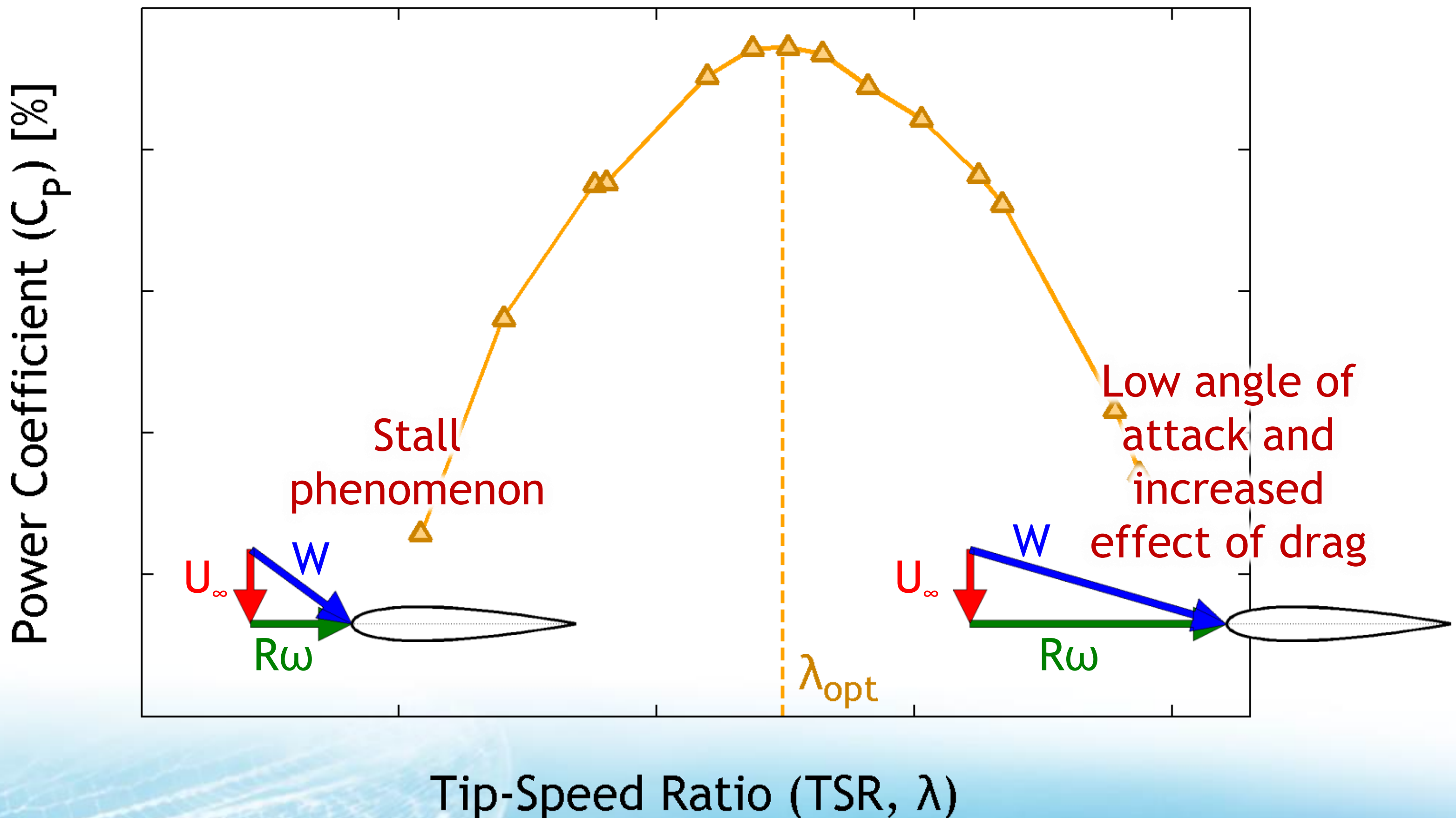
- Cyclic variation of the tangential force (F_t)







Effect of tip-speed ratio (TSR)



What are the current trends?

Deepwind
www.deepwind.eu
(Scientific project DTU/MARIN/ DUWIND/NREL/ MARINTEK/etc...)

Gwind
www.gwind.no
(Gwind)

INFLOW
www.inflow-fp7.eu
(Nenuphar/Technip/ EDF-EN/etc...)

Spinfloat
www.spinfloat.com
(EOLFI, subsidiary of ASAH LM)

VertaxWind
vertaxwind.com
(VertaxWind Ltd, subsidiary of Eurowind Developments)

What are the current trends?

Eggbeater shape

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Helical blades

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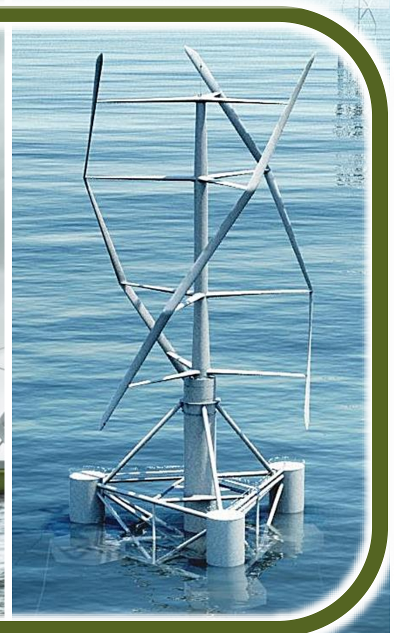

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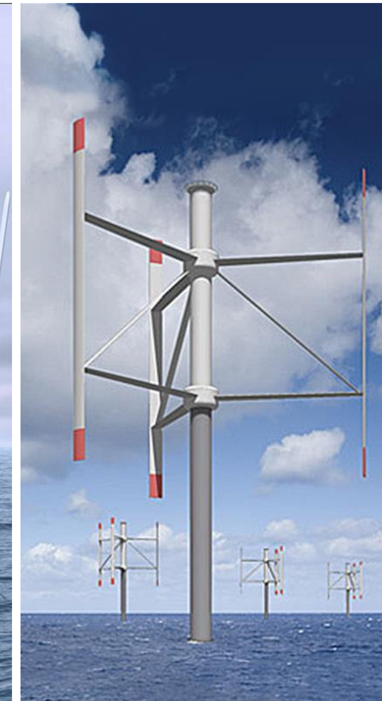

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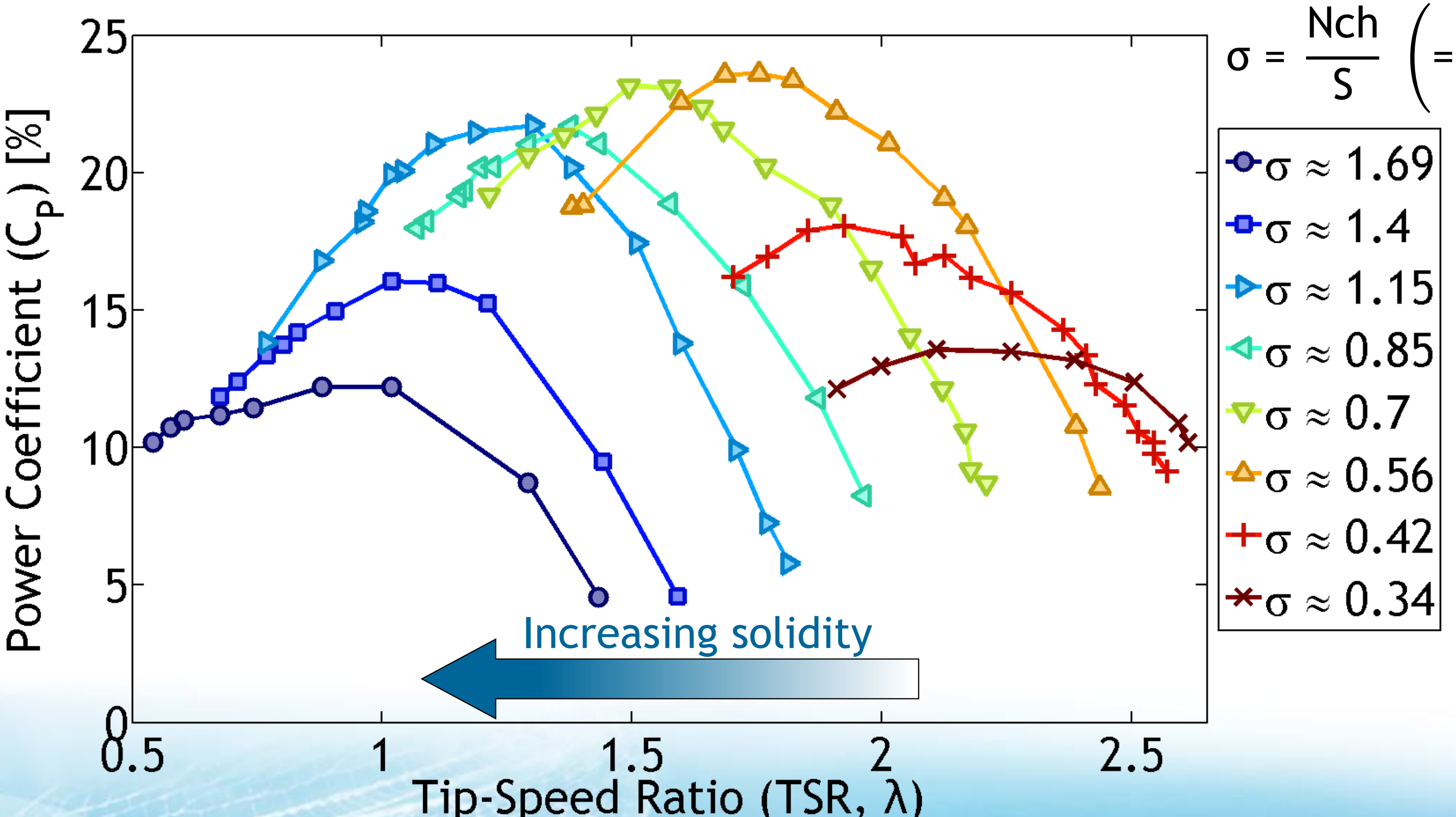
  - Reasons?
    - *Trade-off* resulting from the ranking of the priorities and from the *technical choices and requirements* (structural strength, safety devices, noise emission, price…)
    - *Difficulties to apprehend and model the VAWTs aerodynamics* (questionable performance computations and hard and doubtful operation of optimization)

e.g. effect of solidity (σ)



$$\sigma = \frac{Nch}{S} \left(= \frac{Nc}{2R} \right)$$

From Shiono et al. (2000) on a water turbine

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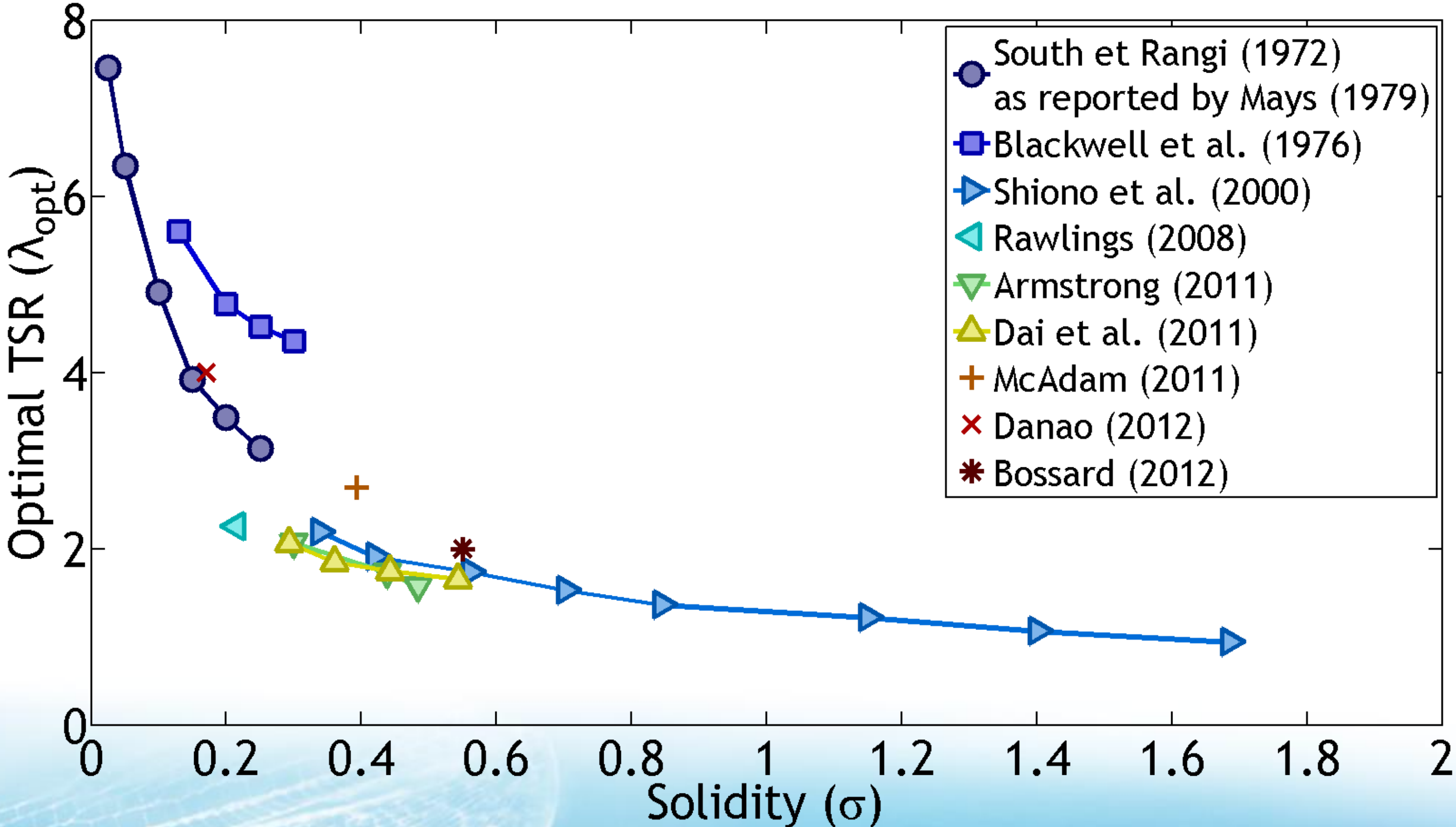

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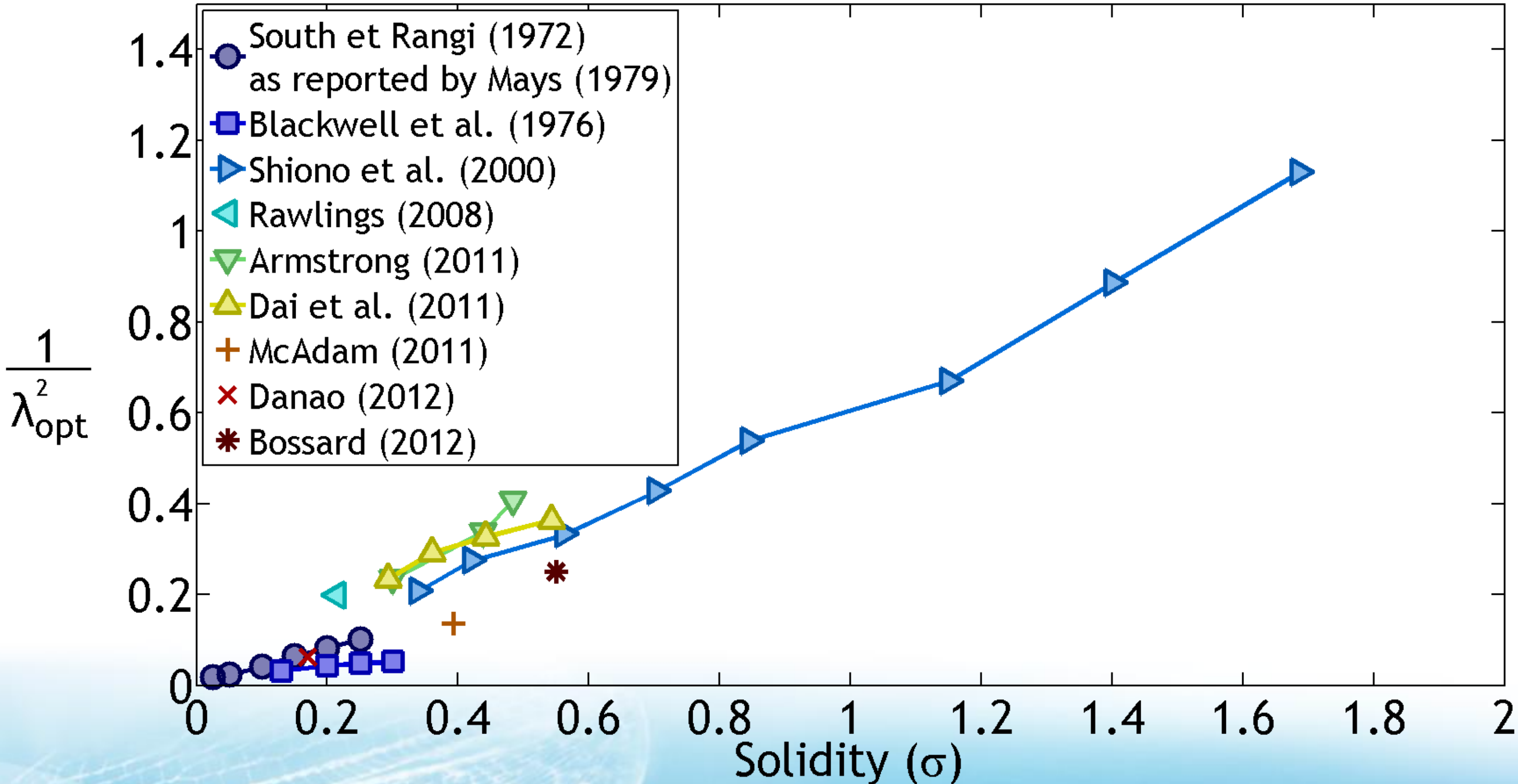

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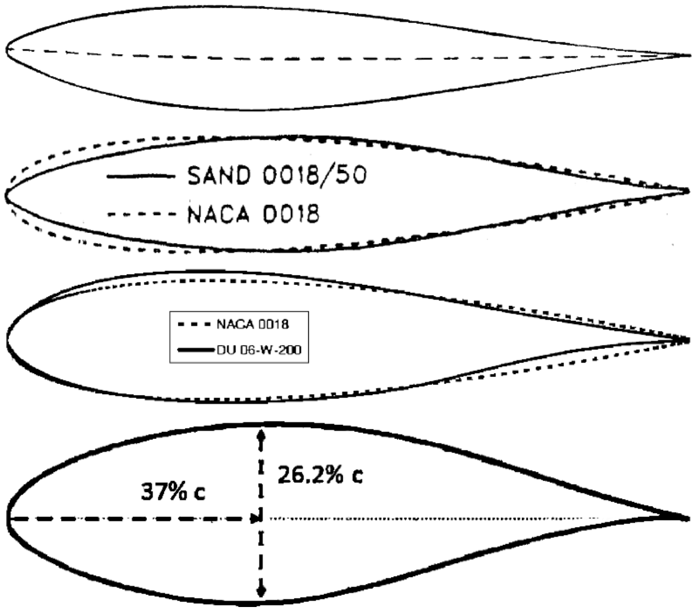

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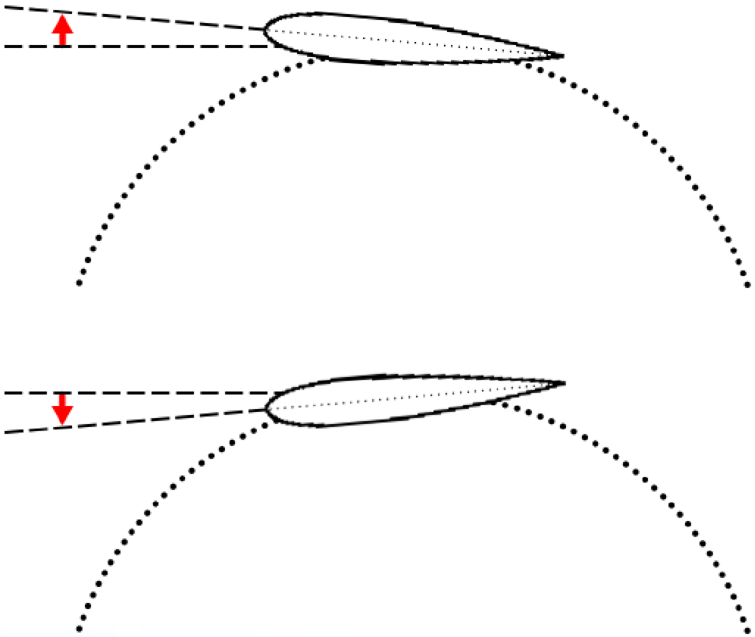

- Preset toe-in and toe-out blade pitch?
- Position of the mounting point (pitching axis)?

