Nantes - 2014

Aérojoules project: Vertical axis Wind Turbine – Blade Aerodynamic optimisation

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Presentation summary

I. Aérojoules project – Aim of the study

II. Understanding Blade aerodynamics :

- a) Blade Element Momentum(BEM) methods
- b) Experimental testing
- c) Computational Fluid Dynamics (CFD)
- d) BEM methods - QBlade

III. Aérojoules design

IV. Conclusions, Perspectives, Future Work

V. Appendices:

- – Wind energy - Shipping Industry
- – Additional information.

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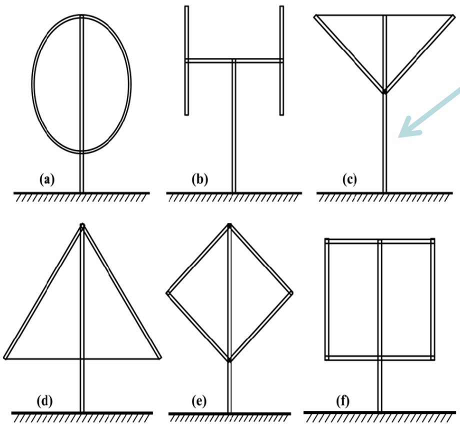
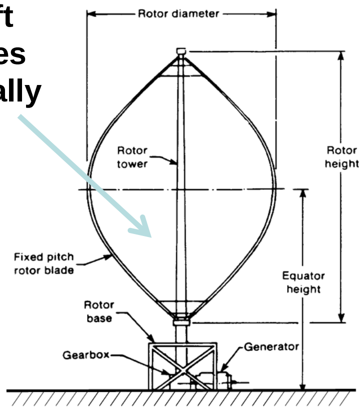
Aim of the study

- Study/optimise design:Darrieus type Vertical Axis Wind Turbine
- Design tools available: **accuracy** vs **rapid assessment.**
- **Aerodynamics – Wind over an airfoil:**
  - what is the flow?
  - How can it be understood & assessed with accuracy in a realistic time period?
  - How can it help in design decisions?

What is a Darrieus VAWT?



Shaft rotates vertically

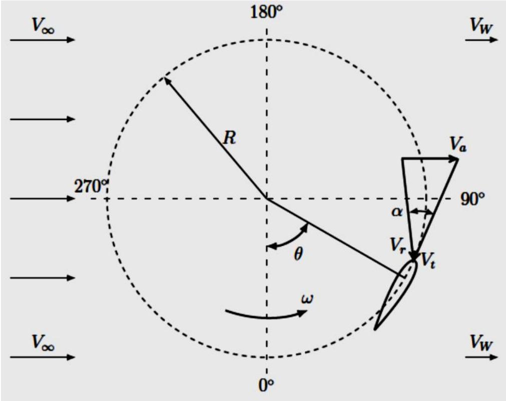


A **wind turbine** is 'a device which converts the power in the **wind** into **electricity**'

Darrieus turbine uses aerodynamic forces (the lift force of an air foil).

Theory of VAWTs – Blade aerodynamics

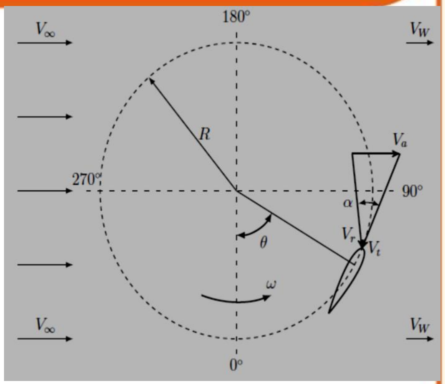
- VAWTS: **Simple devices**:
- Fixed geometry blades,
- easy access to the generator for maintenance
- no yaw control is required.



- **However** such simplicity does not extend to the turbine **aerodynamics**.
- The blade elements travel along circular paths through air, whose relative speed and direction are constantly changing.
- Darrieus turbine blades operate with **unsteady, non-linear**, **interfering** aerodynamics.

BEM methods

- Simplify the problem
- Allow rapid assessment
- Need input on:
  - **Lift & drag coeficients**
  - **Blade wake**

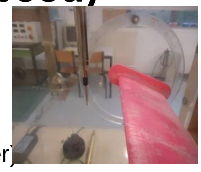


Experimental Analysis:

Tools available

- Wall flow visualisation techniques: **observe the flow**
  - **String method**
  - **Ink droplets:**

- Velocity measurements: **Measure the flow (speed)**
  - **hot-bulb anemometer**

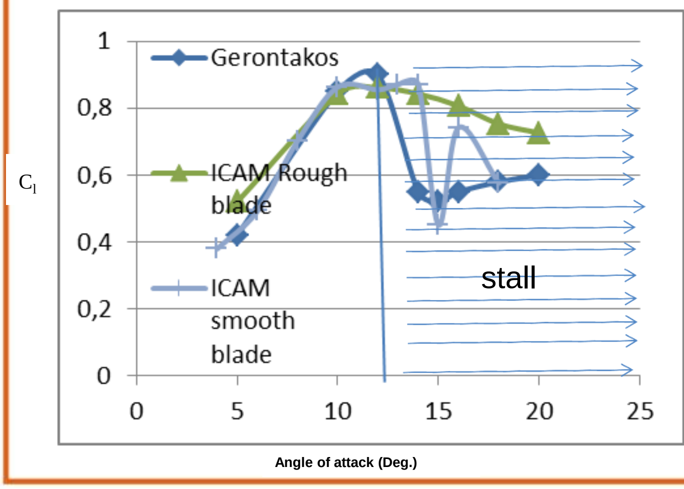


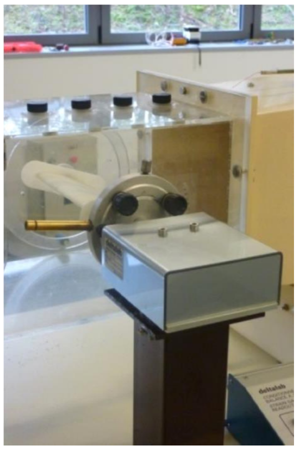
- Aerodynamic forces : **Measure global loads**
  - **Strain guage** (Delta lab 38340 strain gauge balance conditioner)

Experimental Analysis

Aerodynamic forces

Device: Delta lab 38340 strain gauge balance conditioner.





Experimental Analysis

Future work

- Frequency convertor (**control speed**)
- Stepper motor (**control blade pitch**)
- Hot wire anemometer and/or Particle Image velocimetry.
- Can simulate a complete rotation of the VAWT in real time.
- Effects of dynamic stall can be captured.

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Computational Fluid Dynamics (CFD)

- Equations must be solved numerically due to the complexities of **turbulence**.
- There are two generally accepted methods of modelling turbulence using CFD,
- **Large Eddy Simulation** (LES)
- **Reynolds Averaged Navier Stokes** (RANS) equations.

Time vs accuracy

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Computational Fluid Dynamics (CFD)

2D vs 3D

Turbulence is 3 dimensional

Stall is 3 dimensional

Accuracy = 3D simulation

2D shows poor agreement in the stall condition.

Reference:

Kitsios V: *Numerical simulation of lift enhancement on a NACA 0015 airfoil using ZNMF jets:* Centre for turbulence research, proceedings of the summer program 2006.

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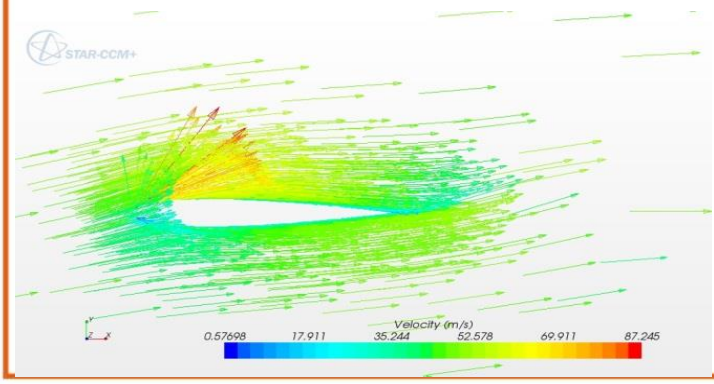
Computational Fluid Dynamics (CFD)

RANS approach

- VAWT design: **Velocity magnitude** & **direction** is very important.
- **Wake** must be known**: interference**.