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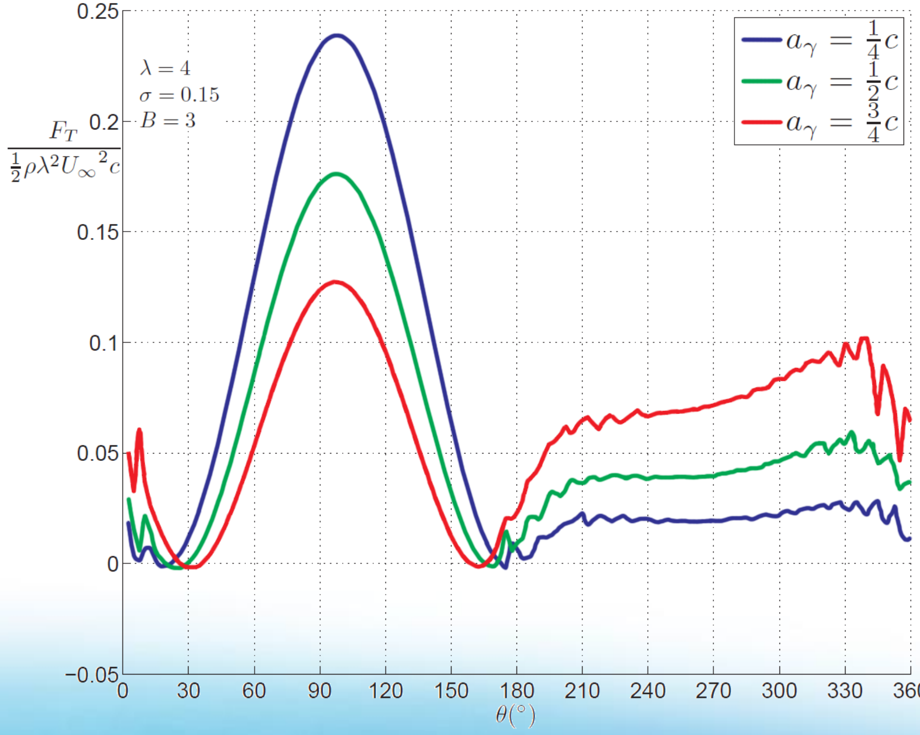
"However, it significantly affects the loading on the blades, *transferring torque between the upwind and downwind blade passages* and changing the average normal force."



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From F. Scheurich (2011)

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"We identified a large design space with significant *improvements to be achieved*. Research on cambered aerofoils and pitching axis location can lead to substantial *gains in the efficiency of VAWT*"

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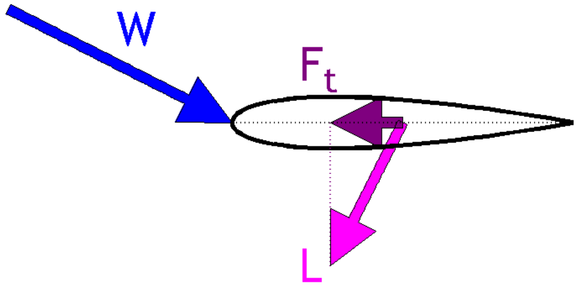

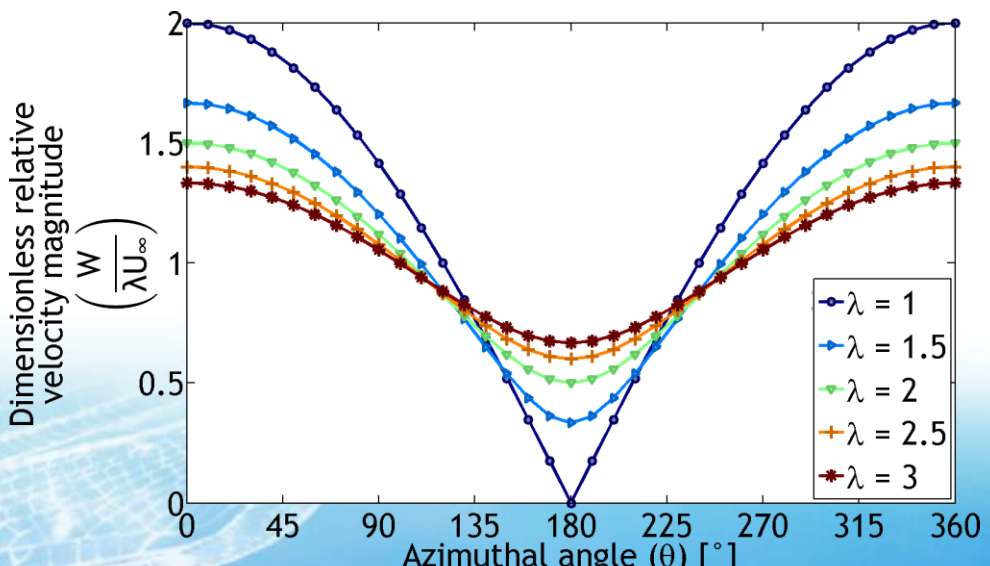

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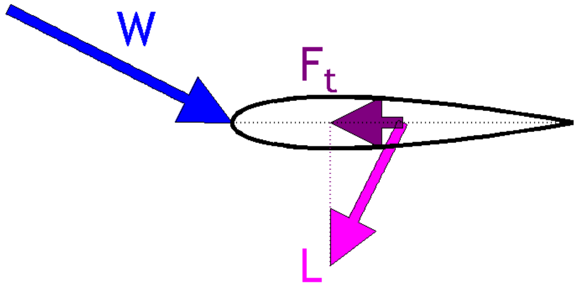

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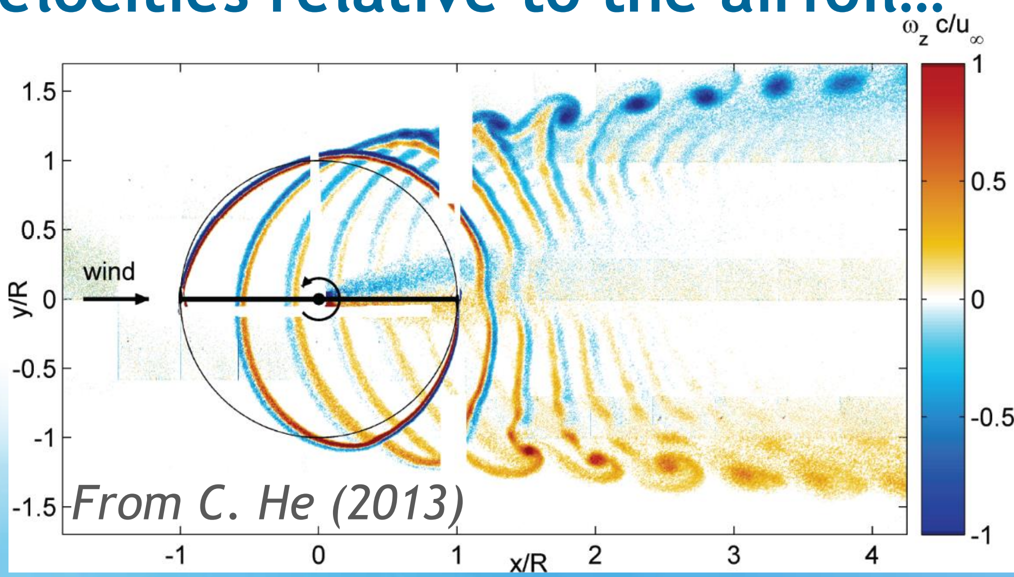

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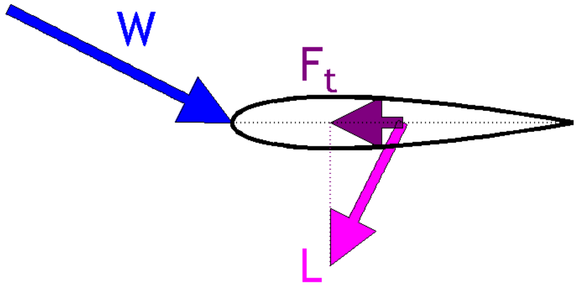

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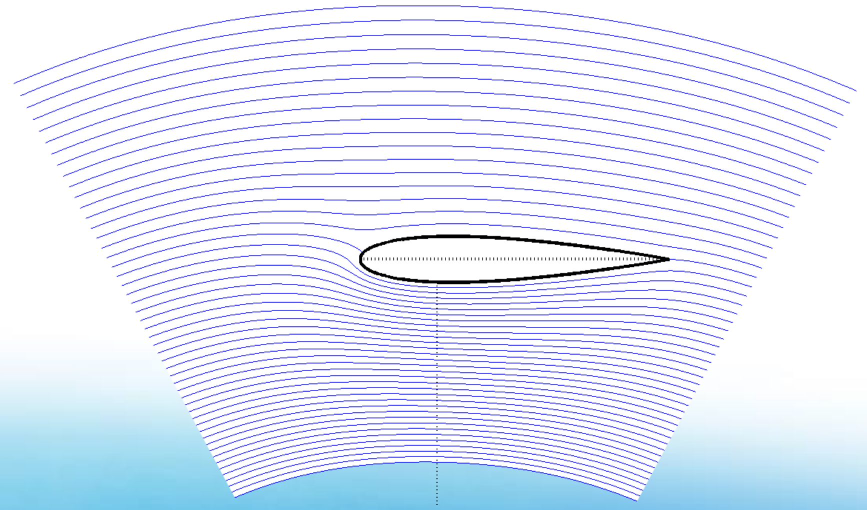

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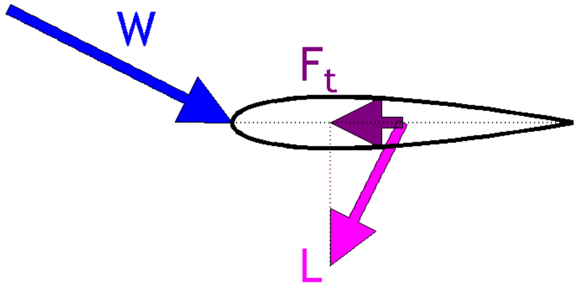

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  - ***3D effects***
    - Tip vortices
    - Helical blades

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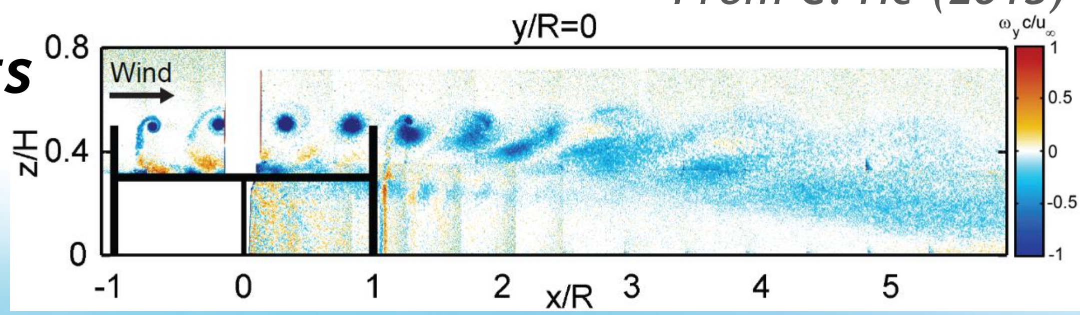
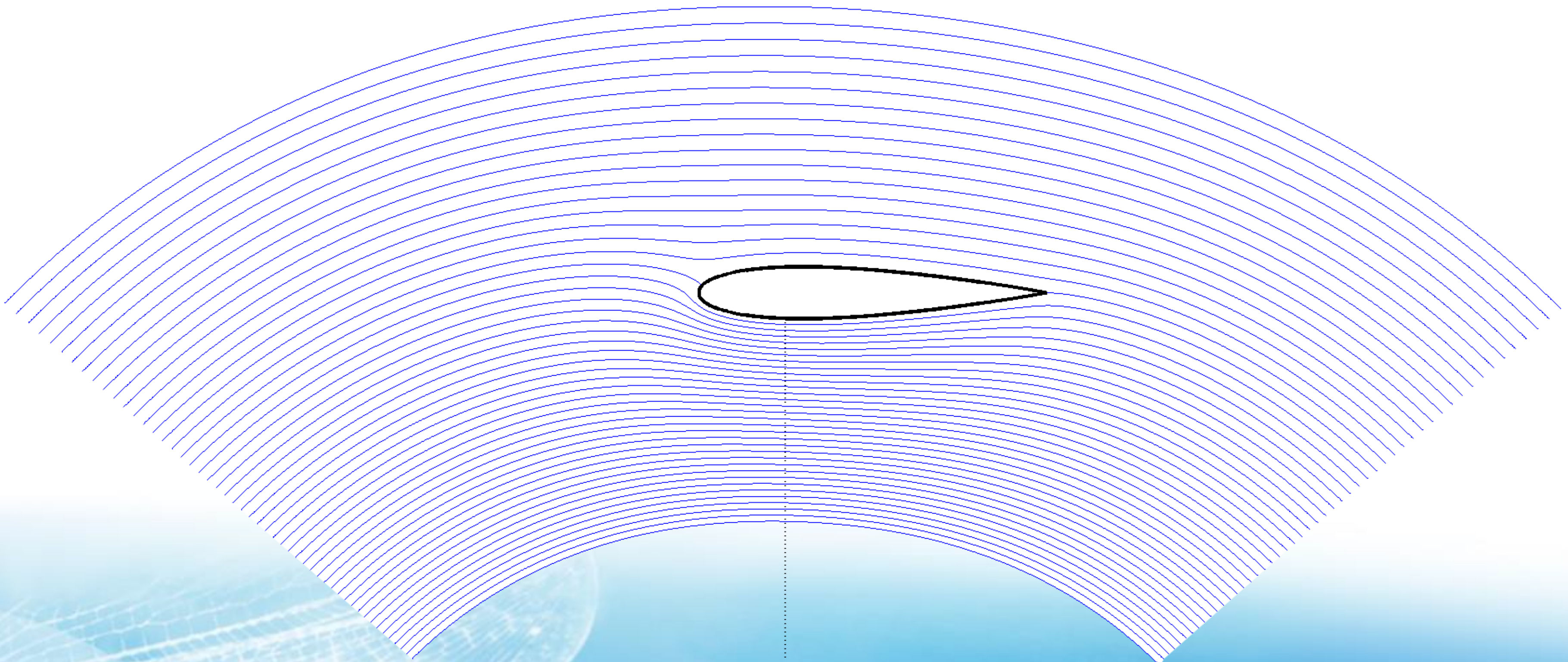


Flow curvature effects

What is flow curvature?

- **Change in the aerodynamic behavior of an airfoil *induced by its own motion***



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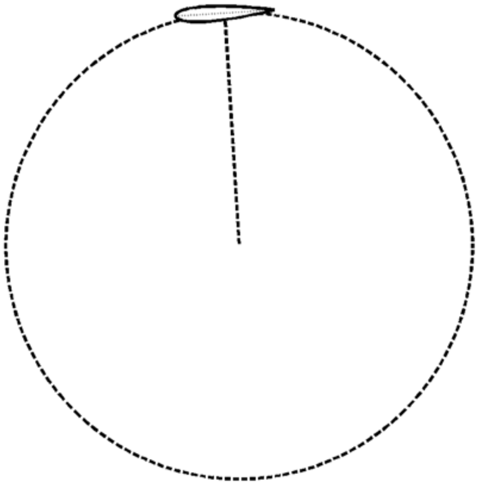

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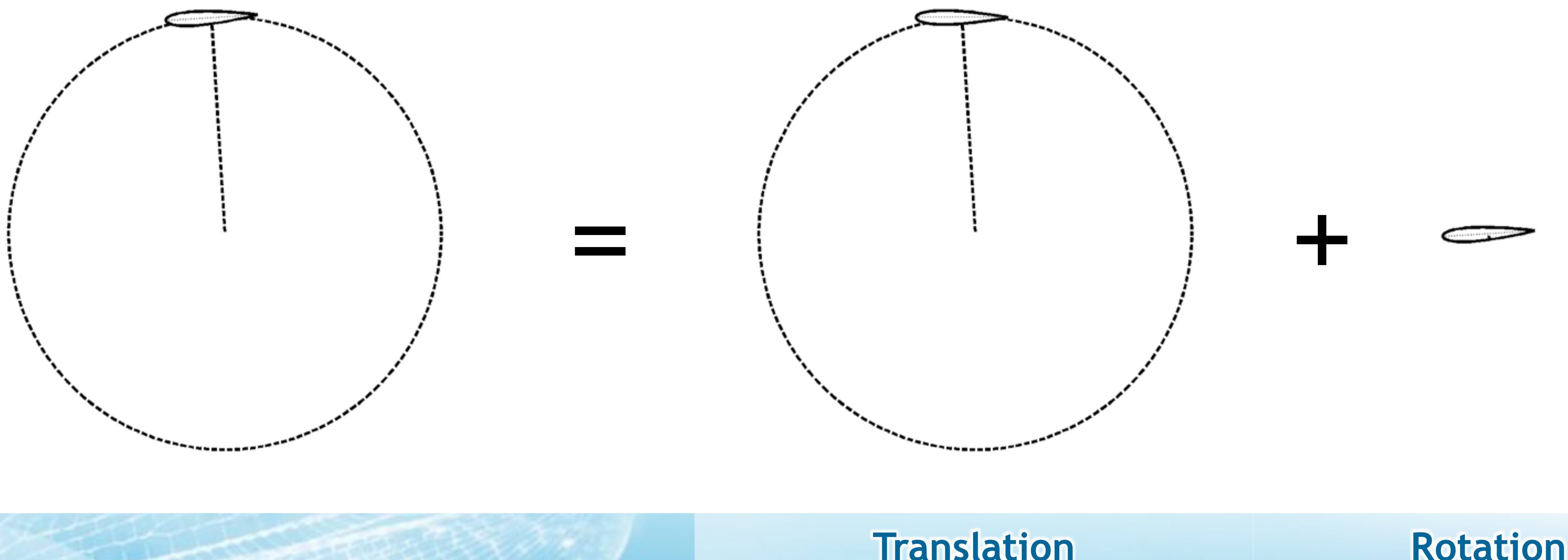
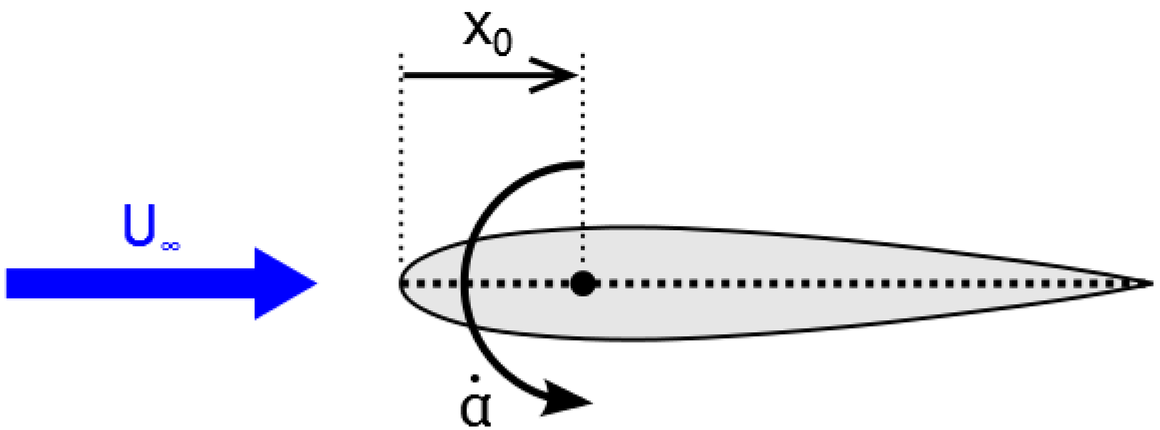
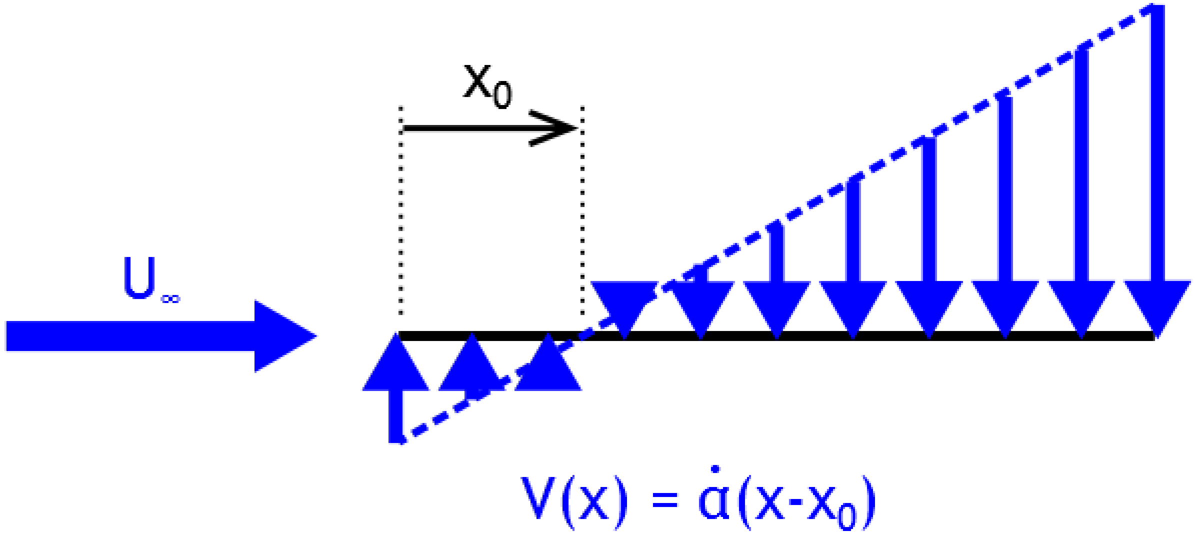


Effect of rotation



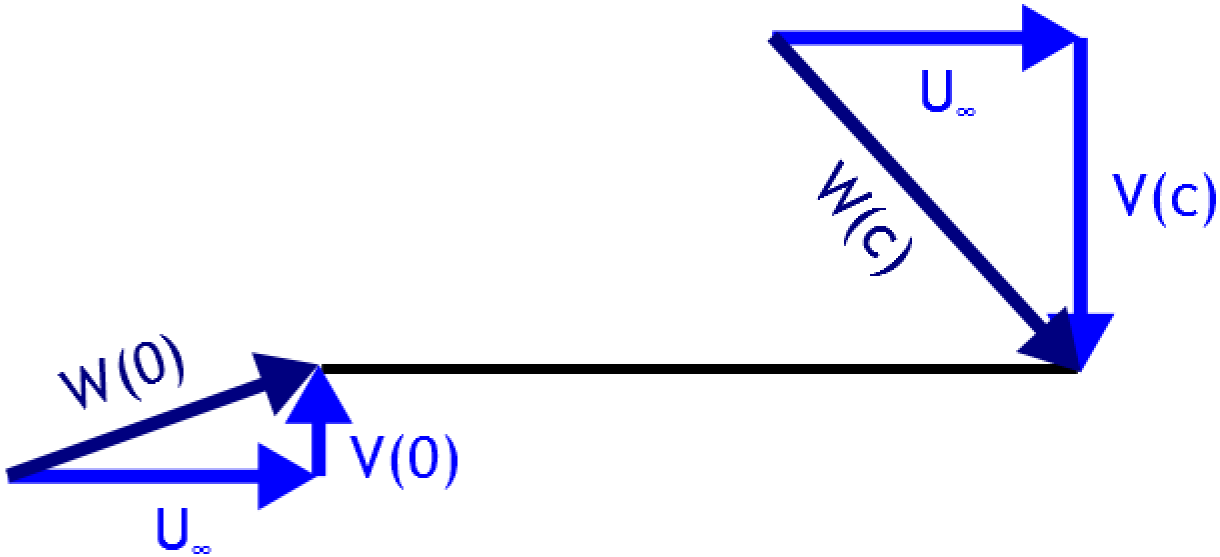
Effect of rotation

- Velocity deflection induced by the airfoil's rotation



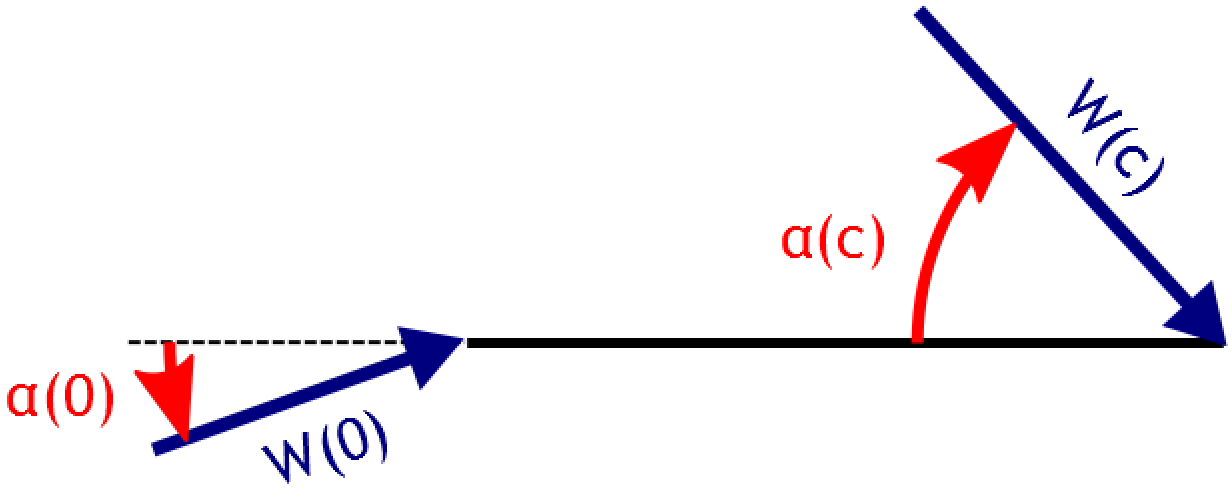
Effect of rotation

- **Relative velocity varies along the airfoil's chord**



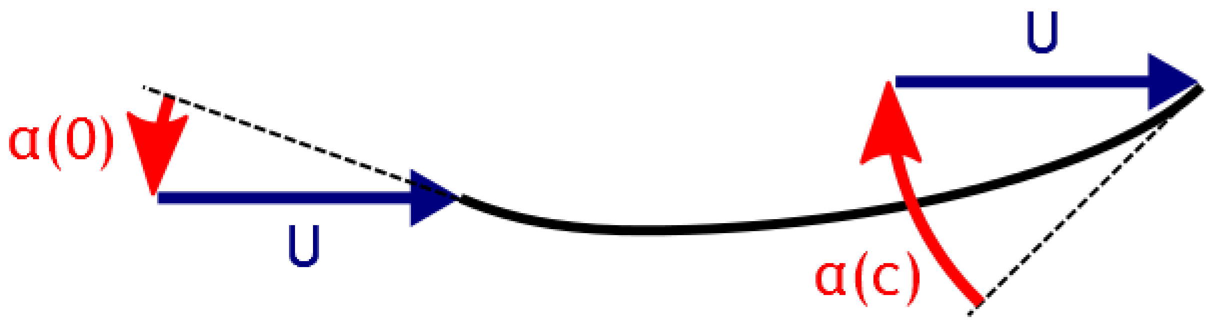
Effect of rotation

- So the angle of attack varies too…



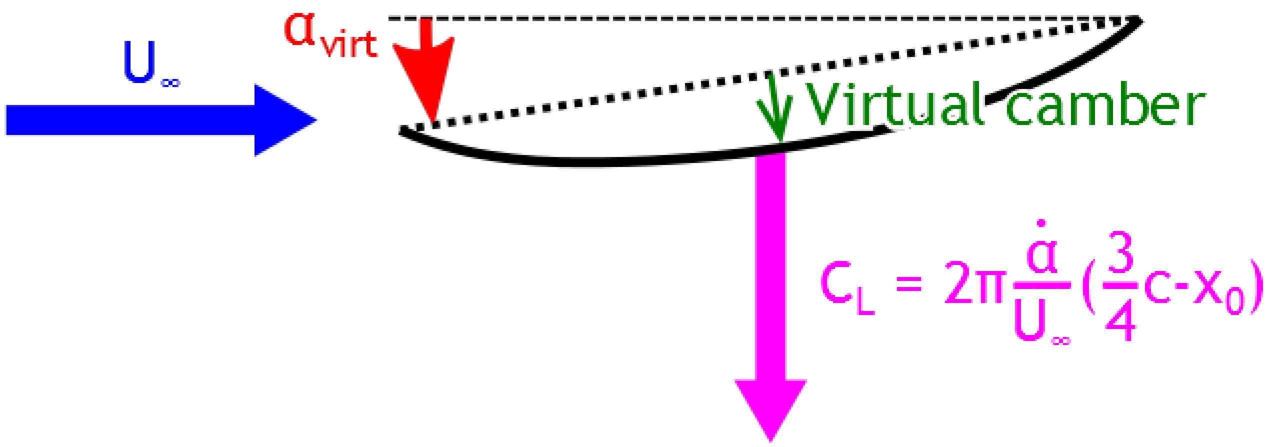
Effect of rotation

- It behaves like a virtual cambered airfoil in a uniform flow field



Effect of rotation

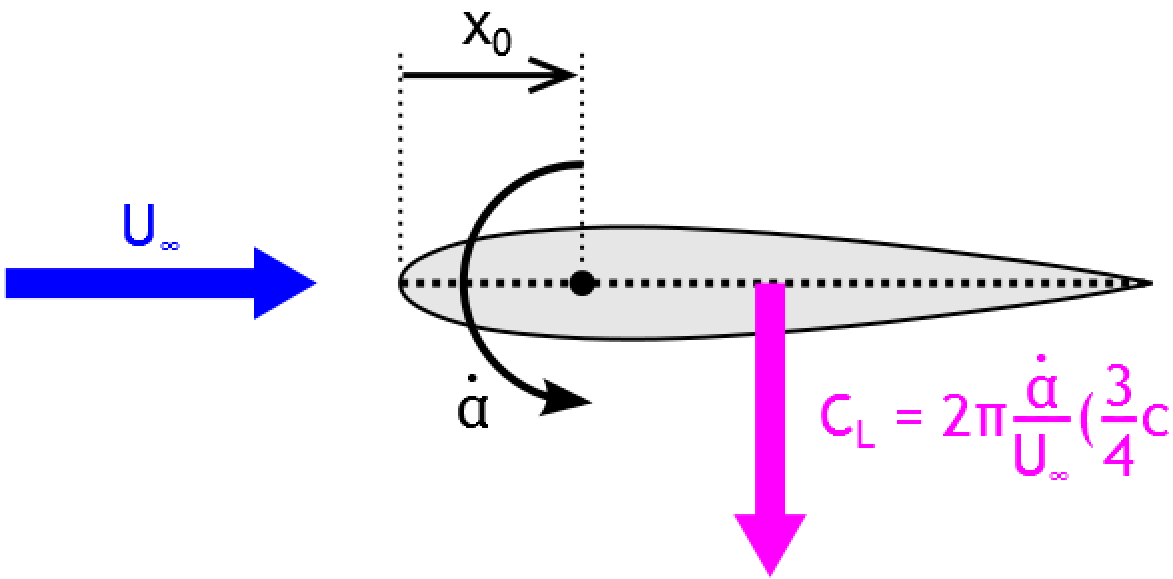
- It generates lift due to its virtual characteristics



See Y.C. Fung (1955)

Effect of rotation

- So the rotating airfoil generates lift by its own motion



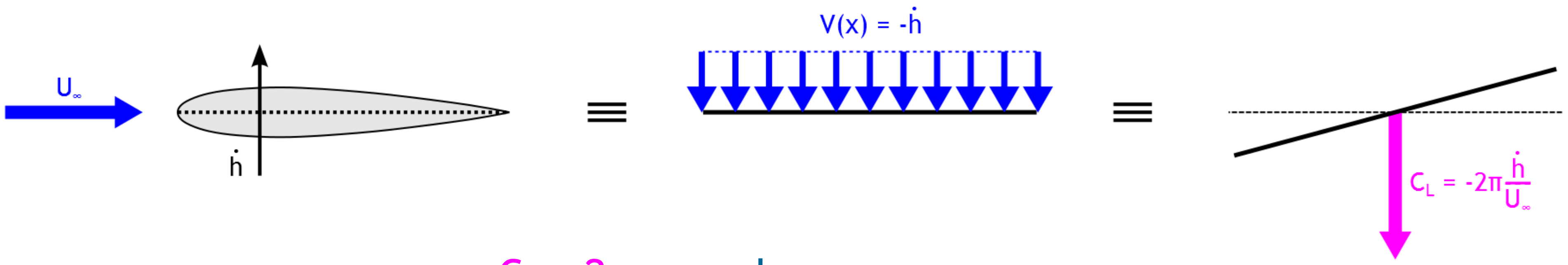
$$C_L = 2\pi \frac{\dot{\alpha}}{U_\infty}\left(\frac{3}{4}c - x_0\right)$$

$C_L = 2\pi\alpha_{eq}$ where $\alpha_{eq} = \alpha_{x\,=\,3/4c}$

See Y.C. Fung (1955)