20 degrees angle of attack: **Does not** simulate the real flow

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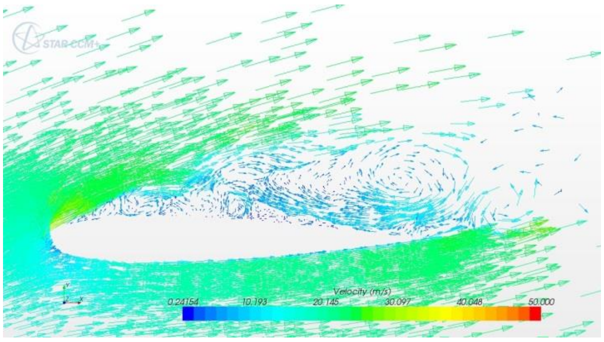
Computational Fluid Dynamics (CFD)

LES simulation

Different approach:

Large eddies are **calculated**

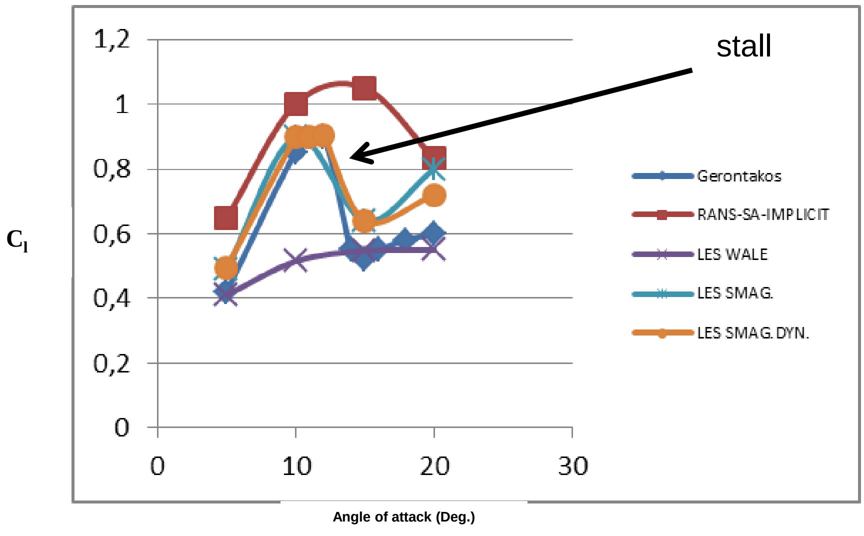
Small eddies are **estimated**.



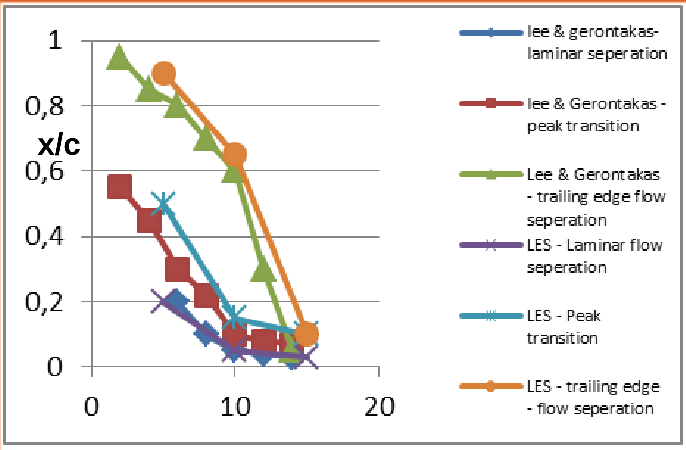
Rotational flow is maintained: good representation of the real flow

Computational Fluid Dynamics (CFD)

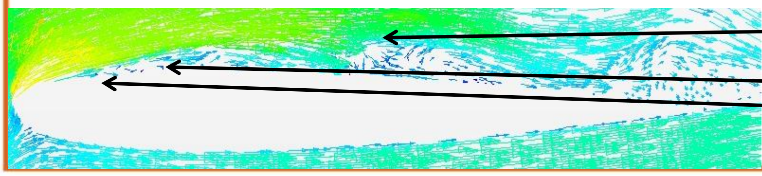
Lift coefficient comparison



Computational Fluid Dynamics (CFD)



Good representation with Lee & Gerontakos



12 deg. angle of attack

Computational Fluid Dynamics (CFD)

LES: **One problem**.

- **Time consuming**: 1 simulation of a fixed angle of attack – 6-8 days (simulation time).
- Not including meshing aswell.
- Need a finer mesh (y+1)

Base size: 0.05m
Number of prism layer: 25
Prism layer stretching: 1.2
Prism layer thickness: 0.007m

Absolute surface
Min: 0.001m
Max: 0.05m

Cells: 4656078 Faces: 22618610 Vertices: 14783318 Memory: 3607MB

Computational Fluid Dynamics (CFD)

CFD Summary

- **Accuracy** =
  - 3 D
  - LES

•LES is a good representation of the flow topology.

Future validation:

•**Small scale models test** ⟺ **LES**

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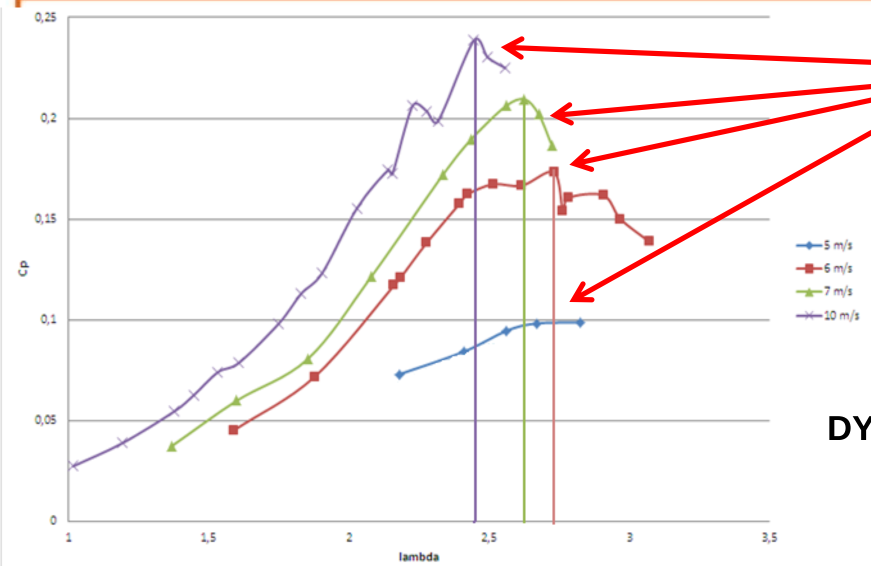
Results: model test 1



WHY?

DYNAMIC STALL

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Dynamic stall

445rpm
Stall angle = 25 deg.
Cl = 2.5
Wind speed = 10m/s
λ= 4,5

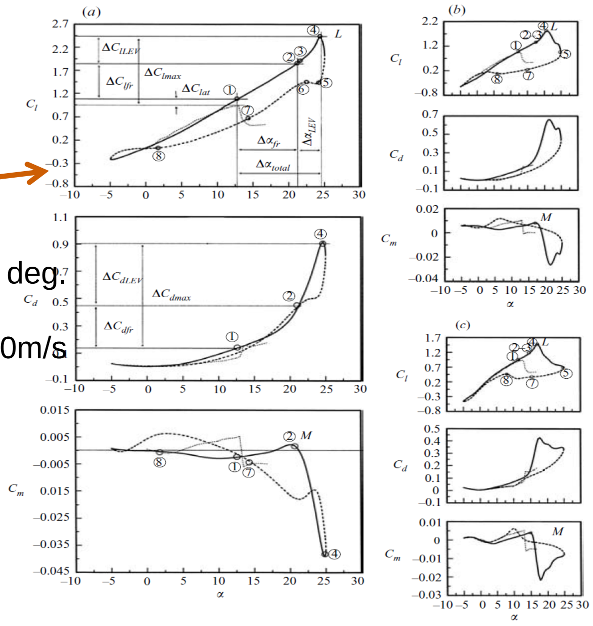


FIGURE 8. Variation of dynamic load-loops with reduced frequency for $\alpha(t) = 10° + 15° \sin \omega t$. (a) $\kappa = 0.1$, (b) $\kappa = 0.05$, (c) $\kappa = 0.025$. ①, onset of flow reversal; ②, end of upward spread of flow reversal; ③, turbulent breakdown; ④, lift stall; ④–⑤, full stall; ⑥, onset of secondary vortex; ⑦, onset of flow reattachment; ⑧, end of flow reattachment. ——, increasing α; ····, decreasing α; · · · ·, static values; M, moment stall; L, lift stall.