Effect of translation

- Translation ***perpendicular to U_∞***



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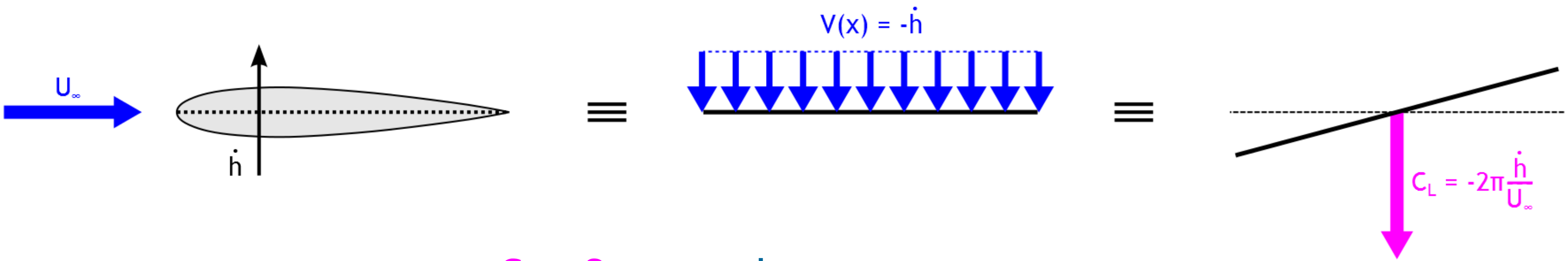
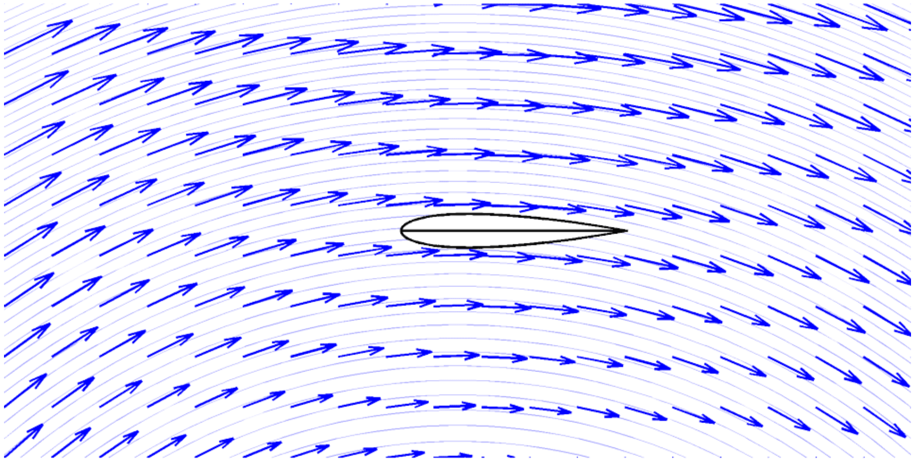


$C_L = 2\pi\alpha_{eq}$ where $\alpha_{eq} = \alpha_{x=3/4c}$

- Translation *parallel to U_∞*
  - Make the magnitude of the relative velocity change over time

Flow curvature in a VAWT

- **Combined effects of rotation and translation**



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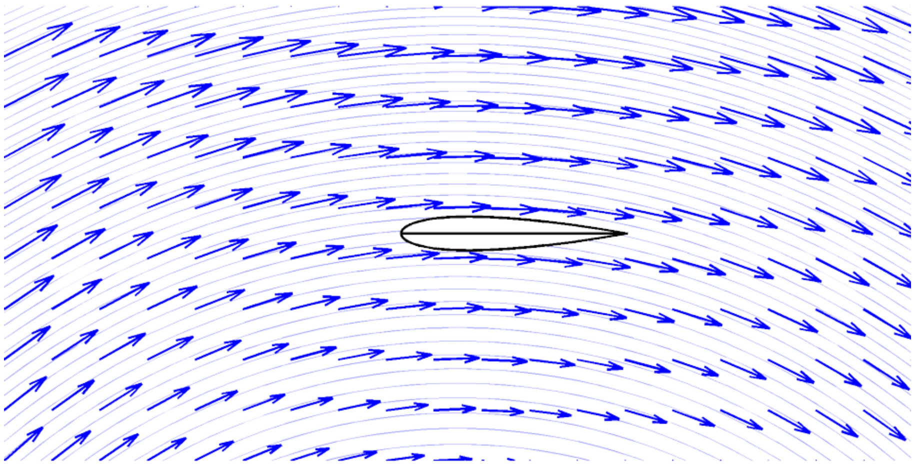

- Conformal mapping

$$F(Z) = -Z_n \ln\left(\frac{Z_n - Z}{Z_n}\right) \text{ where } W(Z_n) = 0$$

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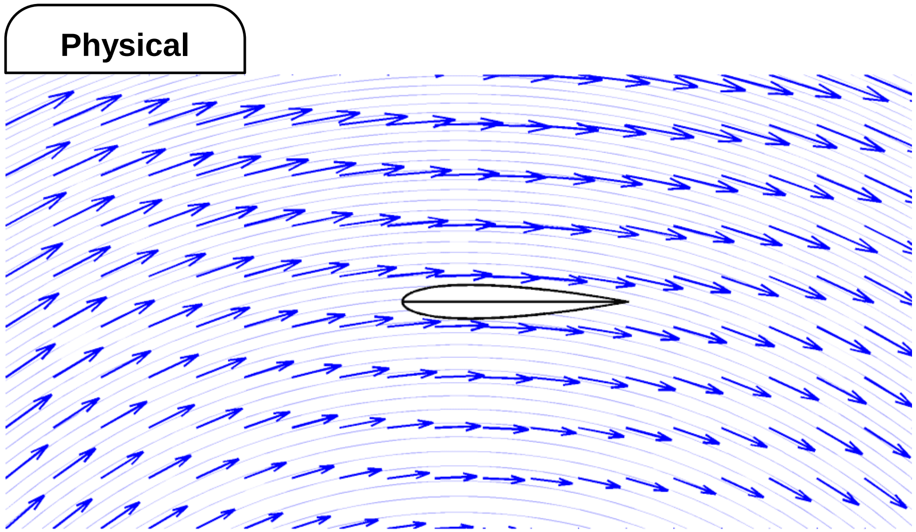

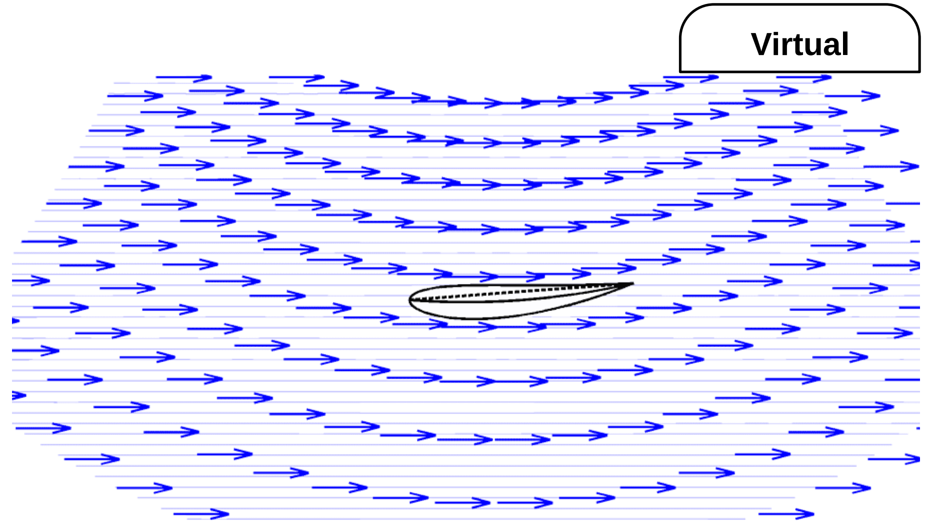

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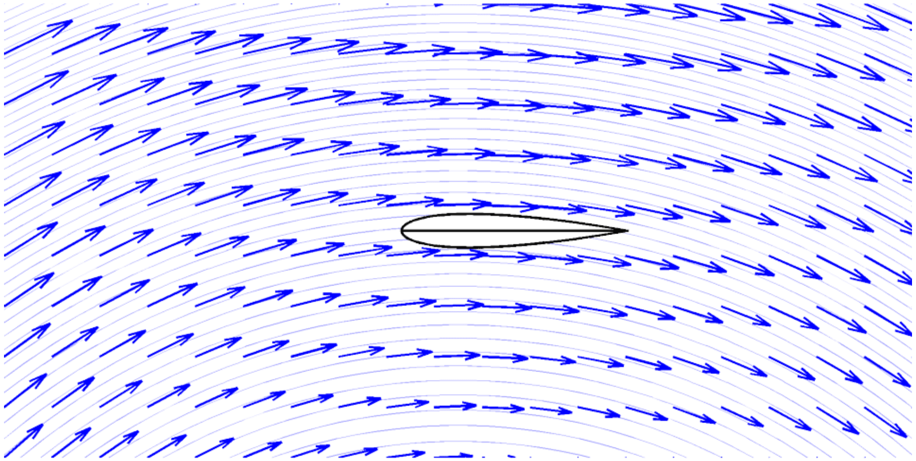

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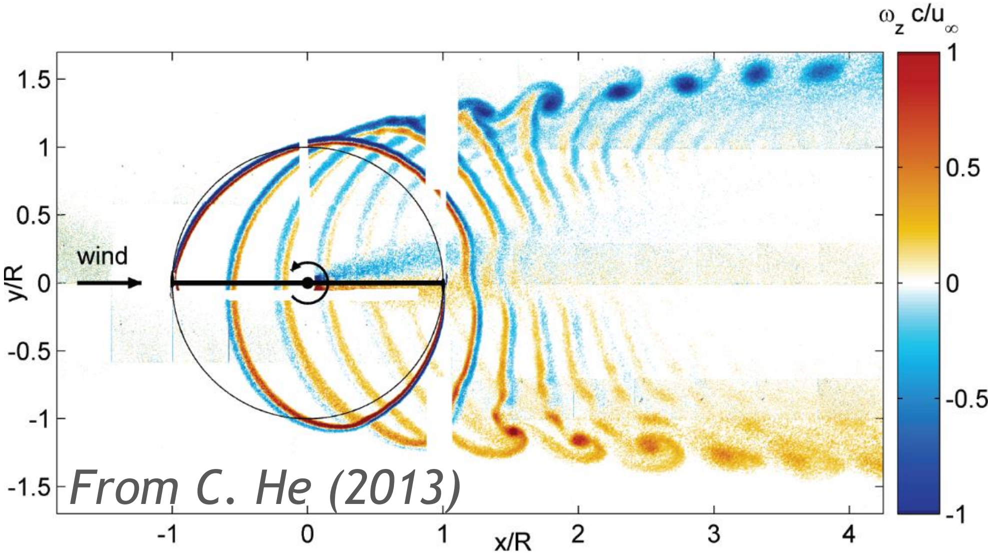

From C. He (2013)

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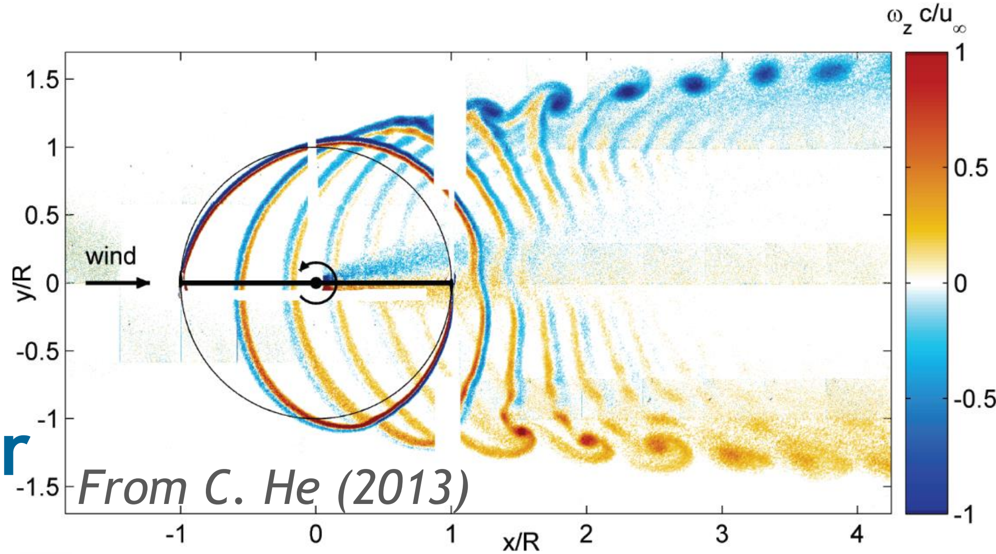

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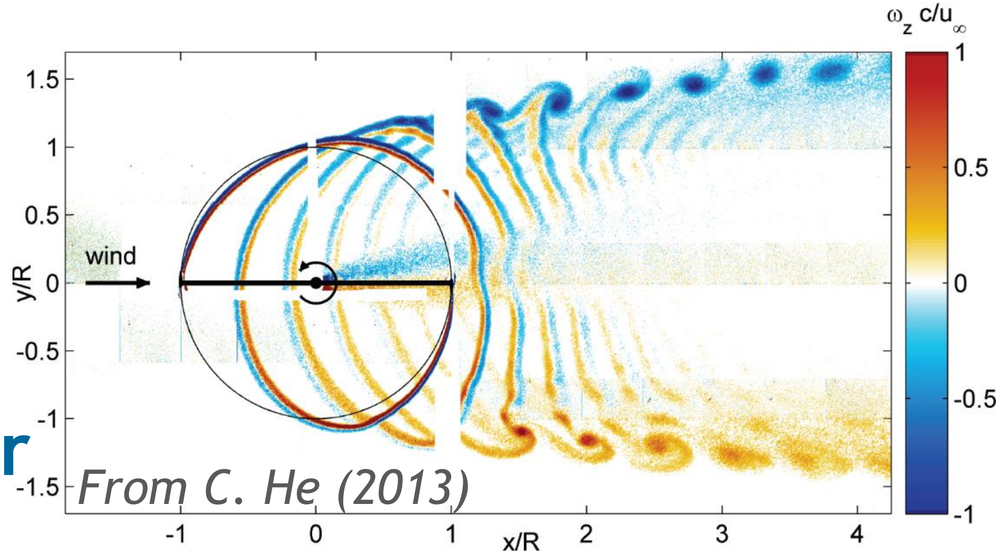
- Why to calculate it?
  - For its use in all actuator point/line models and in all dynamic stall models



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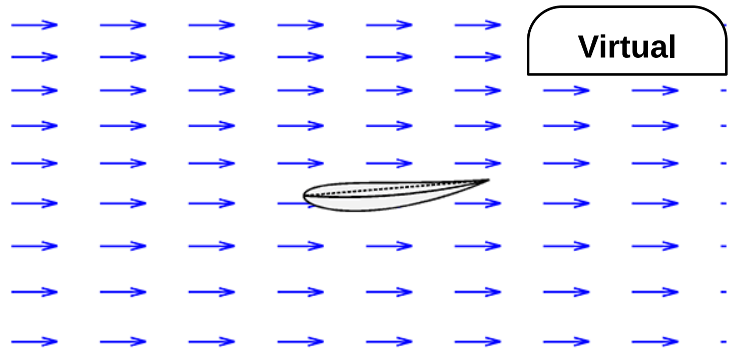
  - Takes into account some flow curvature effects
- Remove the velocity induced by the ***near wake***
- Add compensation terms in the computation of loads, e.g.
  - $\Delta C_N \approx -C_{L_\alpha}\left(\frac{3}{4}c - x_m\right)\frac{\omega}{W} \approx -\frac{\pi c \lambda U_\infty}{2RW}$

See D.J. Sharpe (1984)

To go further…

- **Analogy with flapping wing**
  - *D. N. Gorelov (2009), Worasinchai et al. (2012, 2014)*: **"This analogy suggests that unsteadiness could be exploited to generate additional thrust and that this unsteady thrust generation is governed by rotor geometry"**



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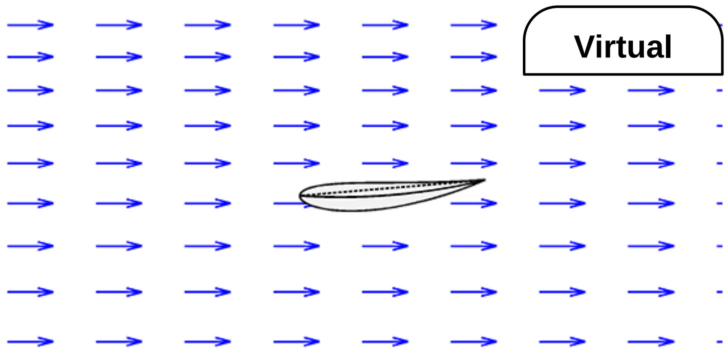
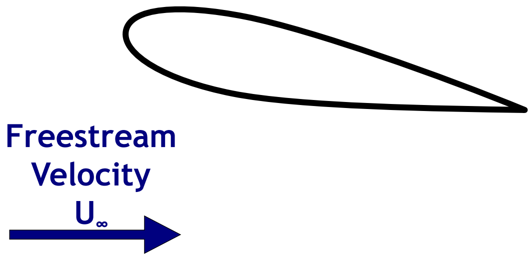


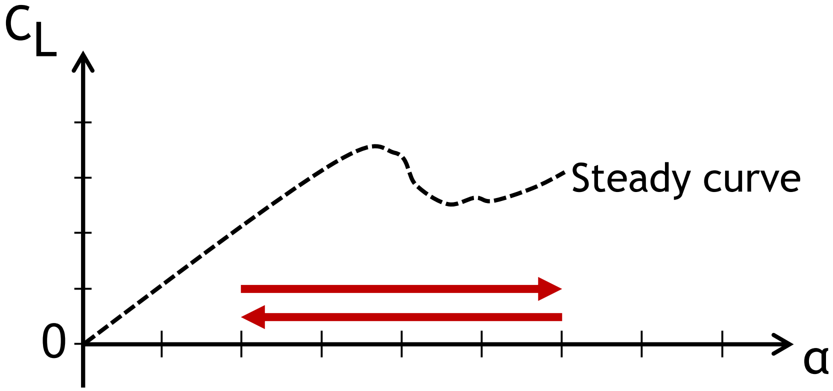
- Viscous effects of flow curvature:
  - Additional drag (*Hirsch and Mandal (1984)*)
  - Centrifugal effects boundary layer (*Migliore et al. (1980)*)
  - Impact on boundary layer separation (dynamic stall)

Dynamic stall in a VAWT

What is dynamic stall and in which conditions does it happen?