223rpm
Stall angle = 20deg.
Cl = 1.7
Wind speed = 10m/s
λ = 2,4

111rpm
Stall angle = 16 deg.
Cl = 1.5
Wind speed = 4,5 m/s
λ =2,7

Aéreojoules design

- **Need to manage stall.**
  - **» Blade tip speed ratio > 3.5**
- **Need to manage interference:**
  - **» Radius**
  - **» Chord length**
- **Helicoidal blades: Complicate blade flow – especially in stall.**
- **Understand Dynamic stall**

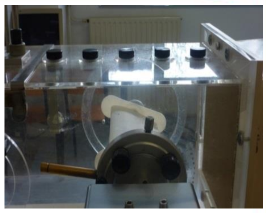
Conclusions, Perspectives, Future Work

- A good understanding of VAWT design has been achieved.
- **Stall** vs **Interference** managed for optimal aerodynamics.
- Flow phenomena is **complicated** – especially with **helicoidal blades**

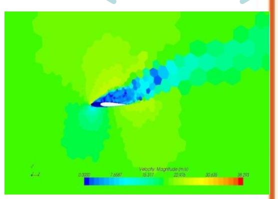
Conclusions, Perspectives, Future Work

Experimental (Full scale)

Experimental (single blade)



xc



Simple LES CFD

BEM models

Conclusions, Perspectives, Future Work

- Future experiments:
- Stepper motor-frequency convertor
- (flapping foil experiment)
- CFD LES – Wind tunnel validation.
- Real scale bench test.
- European Wind Energy Association (EWEA) conference, Barcelona, Spain 2014: '*Using experimental & CFD models for selecting blade profiles for a small vertical axis wind turbine*'

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Appendices

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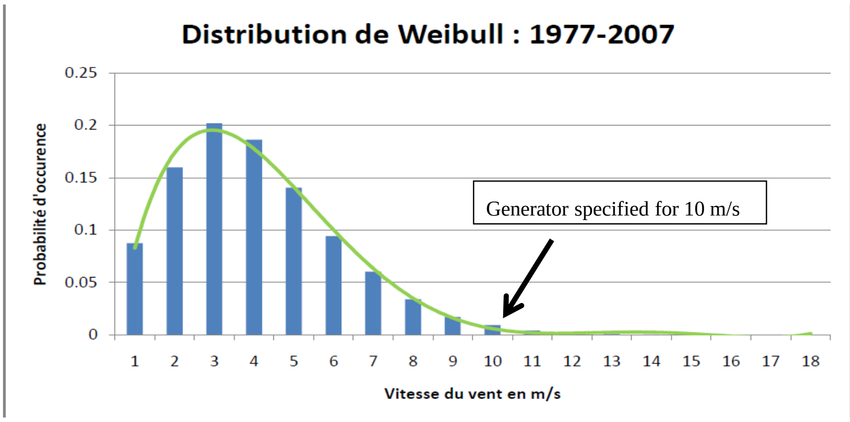
Wind energy – Nantes region

- Generators specified for a 2% operational life.
- Generator + frequency convertor = Costly – inefficient.



Ideal wind conditions: Weibull distribution

- A high probability of occurrence within a small range of wind speeds. (the Weibull curve is tall and narrow)
- Such wind speeds are high enough to provide enough power to be useful electrical energy. (The curve is further to the right in the higher electrical energy range).
- Operating at the turbines nominal generation capacity Yasseri(2012) recommended a load factor of 34-37% as acceptable.
- Yasseri S: *Economic profiling of wind energy*; Safe Sight technology, UK, RINA 2012

Offshore wind

Higher density – more reliable

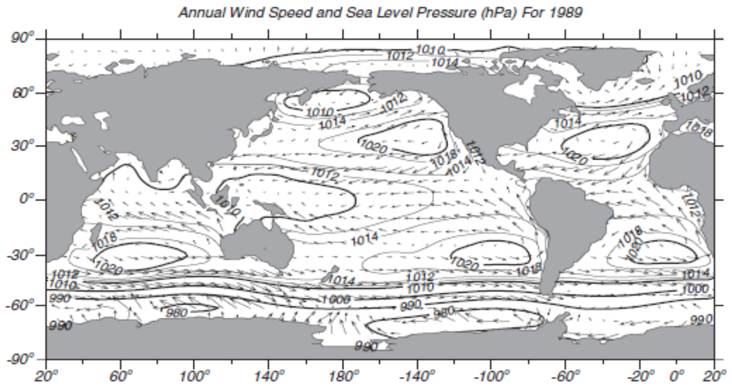


Figure 4.2 Map of mean annual wind velocity calculated from Trenberth et al. (1990) and sea-level pressure for 1989 from the NASA Goddard Space Flight Center's Data Assimilation Office (Schubert et al. 1993). The winds near 140°W in the equatorial Pacific are about 8 m/s.

Ships operational profile

Time at sea:

- Bulk carriers spend on average 75% of their time at sea,
- Tankers 60-70% and
- Container ships approx. 75%.

Good operational profile

Cargo ship study:

Ship type	Size(Length)	Design Speed (kn)	Available wind (m/s)	With ocean allowance factor (5 m/s)	Sea hotel load (KWe)	Total installed capacity (KWe)
Tanker	180-300+ m	16,00	8,23	13,23	400,00	4000,00
Bulk carrier	115-300+m	15,00	7,72	12,72	300,00	2000,00
Container ship	150-350m	25,00	12,86	17,86	12000,00	15000,00
Ro-Ro ship (conventional)	150-200m	20,00	10,29	15,29	500,00	4000,00
Ro-Ro Catamaran.	130m	45,00	23,15	28,15	300,00	1500,00

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Cargo ship study

Ship type	Max. size possible	Location	Electrical power available (KW)	% of installed power	% of Hotel load
Tanker	**2x D=2m, H=3m**	**Forecastle**	**6,00**	**0,15**	**1,50**
Bulk carrier	**2x D=5m, H=8m, 2x D=2m, H=3m**	**Amidships above ballast tanks & Forecastle**	**46,00**	**2,30**	**15,33**
Container ship	**2 x D=1,5, H=2,75**	**Forecastle**	**10,00**	**0,07**	**0,08**
Ro-Ro ship (conventional)	**2x D=1,5, H=2,75**	**Forecastle**	**6,00**	**0,20**	**1,20**
Ro-Ro Catamaran.	**2x D=2m, H=3m**	**Forecastle**	**56,00**	**2,80**	**18,67**

Not a large impact on installed power or hotel load

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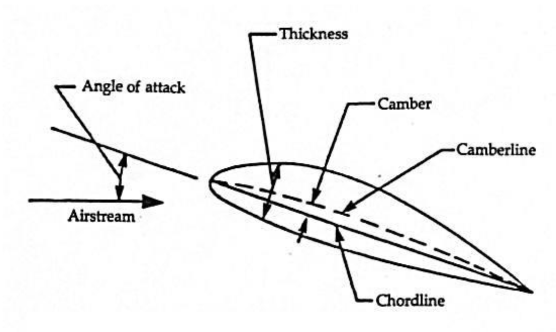
Cargo ship study

- **Reduce a ships wind resistance.**
- **Optimal blade aerodynamics to disturb the wind field around a ships superstructure.**

- **Further study proposal**

Key terms

Angle of attack : α



Key terms

Reynolds number

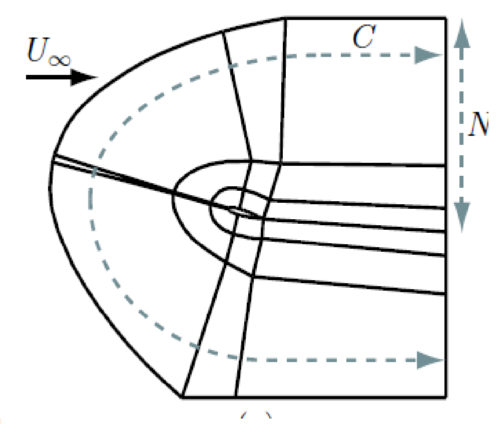
$$Re = \frac{v \cdot L \cdot \rho}{\mu}$$

where v = velocity of fluid flow; dimension: m/s
L = representative linear size (e.g., inner diameter of a pipe); dimension: m
ρ = density of fluid; dimension: kg/m^3
μ = dynamic viscosity of fluid; dimension: kg/(m·s)

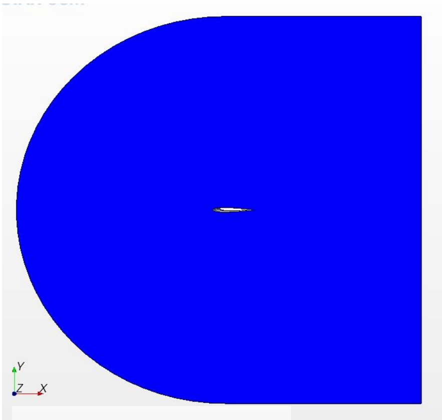
- Used to characterise the nature of the fluid flow – **laminar** or **turbulent**.
- L = chord length (m)
- V = relative velocity (m/s)

Meshing study

LC –LN- LZ = 28c -6c - 1c



LC –LN- LZ = 28c -5c - 2c

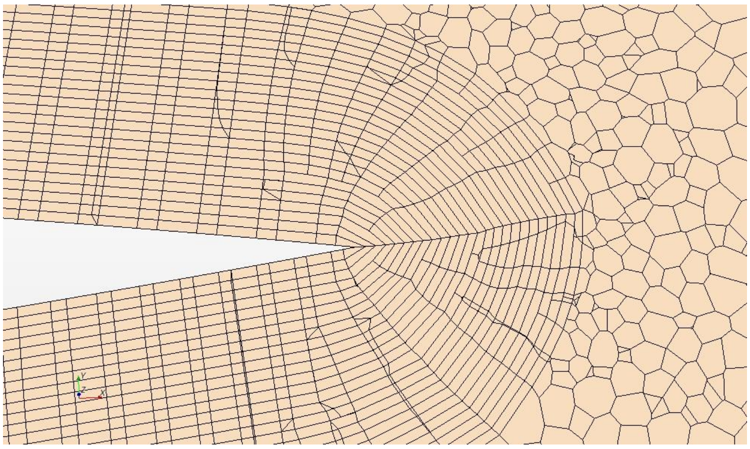


Span = 0.2m

Kitsios V: *Numerical simulation of lift enhancement on a NACA 0015 airfoil using ZNMF jets:* Centre for turbulence research, proceedings of the summer program 2006.

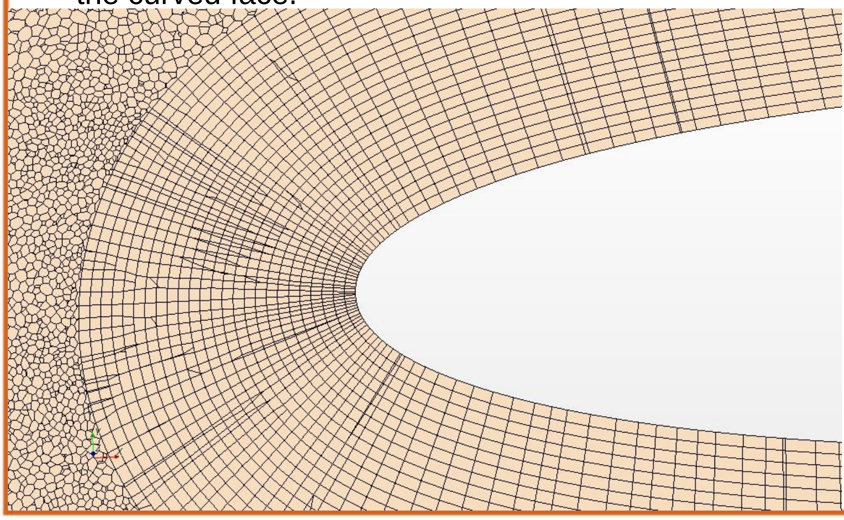
Meshing study

Blade trailing edge: To minimise the size of the x+ in this region, it is important to define a Minimum & Maximum value of the surface size on the prism layer.



Meshing study

- **Blade leading edge:** To accurately model the surface curvature the surface curvature function must be used to define the number of surface points on the curved face.



Meshing study

mesh details	1	2	3	4	5
base value (m)	0,1	0,05	0,05		0,05
number of prism layers	25	25	30	25	25
prism layer stretching	1	1	1,1	1	1
prism layer thickness (m)	0,04	0,035	0,03	0,085	0,009
surface curvature (pts./circle)	100	100	100	100	100
curvature deviation	200	200	200	200	200
curvature deviation distance (m)	0,01	0,01	0,01	0,01	0,01
surface growth rate	1,3	1,3	1,3	1,3	1,3
surface proximity (points in gap)	2	2	2	2	2
absolute surface size					
min. (m)	0,025	0,001	0,001	0,001	0,001
Max. (m)	0,1	0,1	0,1	0,1	0,05
Regions					
faces: min. (m)	0,0005	0,001	0,001	0,001	0,0001
Max. (m)	0,005	0,005	0,005	0,005	0,001

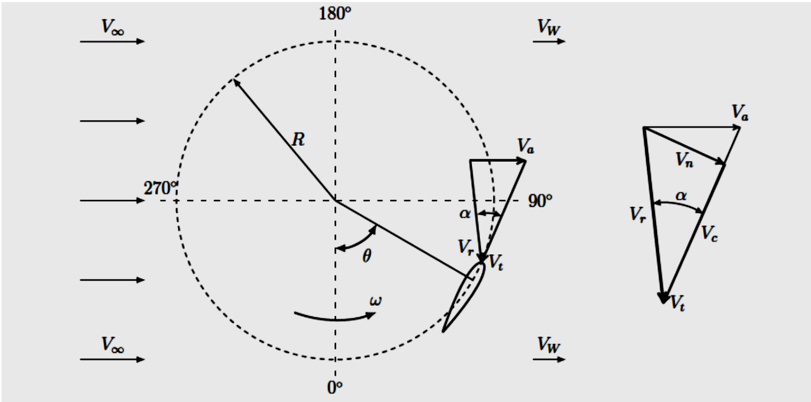
Meshing study

RANS/LES	RANS	RANS	RANS	RANS	RANS	RANS	RANS	RANS	RANS	RANS
Turbulence model	SA (Stan.)	SA (Stan.)	SA (Stan.)	SA (Stan.)	k-e	k-e	k-e	k-e	SA(HR)	SA(HR)
steady/unsteady	steady	steady	steady	steady	steady	steady	steady	steady	steady	steady
Angle (Deg.)	0	5	10	15	0	5	10	15	10	15
Convergence	yes	yes	no	no	yes	yes	yes	no	yes	yes
Y+ value	30	30	30	30	30	30	30	30	30	30
Mesh type	1	1	2	2	2	2	2	2	2	2
Time (iterations)	200	600	1000 runs	1000 runs	300	650	800	1000 runs	500	600

Key terms

Blade tip speed ratio : λ

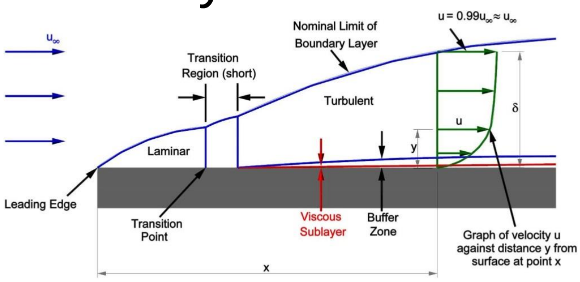
- $\lambda = (Vt)/(V_\infty)$ (usually) or $\lambda = (Vt)/(Va)$ (blade element momentum models)



Key terms

Turbulence

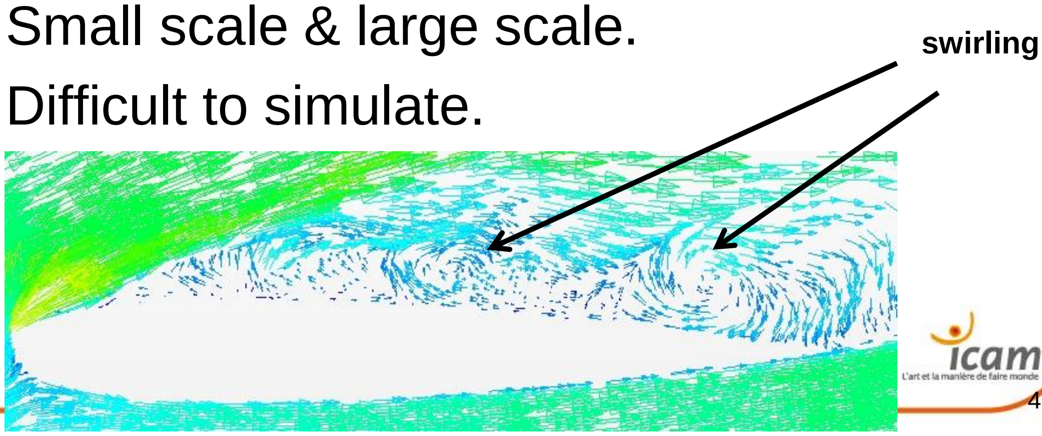
- Unsteady flow
- 3 dimensional
- Rotational
- Occurs at Reynolds numbers > 2000



Key terms

Eddies

- Swirling of a fluid flow.
- Often caused by Reverse Flow.
- Small scale & large scale.
- Difficult to simulate.



Key terms

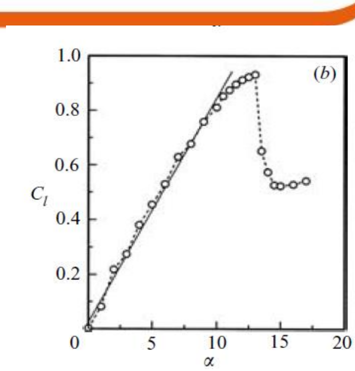
Stall (static)

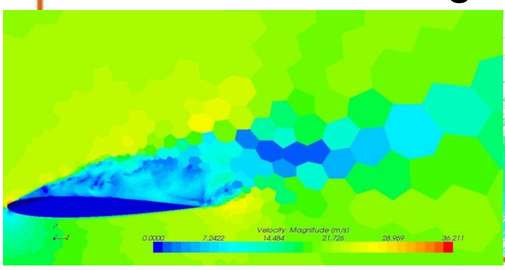
Separation of boundary layer.