- ***Dynamic stall*** is the ***stall*** phenomenon associated with the ***unsteady motion*** of lifting surfaces at ***high angles of attack***





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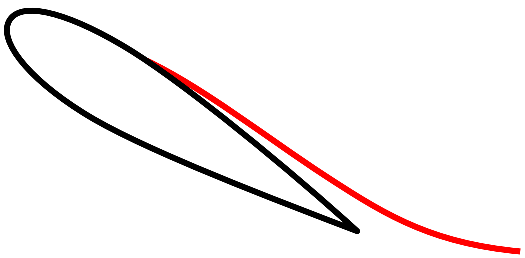

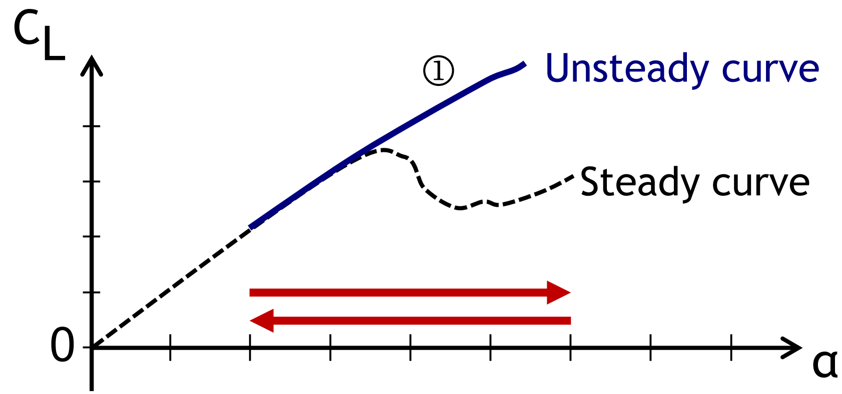

- **① Delay in boundary layer separation**

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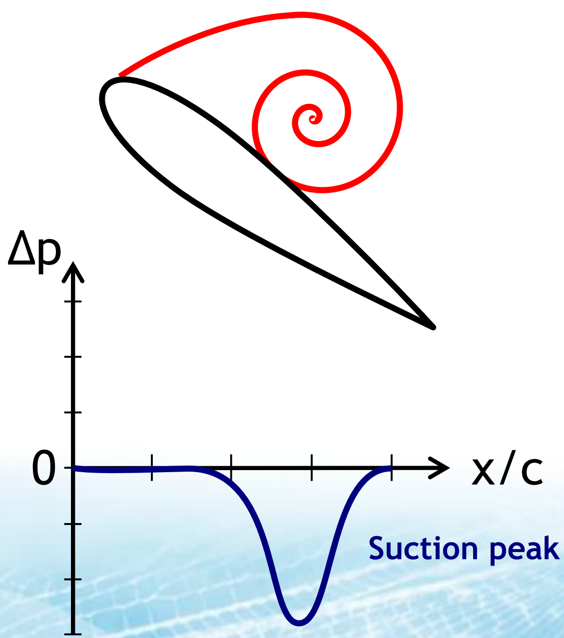

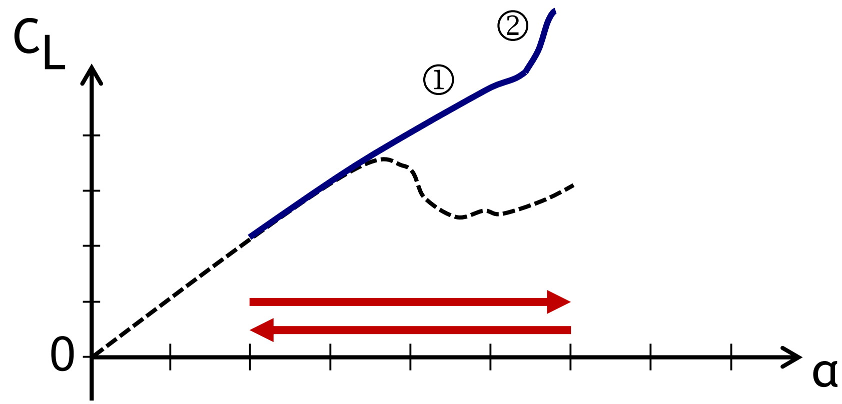

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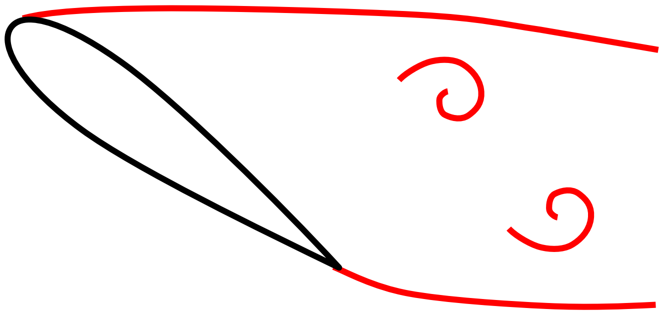

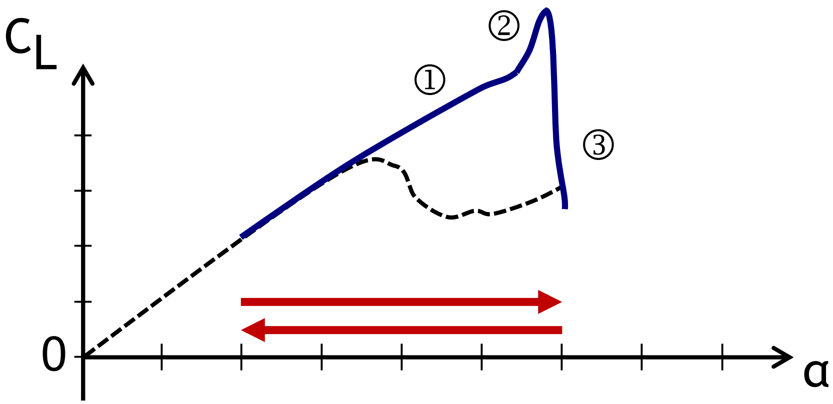

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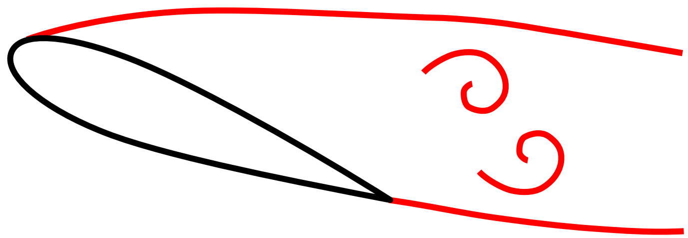

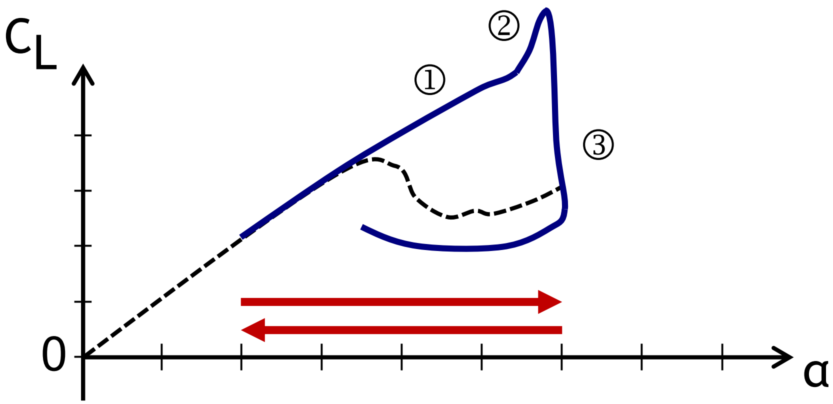

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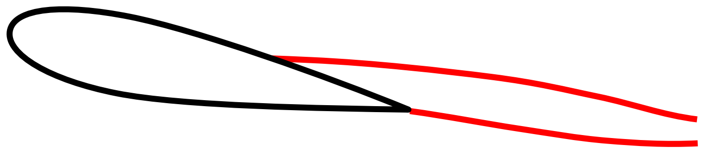

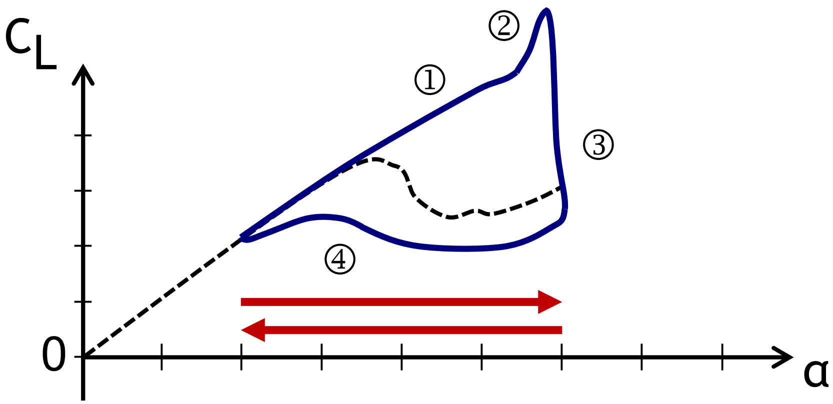

- ① Delay in boundary layer separation
- ② Creation of a leading edge vortex (LEV)
- ③ Shedding of the LEV
- ④ Delay in boundary layer reattachment

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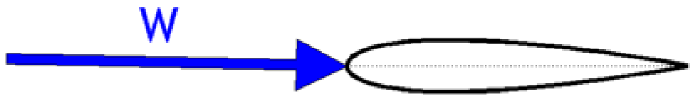

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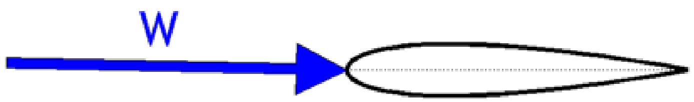

$$k = \frac{\omega c}{2U_{ref}} = \frac{c}{2R}\left[(\lambda-1)\operatorname{atan}\left(\left(\lambda^2-1\right)^{-1/2}\right)\right]^{-1}$$

See Laneville and Vittecoq (1986)

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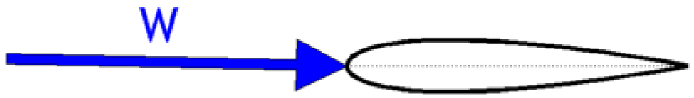
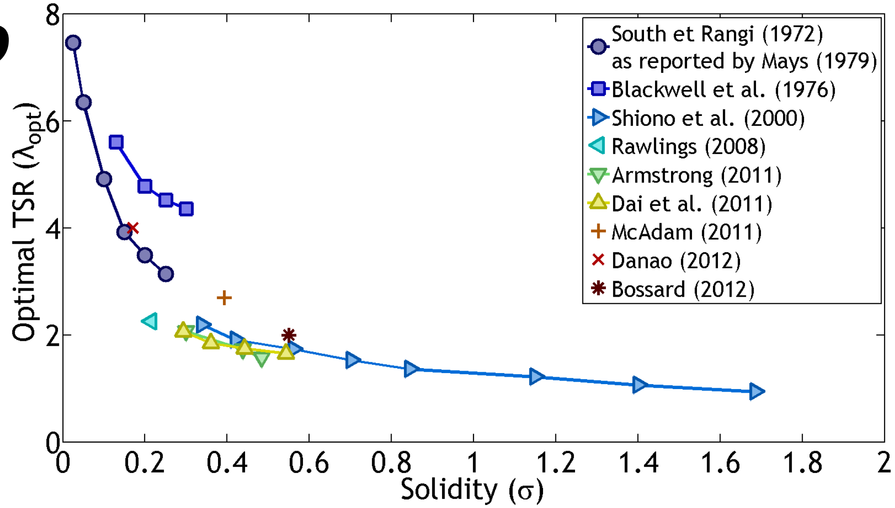
    - *Low TSR and high chord-to-radius ratio* for high unsteadiness



What is dynamic stall and in which conditions does it happen?

- ***High chord-to-radius ratio***
  - So high solidity $\left(\sigma = \frac{Nc}{2R}\right)$
  - Chosen design for low optimal TSR



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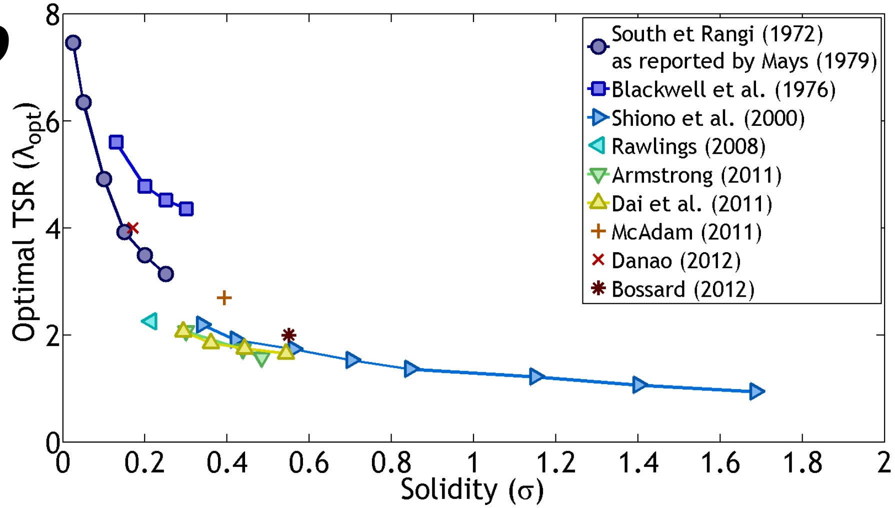

- ***Low TSR*** $\left(\lambda = \frac{R\omega}{U_\infty}\right)$
  - During usual operation for a high solidity VAWT
  - During start-up ($\omega \approx 0$)
  - For stall regulation (prescribed ω)

Why does dynamic stall in a VAWT differs from a usual one?

- Reference:
  - Sinusoidal pitch in a steady uniform flow

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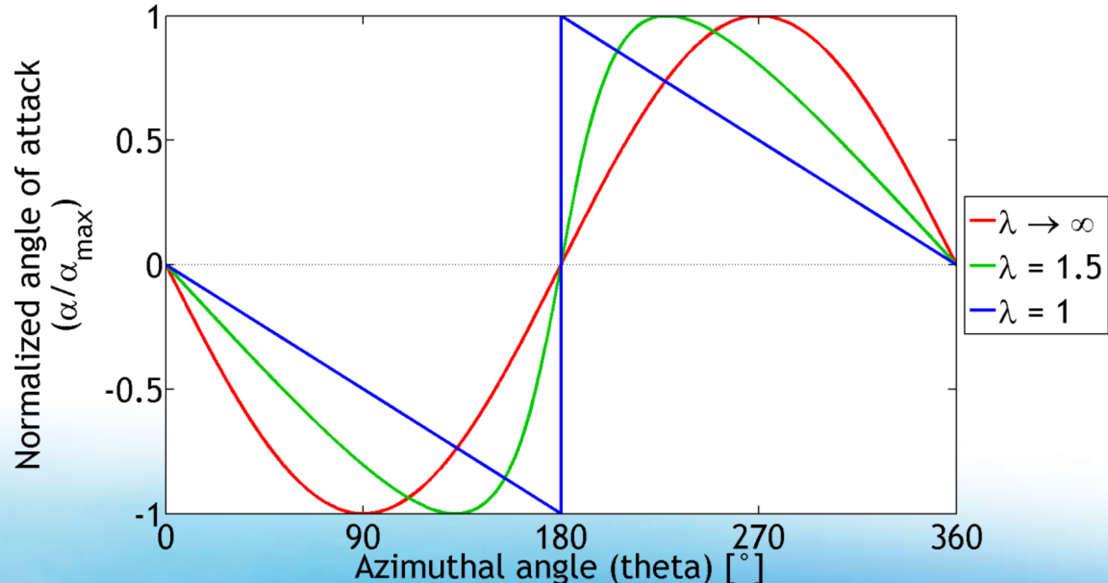

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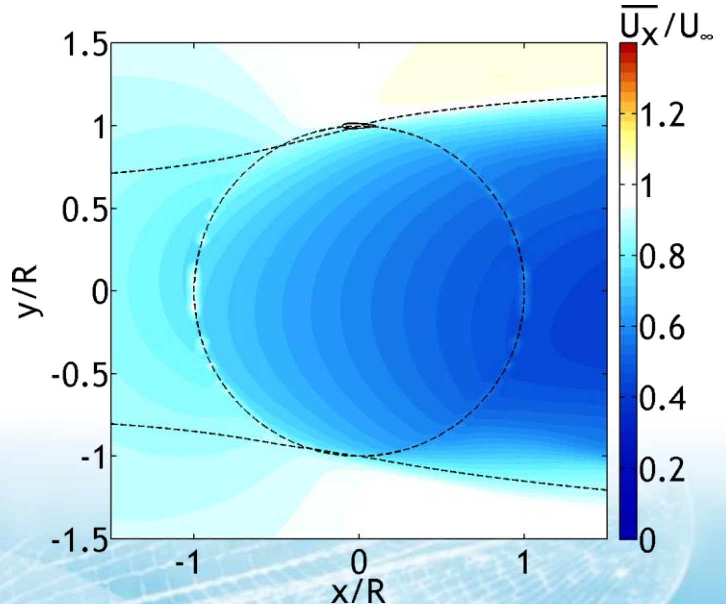

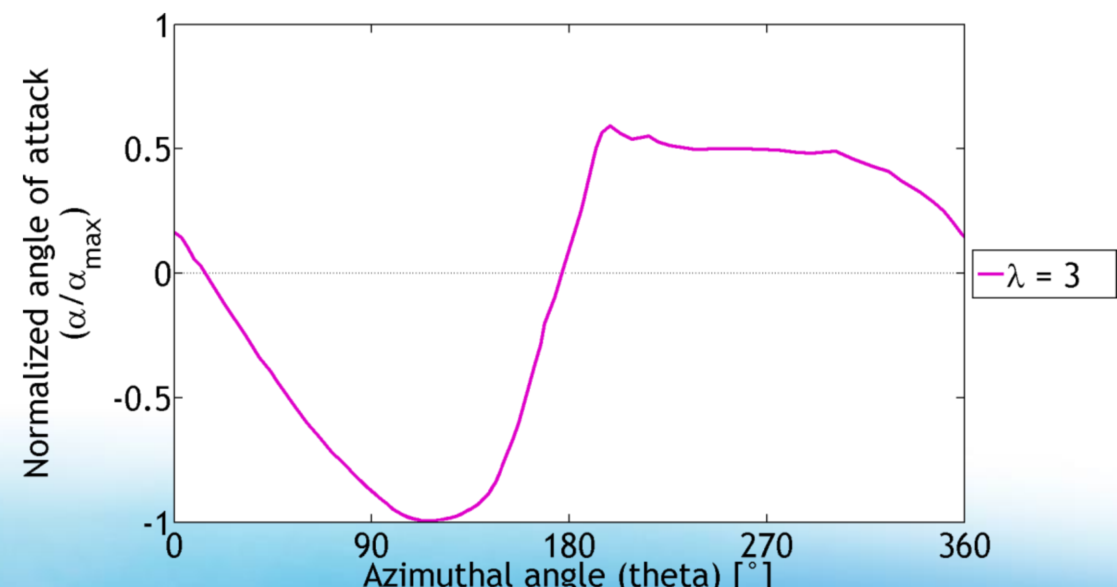

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- Reference:
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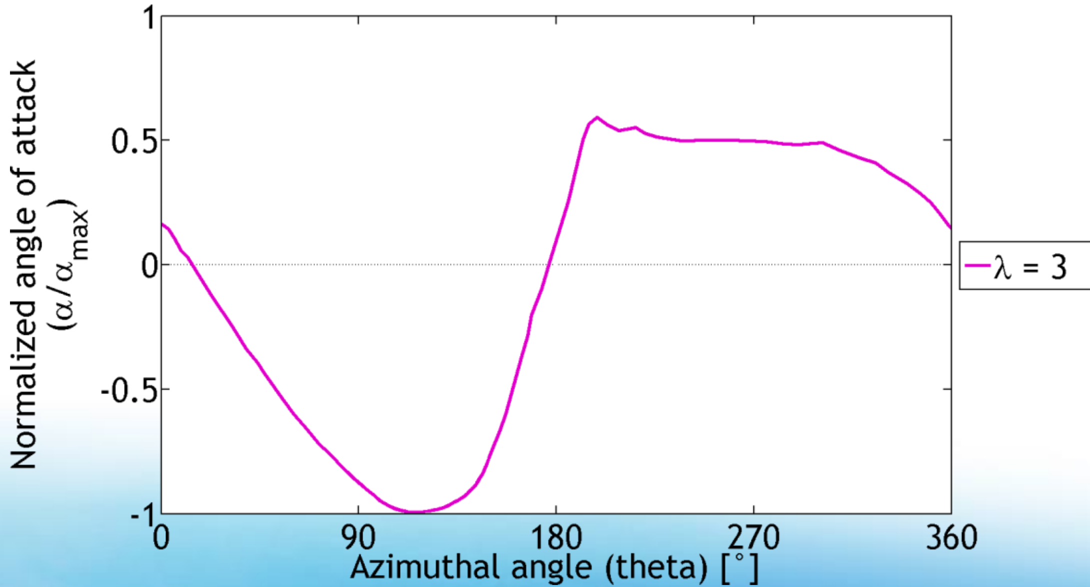
    - Positive and negative high angles of attack
    - Fast and changing pitch rate (high k)