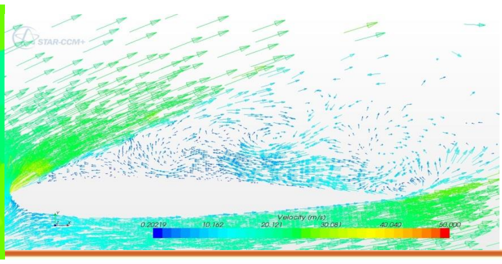
Loss of lift force

Large unsteady wake

Bursting of boundary separation bubble – at leading edge.







Key Terms

Stall (Dynamic)

- As the **frequency** of **pitching decreases**, the **stall angle of attack** is **lower** and the **lift coefficient** is **less**.

- As the **frequency** of **pitching increases**, the **stall angle of attack** is higher and the maximum **lift coefficient** is **higher**

References:

- **Lee & Gerontakas** : '*Investigation of foil over an oscillating airfoil*' – Mcgill University, Montreal @ 2004 cambridge university press.

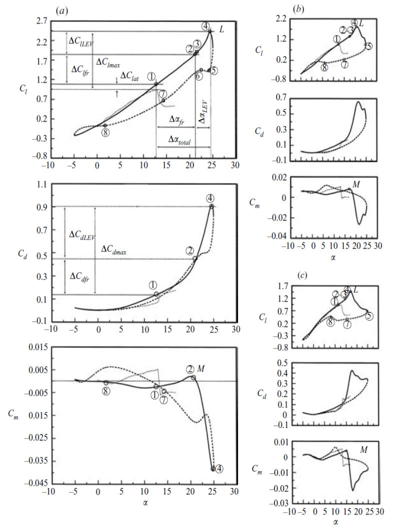


FIGURE 8. Variation of dynamic load-loops with reduced frequency for $\alpha(t) = 10° + 15° \sin \omega t$. (*a*) $\kappa = 0.1$, (*b*) $\kappa = 0.05$, (*c*) $\kappa = 0.025$. ①, onset of flow reversal; ②, end of upward spread of flow reversal; ③, turbulent breakdown; ④, lift stall; ④–⑤, full stall; ⑥, onset of secondary vortex; ⑦, onset of flow reattachment; ⑧, end of flow reattachment. —, increasing α; ····, decreasing α; - - -, static values; *M*, moment stall; *L*, lift stall.

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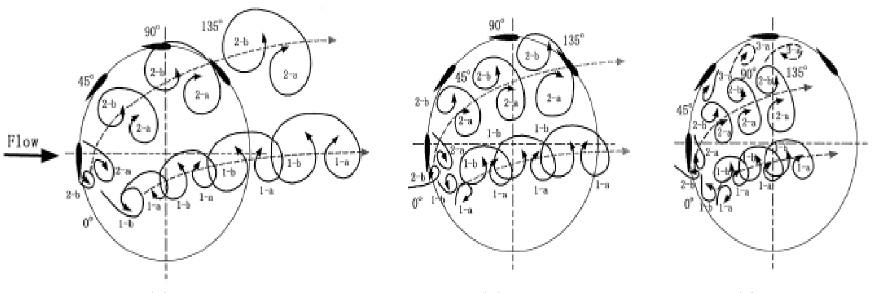
Key terms

Interference

- Blade disturbance
- Disrupting the clean air on a blade.
- Understanding **Blade wake** is very important.



(a) $\lambda = 1$ (b) $\lambda = 2$ (c) $\lambda = 3$

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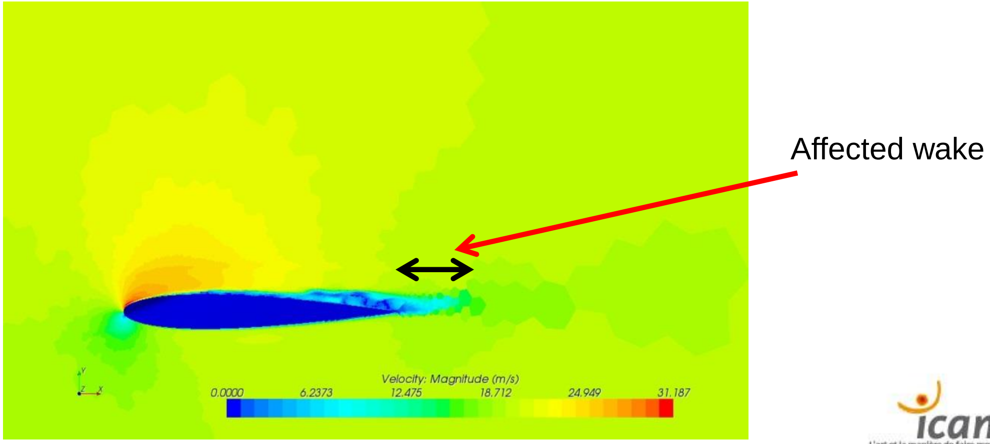
Blade wake

- The velocity profile at the trailing edge.



Computational Fluid Dynamics (CFD)

- **CFD** is the numerical simulation of a physical problem by the use of digital computers
- Regulated by the **Navier-stokes** equations:
- **Hypothesis**: **Incompressible fluid**

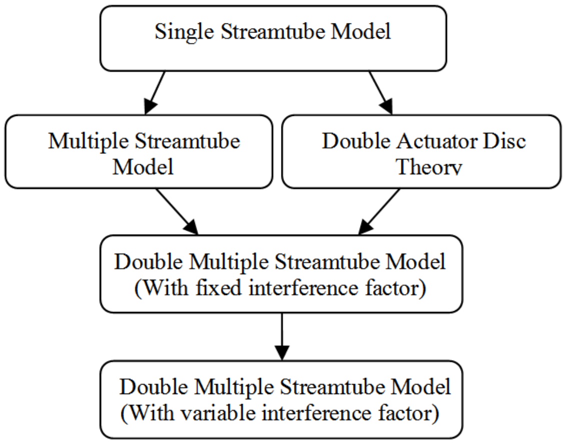
$$\frac{\partial u_i}{\partial x_i} = 0$$

Unsteadiness	Convection	Pressure effects	viscous effects	Volume forces (gravity)

$$\frac{\partial u_i}{\partial t} + u_k \frac{\partial u_i}{\partial x_k} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_k \partial x_k} + f_i$$

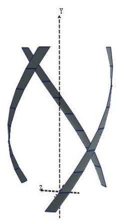
BEM models

- In-house development
- Q-blade
- A good approach if 3D effects, stall & interference are incorporated in the model.



Q-blade

- Wind energy group at the **Berlin Technical University** Department of Experimental Fluid Mechanics.
- Qblade contains 3 simple sections:
  - blade design and optimisation
  - rotor simulation
  - turbine definition and simulation

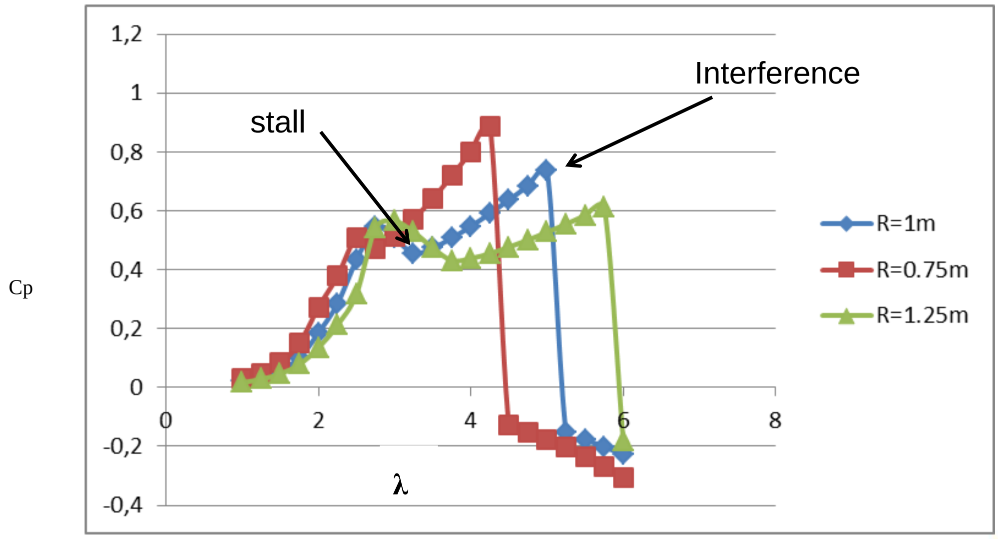


Q-blade

3 simulation types:

- Ideal conditions with some interference factor.
- A more advanced interference factor is added.
- Tip speed losses are also taken into account.

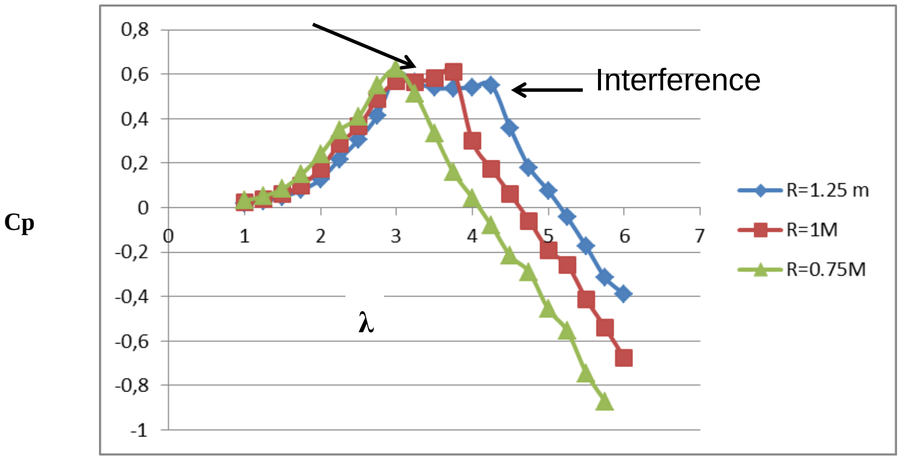
Q-blade:Change of radius



Ideal conditions: interference factor

Q-blade:Change of radius

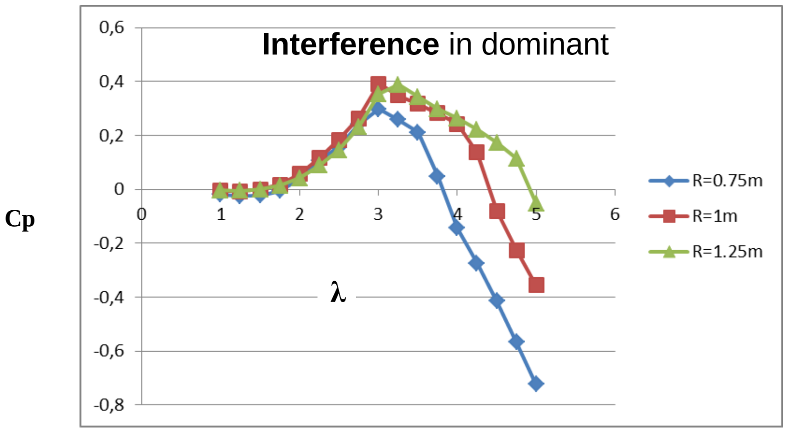
stall



Additional interference factor

Q-blade:Change of radius

Most representative of model test:



Radius = 1 m is the highest power coeficient at a desired speed

Tip speed losses factor (relevant for Helicoidal blades)

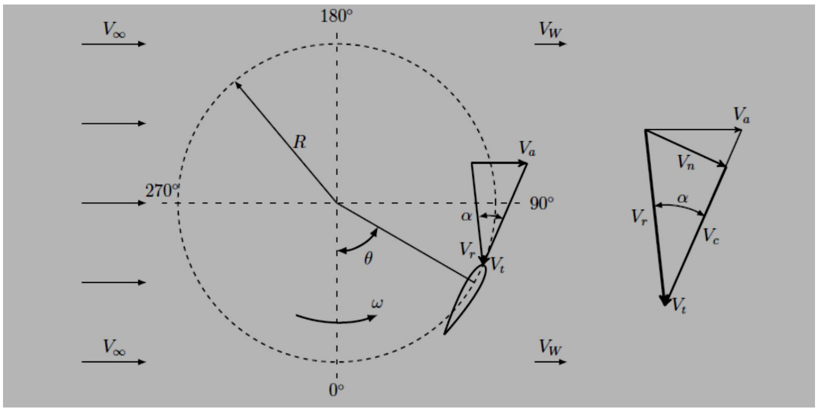
Velocity & angle of attack

$$V_t = R\omega$$

$$\lambda = \frac{V_t}{V_a} = \frac{R\omega}{V_a}$$

$$V_r = \sqrt{V_a\left(\frac{R\omega}{V_a} + \cos\theta\right)^2 + V_a \sin^2\theta}$$

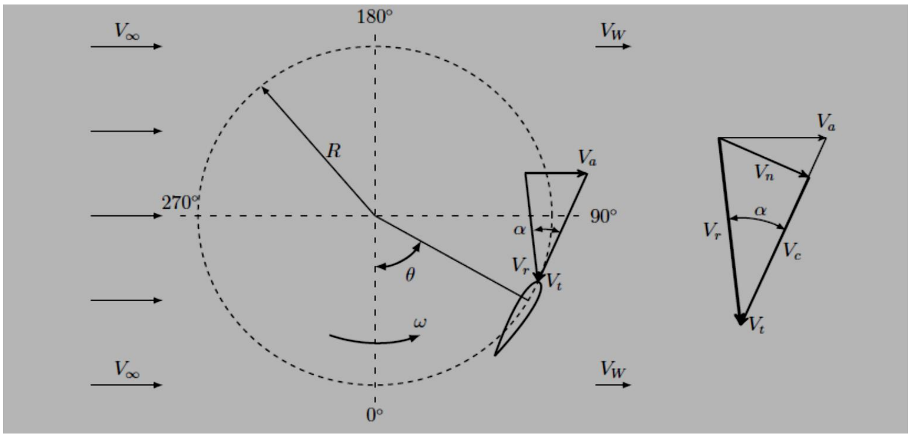
$$= V_a\sqrt{(\lambda + \cos\theta)^2 + \sin^2\theta}$$



Velocity & angle of attack

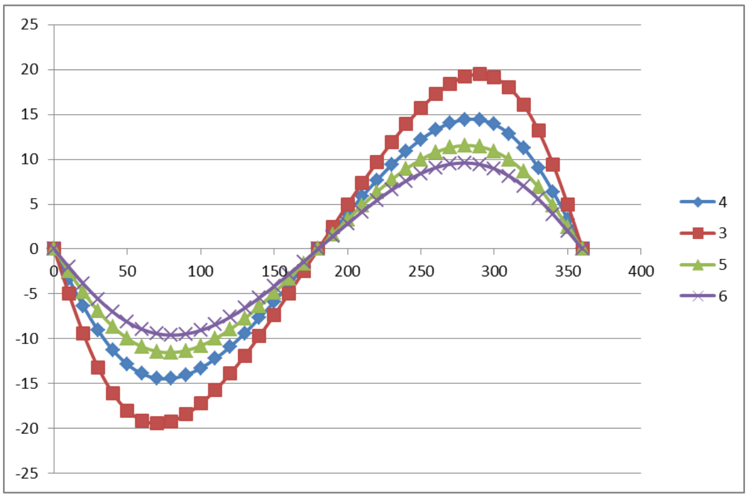
$$\alpha = \tan^{-1}\left(\frac{V_n}{V_c}\right)$$

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{(\lambda + \cos\theta)}\right)$$



Blade angle of attack

Angle of attack (Deg.)



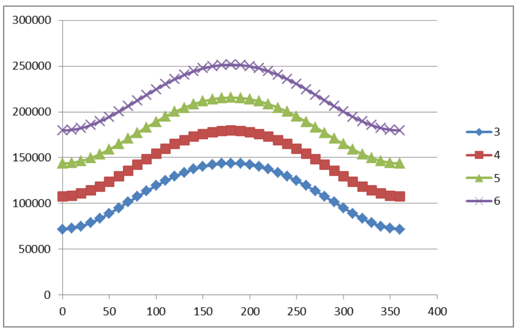
Blade Azimuth. angle (Deg.)

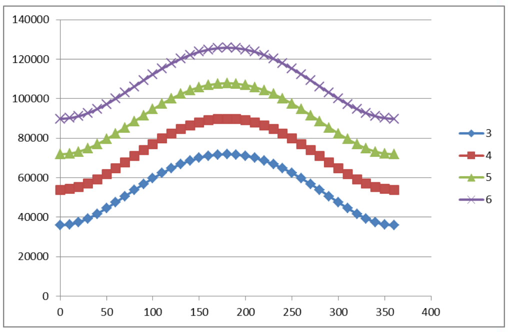
Reynolds number (velocity)

Vw = 10m/s

Vw = 5m/s

RN

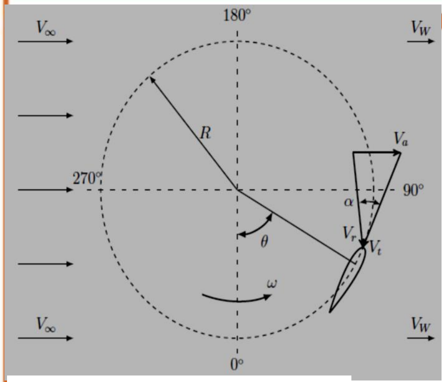




Blade Azimuth. angle (Deg.)