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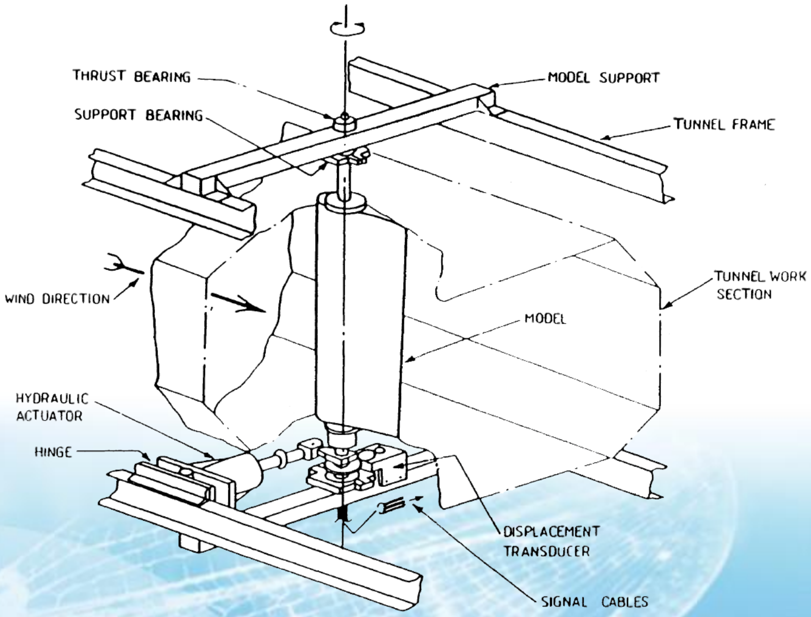

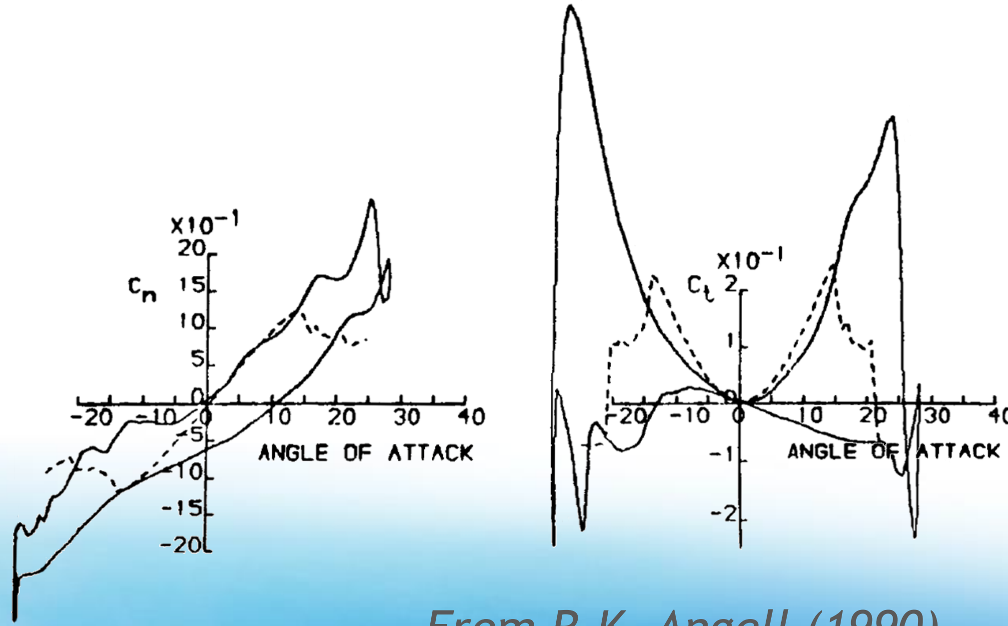

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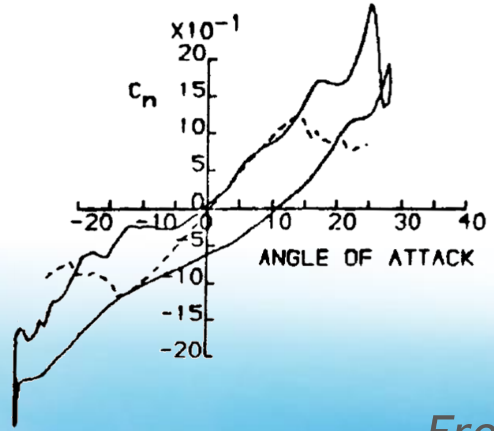

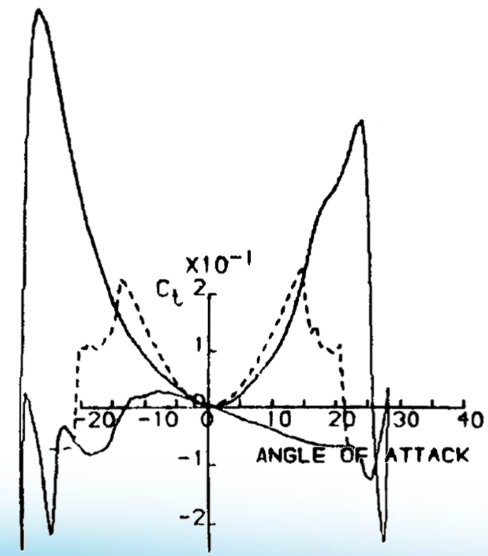

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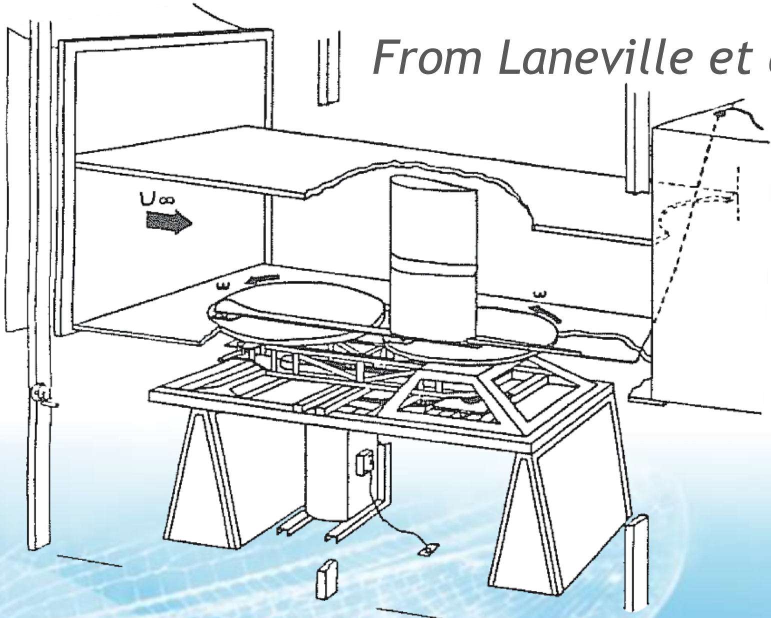
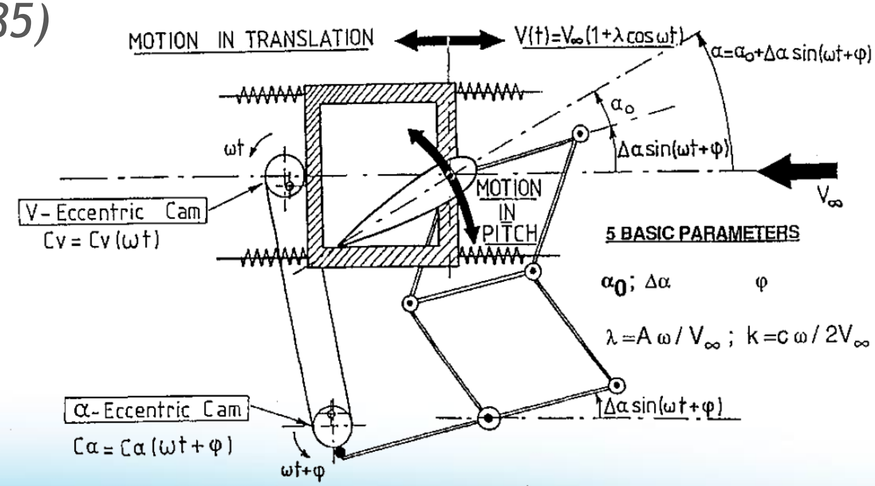


From Laneville et al. (1985)



From Favier et al. (1988)

Why does dynamic stall in a VAWT differs from a usual one?

- Reference:
  - Sinusoidal pitch in a steady uniform flow
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  - Not only pitch, but also *plunge*, *fore and aft motions*
    - Complex combination of synchronized motions
    - Does not seem to change the process, but changes the *triggering and timing* of the elementary steps, and also the *vortex dynamics*

Why does dynamic stall in a VAWT differs from a usual one?

- Reference:
  - Sinusoidal pitch in a steady uniform flow
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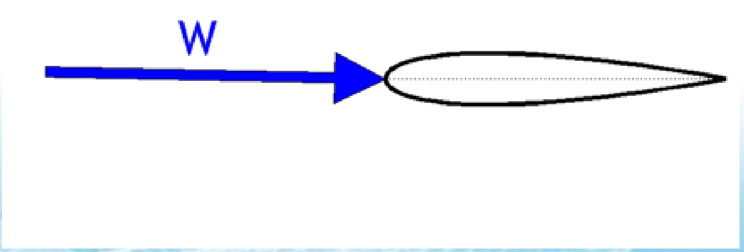

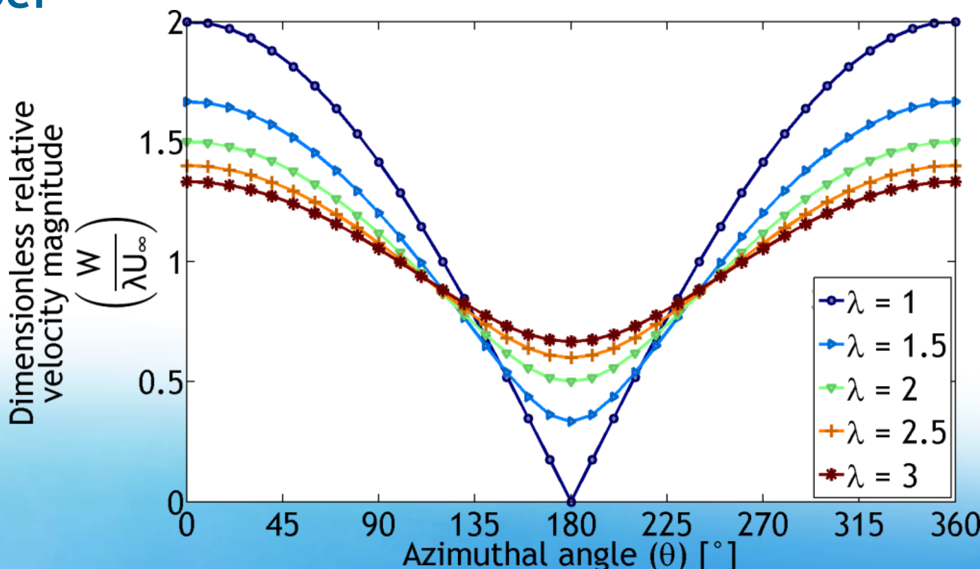

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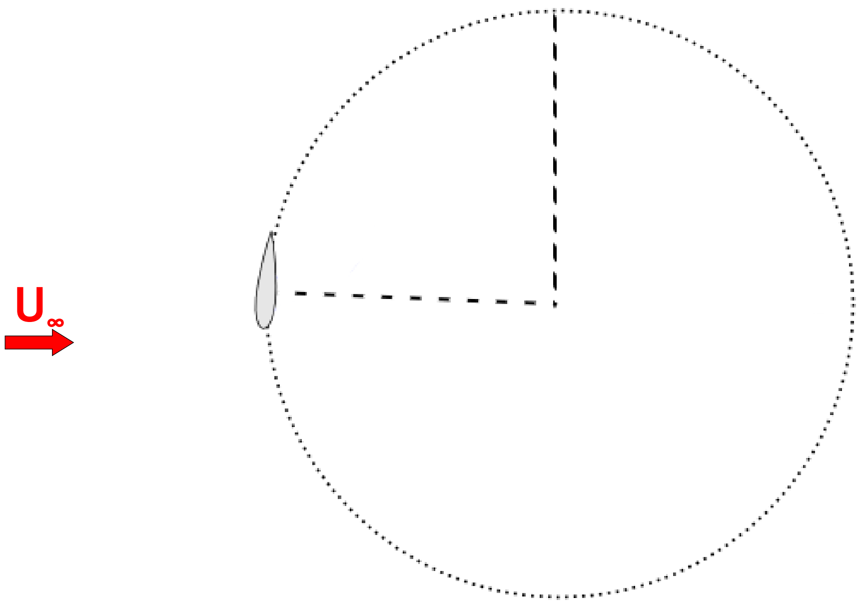
    - Curved flow
      - Unsteadily curved
      - Leads to strong blade-wake interactions

What happens in the rotor?

- Flow visualization in the rotor



2 blades, c/R ≈ 0.33, λ = 2.14, Re_c ≈ 6400

Adapted from Brochier et al. (1986)
on a water turbine

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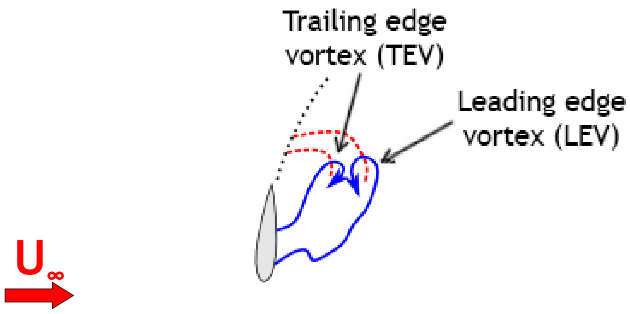

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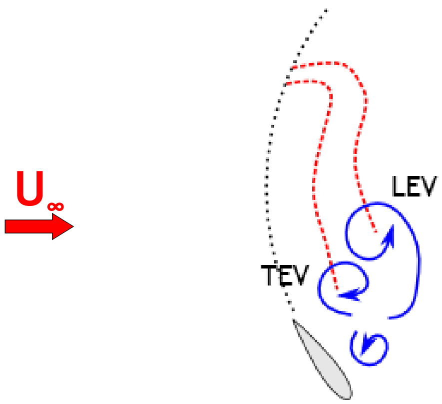

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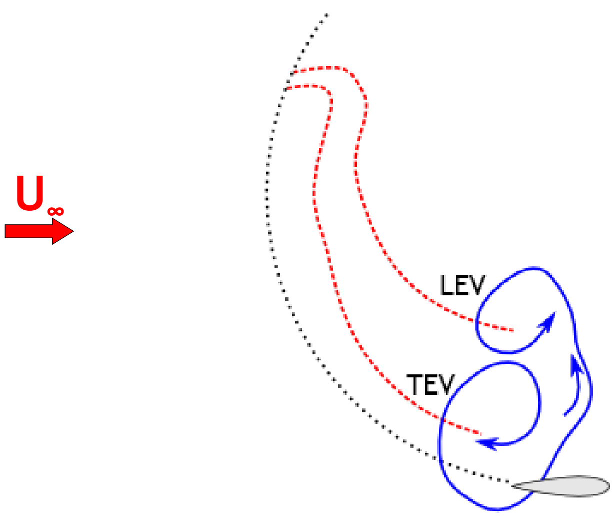

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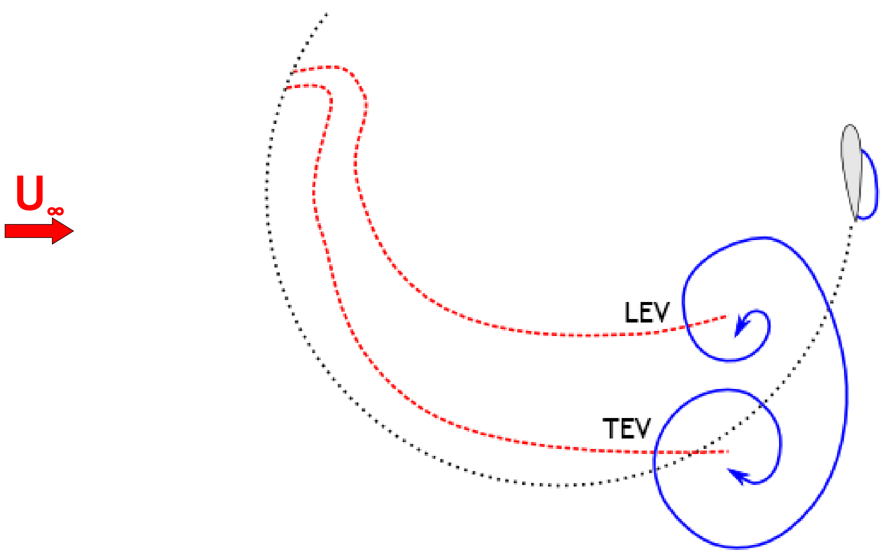