Range = 30000 – 150000 for a λ of 3

Interference



T_s = the time required for the next blade to move into the zone of the previous blade.

$$t_s = \frac{2\pi}{n\omega}[\text{sec}]$$

$$t_w = \frac{s}{V}[\text{sec}]$$

T_w = The time taken for the disturbed wind to reestablish itself (t_w)

$$t_s \approx t_w$$

$$\frac{2\pi}{n\omega} \approx \frac{s}{V} \Rightarrow \frac{n\omega}{V} \approx \frac{2\pi}{s}$$

or $t_s > t_w$ → **Need data on wake**

$$\lambda_{optimal} \approx \frac{\omega_{optimal} r}{V} \approx \frac{2\pi}{n}\left(\frac{r}{s}\right)$$

$$\omega_{optimal} \approx \frac{2\pi V}{ns}$$

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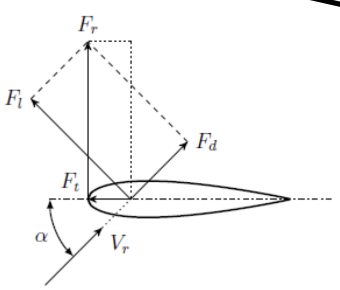
Forces on the airfoil

Need lift & drag coeficients

$$F_l = \frac{1}{2}\rho c l C_l V_r^2$$

$$F_d = \frac{1}{2}\rho c l C_d V_r^2$$



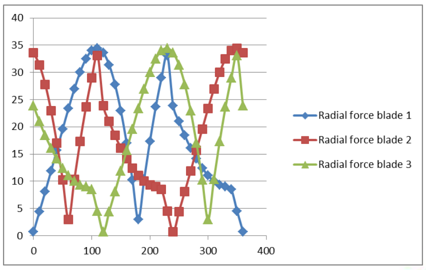
$$F_t = F_l \sin\alpha - F_d \cos\alpha$$

$$F_t = \frac{1}{2}\rho c l V_r^2 (C_l \sin\alpha - C_d \cos\alpha)$$

$$F_r = F_l \cos\alpha + F_d \sin\alpha$$

$$F_r = \frac{1}{2}\rho c l V_r^2 (C_l \cos\alpha + C_d \sin\alpha)$$

Force: (N)



Blade angle (Deg)

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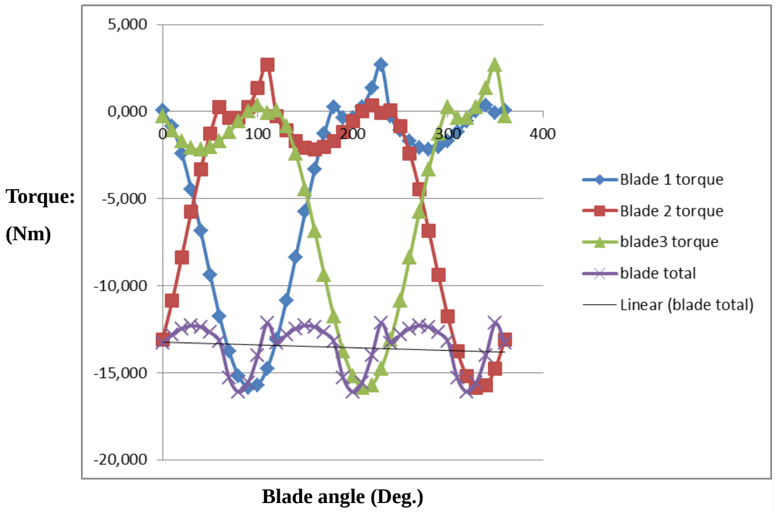
Torque & power output

$$M_t = F_t R$$

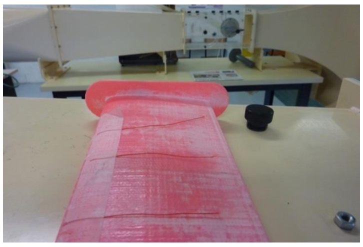
$$P_a = M_{Ta}\,\omega$$

$$C_P = \frac{P_a}{P_w} = \frac{P_a}{\frac{1}{2}\rho S V_\infty^3}$$

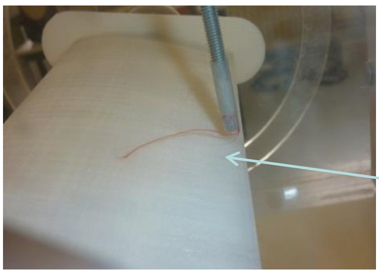


Experimental Analysis:

Observe the flow



Ink droplets before starting the fan and encountering wind.

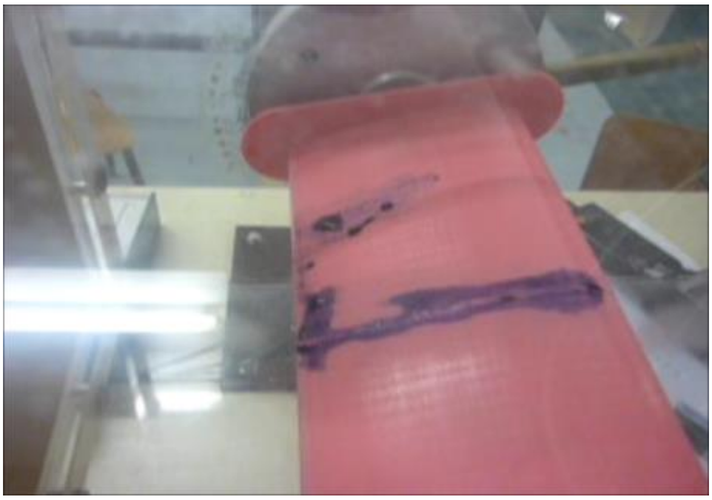


String encountering reverse flow.

length of trailing edge flow separation can be measured

Experimental Analysis:

- Ink droplets : effects of **stall**



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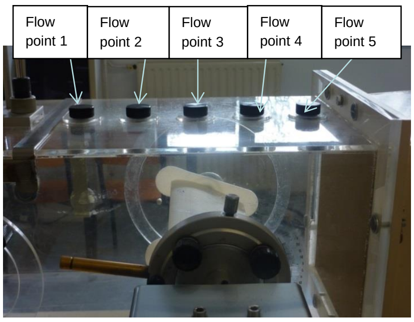
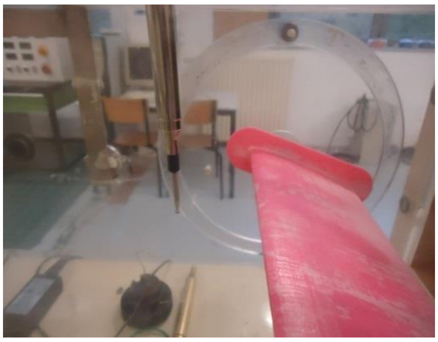
Experimental Analysis

Measure the flow (speed)

- **hot-bulb anemometer** (testo 490 manual hot-bulb anemometer)
- Range (0.1-60m/s -50-200 deg.c) spatial resolution: 0.1deg.





Measurement points

1	2	3	4	5
0.8c	0.2c (fwd.)	0.4c (aft)	TE	0.6c + c

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Computational Fluid Dynamics (CFD)

RANS approach

- Reynolds decomposition and a turbulence model.
- Averages the vector sum of large & small eddies. (velocity in the viscous term is averaged)
- **Turbulence model** that will statistically calculate the turbulence in the small scale regions close to the boundary surface. (y+=30)
- Simulation **time** & computer **Hardware** is reduced: **However**;

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Large scale experiments

- CTSB Jules Verne wind tunnel (Sep. 2012)

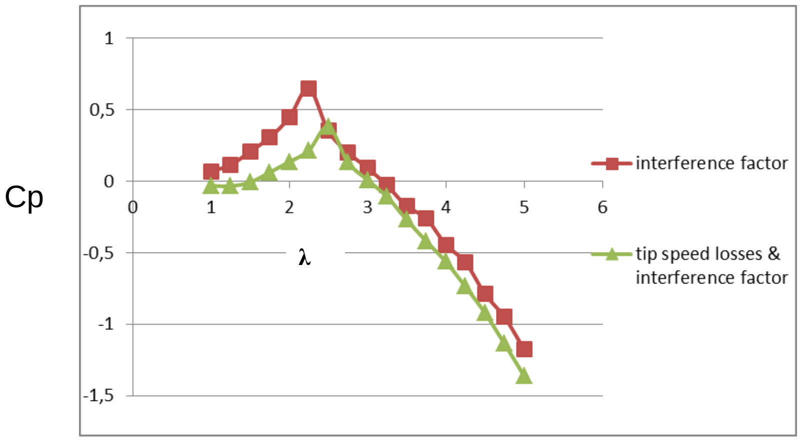
Wind speeds: 5, 6, 7 & 10m/s

Observations:

- Structural vibration is high; a fastening system was needed on top of the turbine above the shaft.
- Bending of the blades occurred, particularly at higher rpm.
- Only a small range of Blade tip speed ratios were tested. (1-3)
- Cp increases as **rpm/wind** speed increases

Model test 2(Jan. 2014)

- **Waiting results:** Comparison with Q-blade.



Conclusions, Perspectives, Future Work

Design spiral:

- Controllable
- Useable

Electrical

Aerodynamics

- Blade flow
- Loads - forces

Noise: Tip speed ratio vs stall

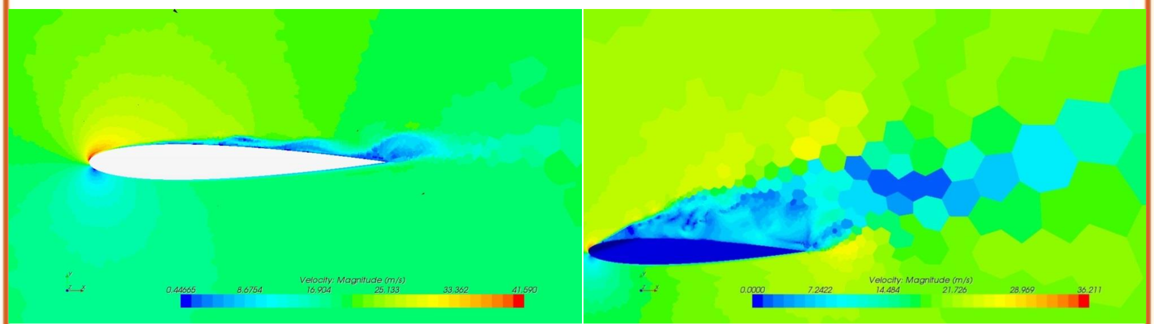
Structures

Vibration
Strength

Computational Fluid Dynamics (CFD)

Captures the wake

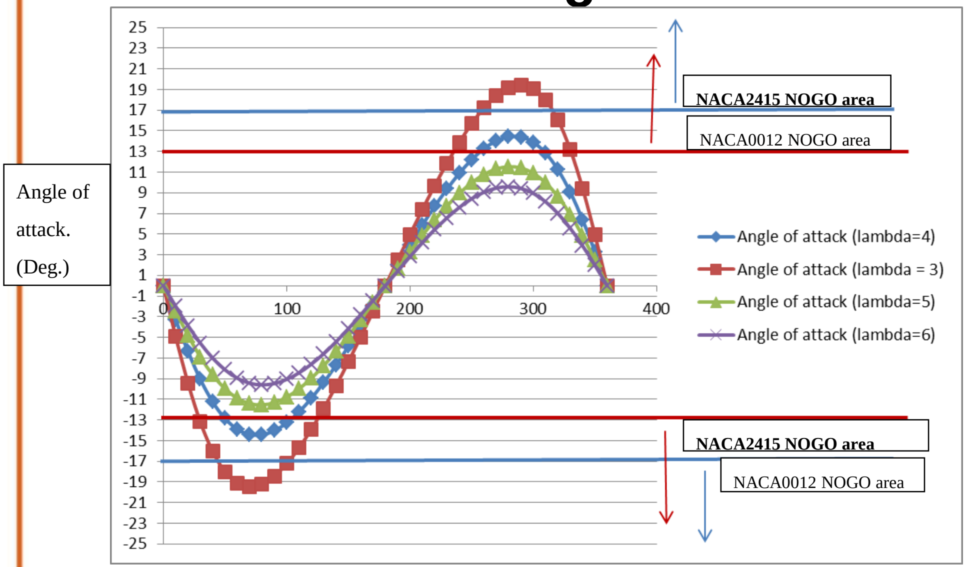
10 deg: **pre-stall** 15 deg: **post-stall**



Velocity magnitude (m/s)

VAWT design

Manage Stall



VAWT design

Manage Interference

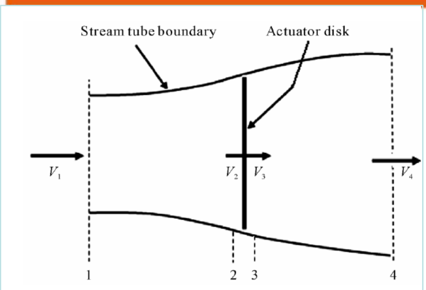
- Blade Chord length.
- Turbine radius.
- Turbine angular speed.
- Optimum free stream wind speed.
- Blade geometry and angle of stall.
- Reynolds number.

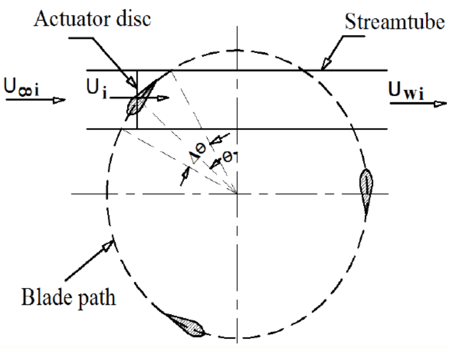
Experimental Analysis

Experimental Errors:

- Excessive vibration on the blades at high angles of attack.
  - Due to blockage, interference, stall or a combination of all.
  - Will effect strain gauge readings, & all observations.
- The **strain gauge** & **Hot bulb anemometer** can also be coupled to a computer for a mean average reading; however for these simulations just a **visual readout** was obtained, which provides an extra margin of error.
- **Blockage**
- **Interference**
- **Pressure drop on monometer – speed drop.**

Understanding Blade Aerodynamics (BEM method)





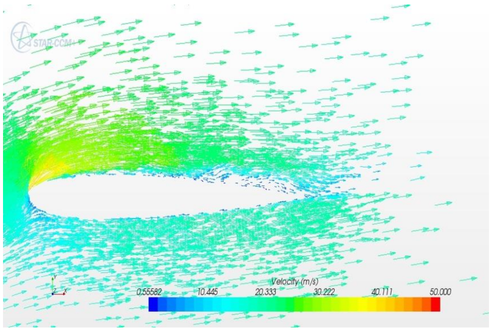
Assumptions:

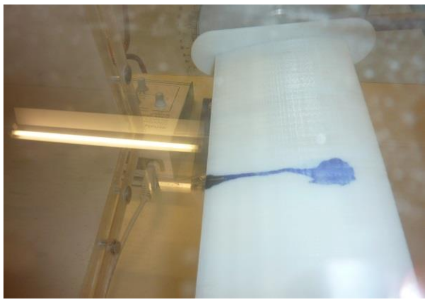
- Homogenous, incompressible, steady state fluid flow with no frictional drag.
- The pressure increment or thrust per unit area is constant over the disk.
- The rotational component of the velocity in the slipstream is zero.
- There is continuity of velocity through the disc.
- An infinite number of blades.

Experimental Analysis

Future work

- **CFD validation** of blade flow.





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Computational Fluid Dynamics (CFD)

LES simulation

2 LES methods of small scale eddies:

StarCCm+ sub-grid kinetic energy is a physical by-product.

LES always uses a sub-grid scale model;

- **Smagorinsky (standard or dynamic)** or;
- **WALE**

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Design Recomendations

•How do we really know the flow dynamics?

•**Bench test** :measure the loads over the electric motor.

•Obtain a **power** vs **speed** curve

•Model test: **What is the flow**? **Visualisation device**? Smoke? Light?

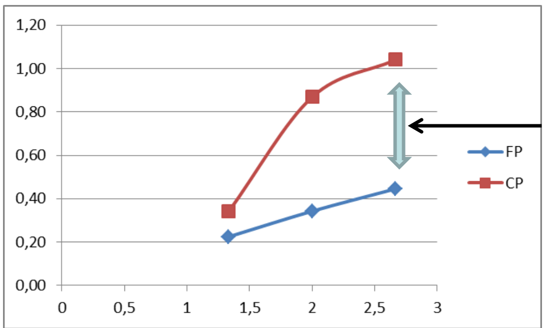
•Does not need to be expensive!

Conclusions, Perspectives, Future Work

- After flapping foil experiments:
- Investigation of **pitch control**:
- Particularly beneficial at low tip speed ratios (no stall)

286rpm : pitching period = 0.21s

(Cp)



Blade Tip Speed Ratio

200+% increase However no power loss in blade control

Experimental Analysis

ICAM Wind tunnel

Span length = 0.2m

Height = 0.2m

Wind speed = 20m/s – 40m/s

A Pitot tube connected to a differential manometer gives a measurement of :

$$P_{A'}-P_\infty = P_A-P_\infty$$

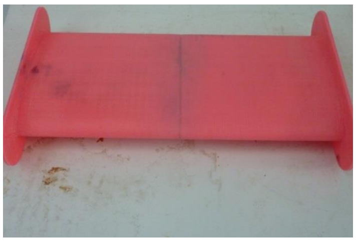
The differential manometers give a pressure difference in mm WC

Experimental Analysis:

Models

- 3D printer – extrusion process
- Acrylonitrile Butadiene Styrene (ABS).
- NACA 0012, NACA 2415

Rough blade: P120 sandpaper (125 μm particel diameter)



Smooth blade: P4000 sandpaper (6 μm particle diameter)