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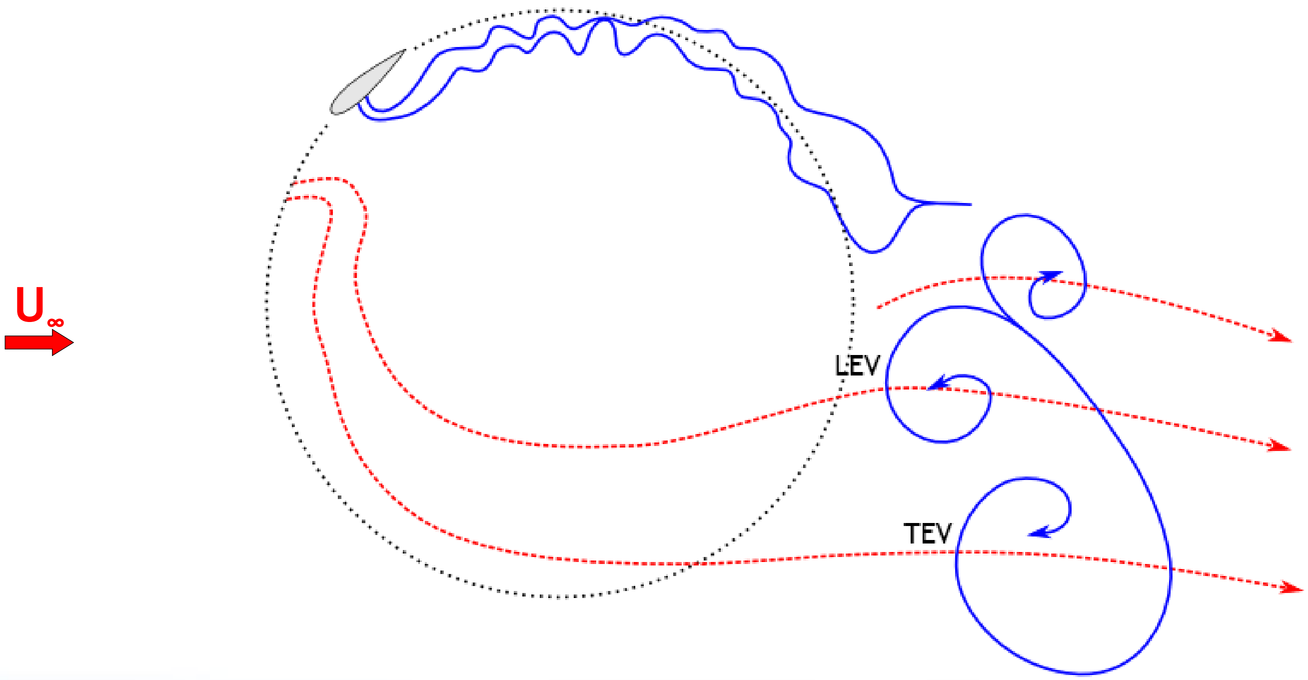

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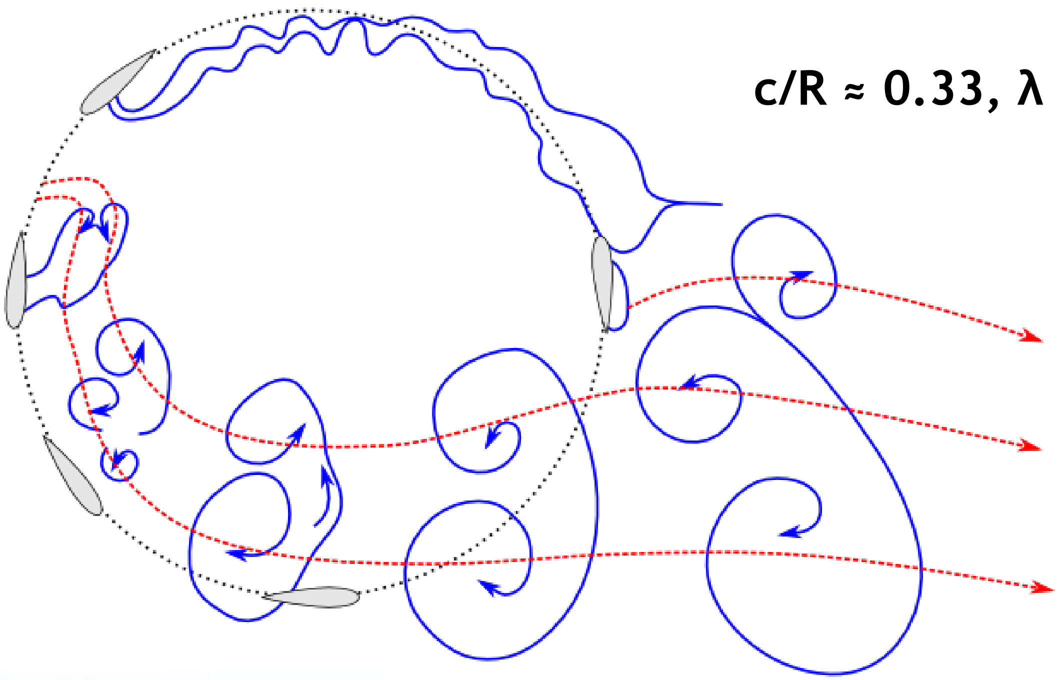
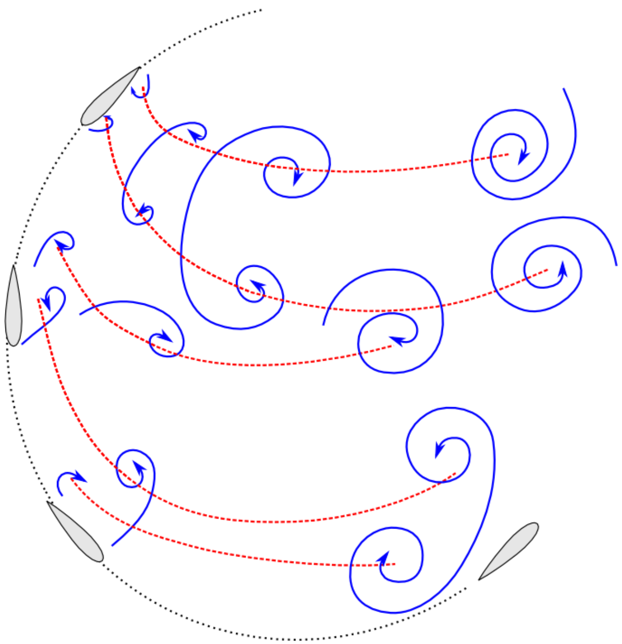


c/R ≈ 0.33, λ ≈ 2



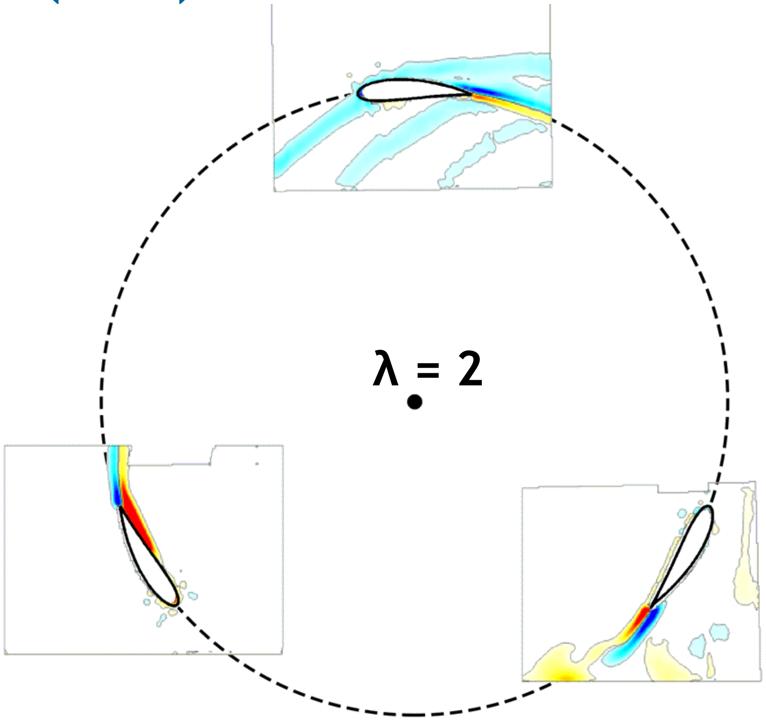
2 blades, $Re_c \approx 6400$
Brochier et al. (1986)

1 blade, $Re_c \approx 1000$
Fujisawa et al. (1995)

What happens in the rotor?

- Particle Image Velocimetry (PIV) near the blade

- Fujisawa et al.
  $\sigma = 0.167$ and $Re_c \approx 1500$
- Brochier et al.
  $\sigma = 0.333$ and $Re_c \approx 6400$
- J. Bossard
  $\sigma = 0.550$ and $Re_c \approx 1.8 \times 10^5$



Vorticity field

3 blades, $c/R \approx 0.37$, $Re_c \approx 1.8 \times 10^5$

Adapted from J. Bossard (2012) on a water turbine

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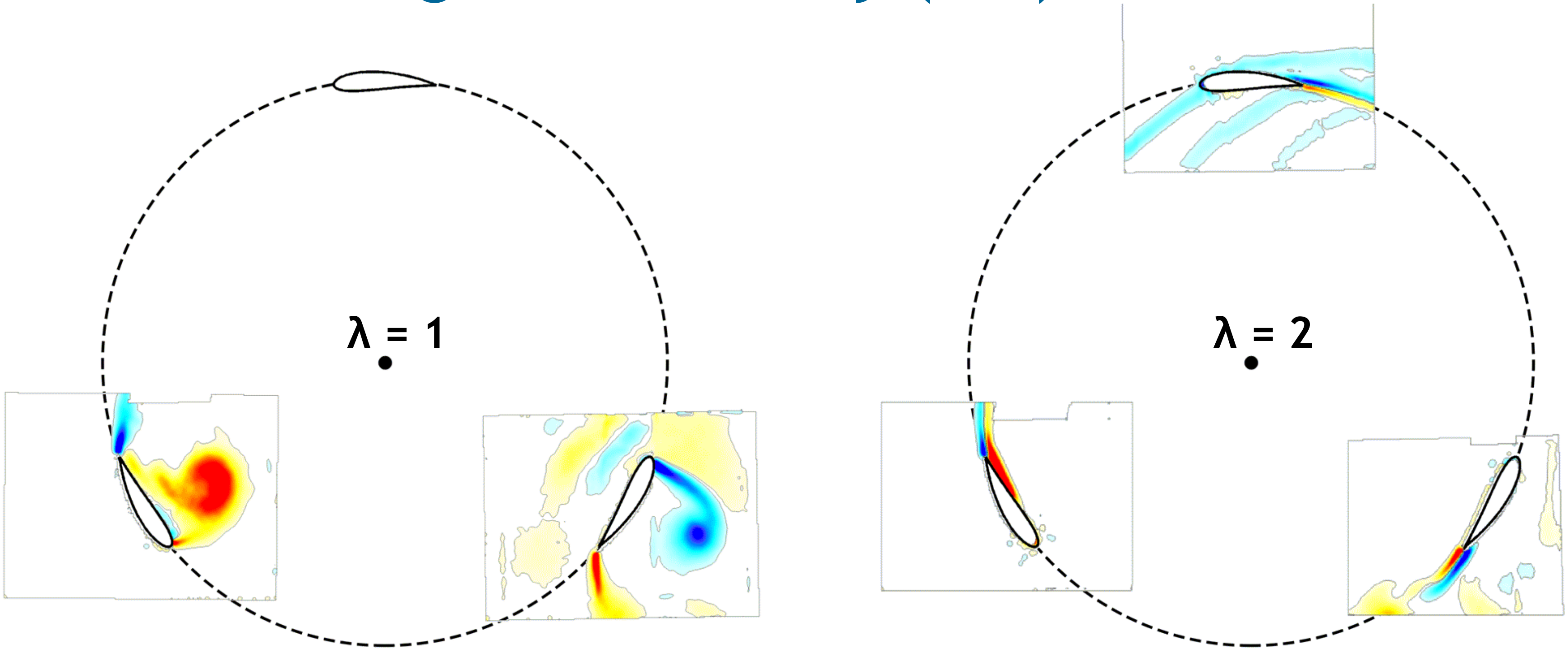

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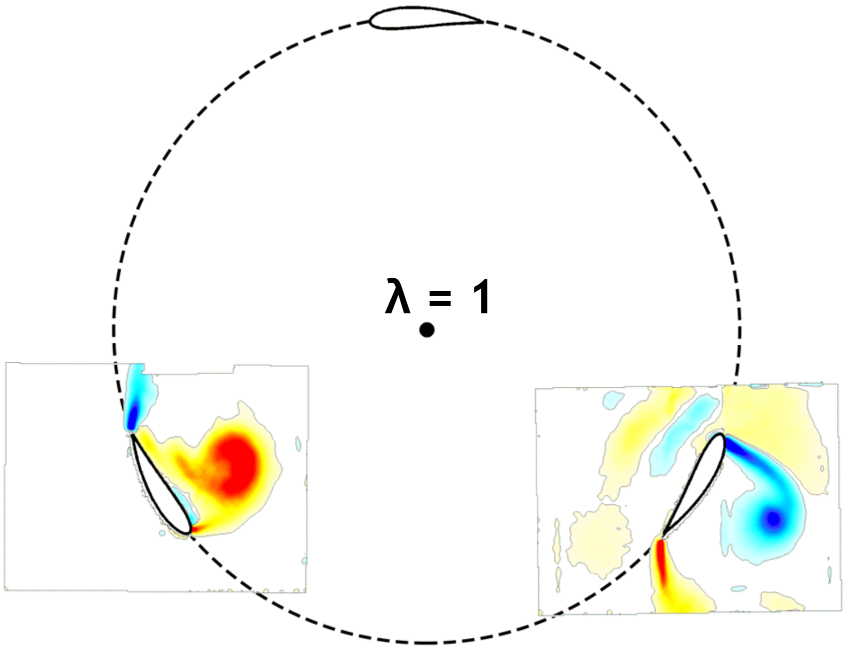
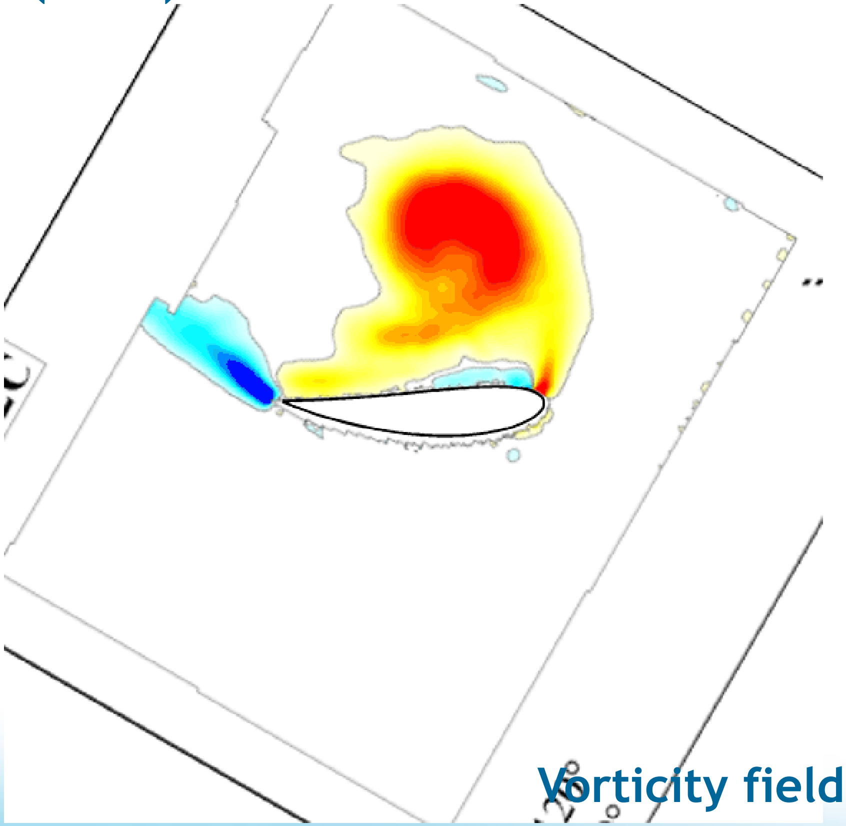




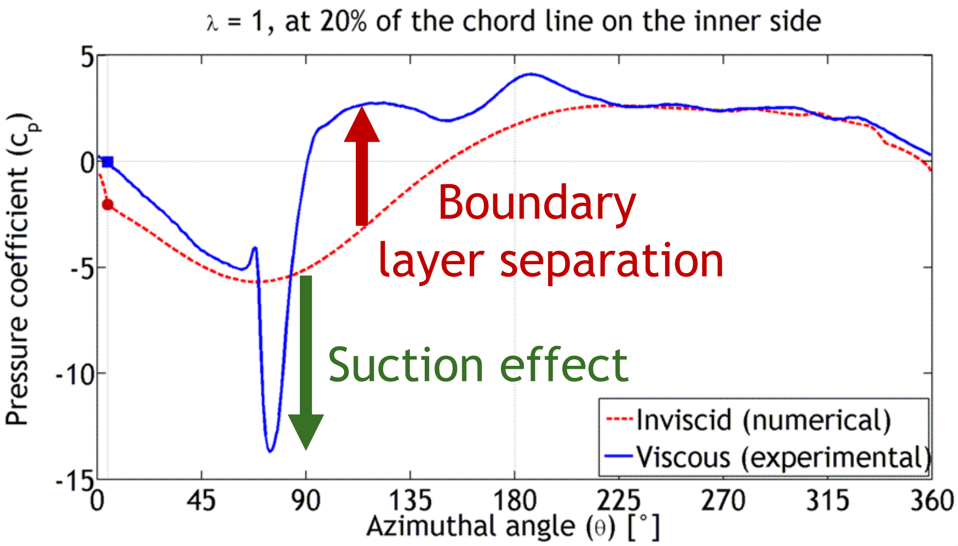
Vorticity field

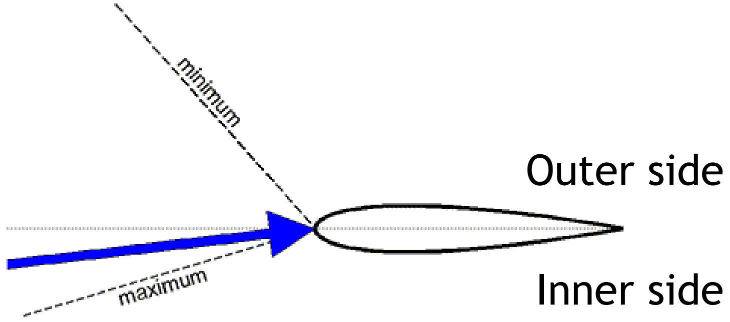
3 blades, c/R ≈ 0.37, $Re_c \approx 1.8\times10^5$

Adapted from J. Bossard (2012) on a water turbine

Direct effects

- **Consequences:**
  - Suction effect of the LEV
  - Boundary layer separation





Adapted from L. Beaudet (2014)

3 blades, c/R ≈ 0.42, λ = 1, Re_c ≈ 1.7×10^5

Direct effects

- Consequences:
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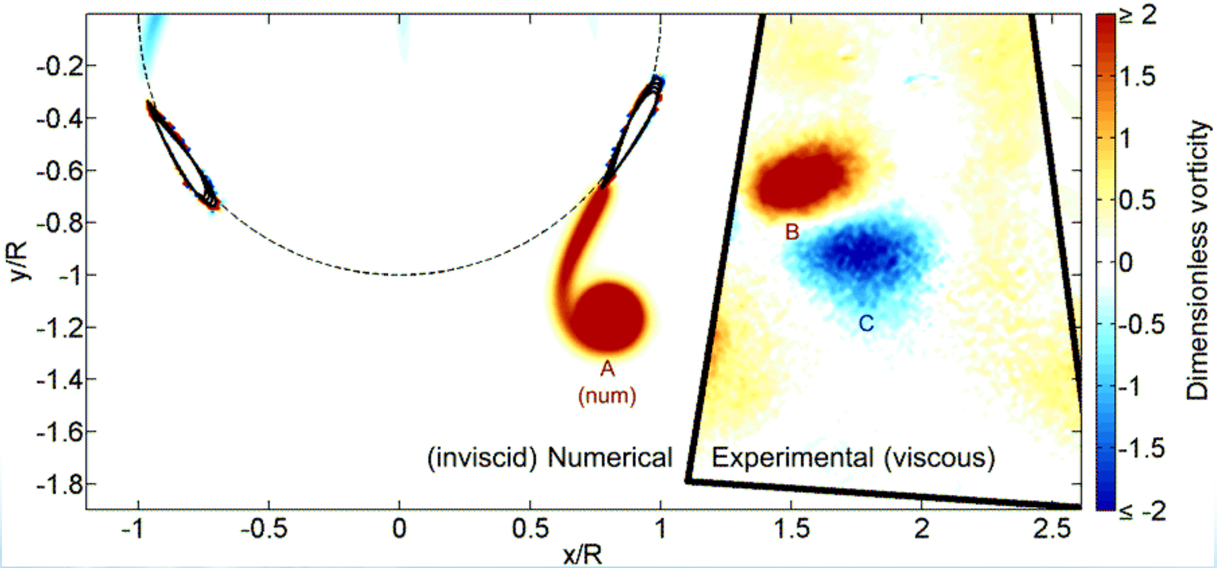
  - Boundary layer separation
  - Blade-vortex interaction

Adapted from L. Beaudet (2014)



3 blades, $c/R \approx 0.42$, $\lambda = 1$, $Re_c \approx 1.7\times10^5$

Consequences

- Dynamic stall affects the whole VAWT:
  - ***High blade loading*** and impact on ***fatigue*** life

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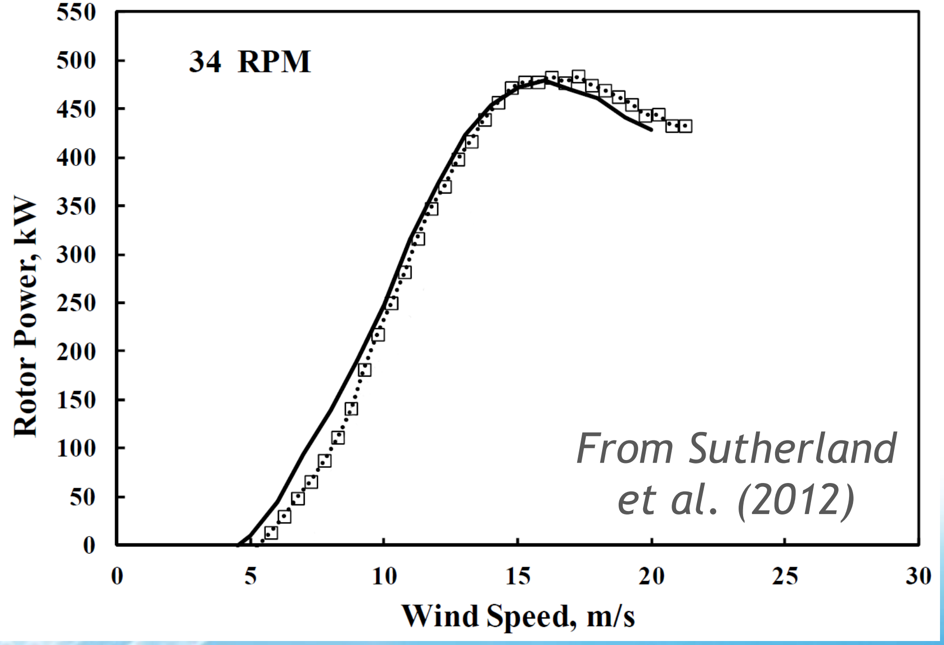

From Sutherland et al. (2012)

Consequences

- Dynamic stall affects the whole VAWT:
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  - Impacts on the *dynamics of the wake* (wind farm)
  - *Noise emission* (vortices and blade-vortex interaction)

Modeling dynamic stall

- Most used solution: ***semi-empirical dynamic stall models*** (Gormont, ONERA, Leishman-Beddoes…)

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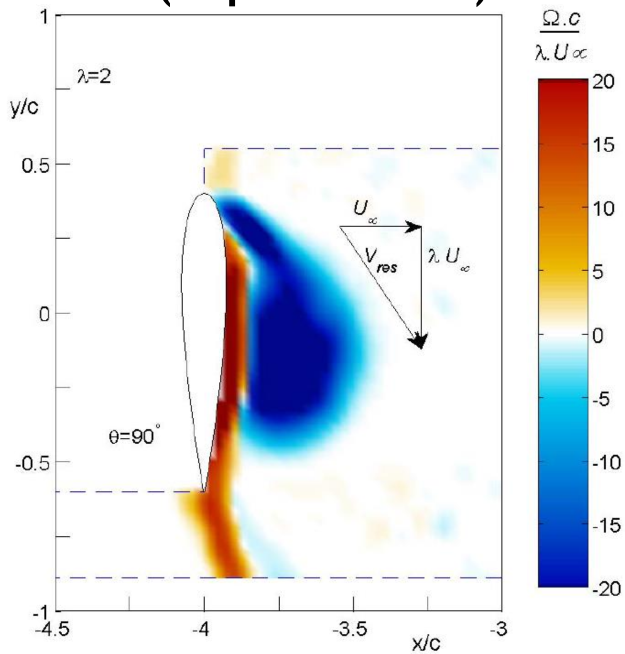
    - Again, how to choose the angle of attack…
    - Affect loads, but neither pressure distribution nor wake…
  - Are based on usual cases of dynamic stall encountered in ***aeronautics***
    - Not necessarily adapted to the specificities of VAWT (Mach and Reynolds numbers, type of motion, flow curvature, etc…)
    - Adaptations exist for wind turbines (e.g. *Sheng et al. (2008)*)

Modeling dynamic stall

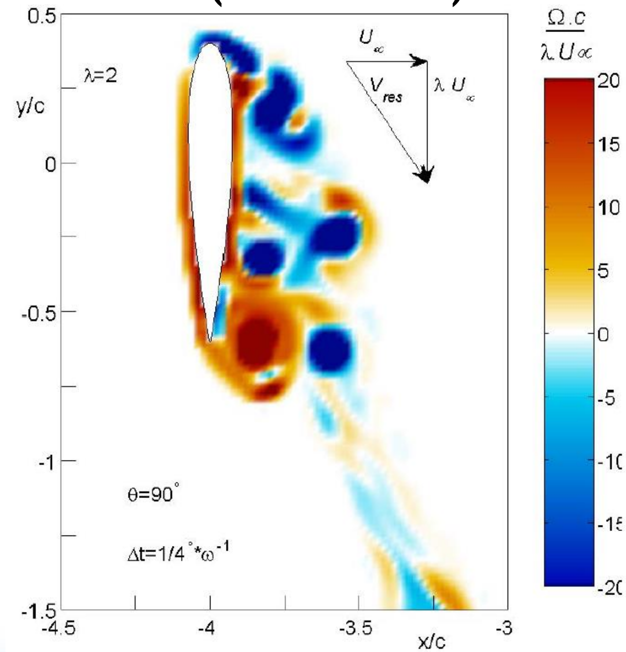
- **Other options:**
  - CFD…

PIV (experimental)



(a) *Average of 30 samples at* $\theta = 90°$.

LES (numerical)



(e) $\theta = 90°$, LES.

From C.J.S. Ferreira (2009)

1 blade, c/R ≈ 0.25, λ = 2, $Re_c \approx 5\times10^4$

Modeling dynamic stall

- **Other options:**
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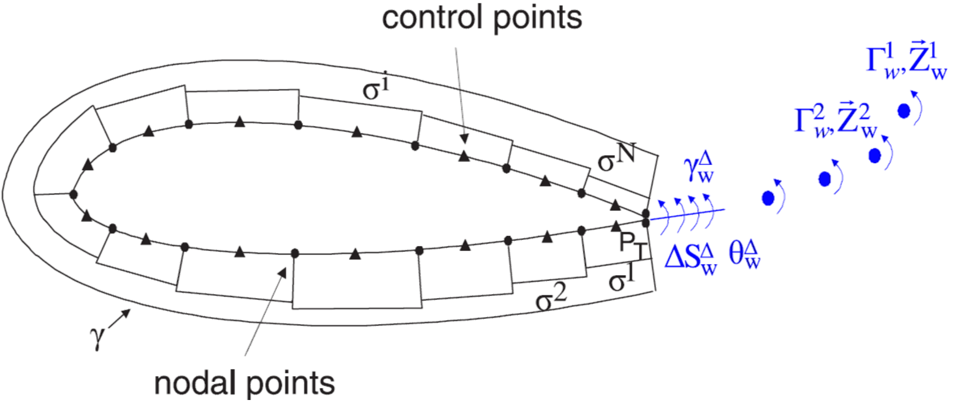


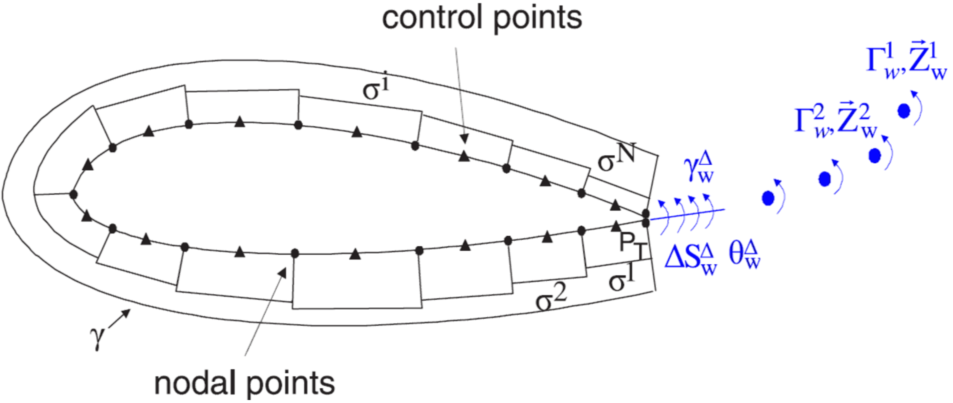
Classical 1-wake panel method

Adapted from Riziotis and Voutsinas (2008)

Modeling dynamic stall

- **Other options:**
  - CFD…
  - Double-wake model (*Zanon et al. (2014)*)

Wake originating from the separation point



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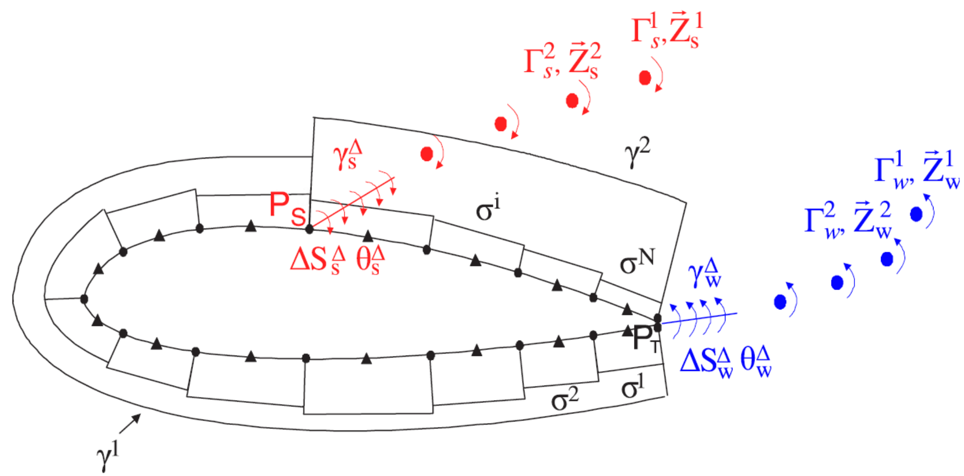


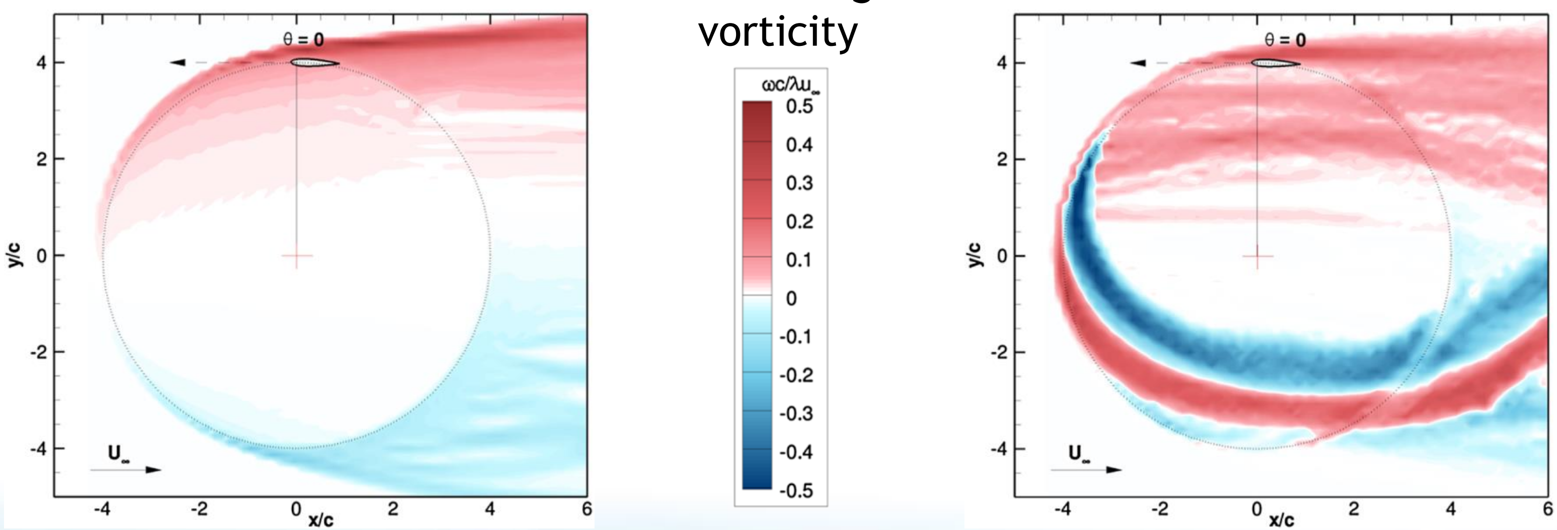
Double-wake model

Adapted from Riziotis and Voutsinas (2008)

Modeling dynamic stall

- Other options:
  - CFD…
  - Double-wake model (*Zanon et al. (2014)*)

Time-averaged vorticity



Classical 1-wake panel method — Double-wake model

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1 blade, c/R ≈ 0.25, λ = 2, $Re_c \approx 5 \times 10^4$

Control of dynamic stall on a VAWT

- **Methods already tested or studied on a VAWT:**
  - **Vortex generators (VGs)**
    - *Sutherland et al. (2012) about tests conducted in the 80ies*: ***"We equipped the Test Bed with vortex generators (…). The results were quite disappointing, as we were not able to detect any significant difference in turbine performance due to the presence of the VGs."***

Control of dynamic stall on a VAWT

- **Methods already tested or studied on a VAWT:**
  - **Vortex generators (VGs)**
  - **Active or passive pitch control**
    - *B.K. Kirke (1998), Staelens et al. (2003)*, etc…
  - **Flap deflection**
    - *D. Rathi (2012)* (numerical simulations only)

Control of dynamic stall on a VAWT

- **Methods already tested or studied on a VAWT:**
  - Vortex generators (VGs)
  - Active or passive pitch control
  - Flap deflection
  - Synthetic jets (steady/unsteady in/out air jets)
    - *Sasson and Greenblatt (2011)* (numerical), *Yen and Ahmed (2013)* (experimental)
  - Plasma actuators
    - *Greenblatt et al. (2012, 2014)*

Conclusion

Aerodynamic challenges to be tackled

- ① Better ***understanding of the physical processes*** of the aerodynamic phenomena and ***assessment of their effects*** at different scales
  - Flow curvature, dynamic stall, 3D effects, wake development, aeroelasticity, etc…

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- ② ***Modeling*** of these phenomena
  - CFD, vortex models, semi-empirical dynamic stall models, etc…
- ③ Adaptation of numerical tools to ***optimize VAWT's geometry*** or to control the effects of the aerodynamic phenomena with ***actuation***

Any question?

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