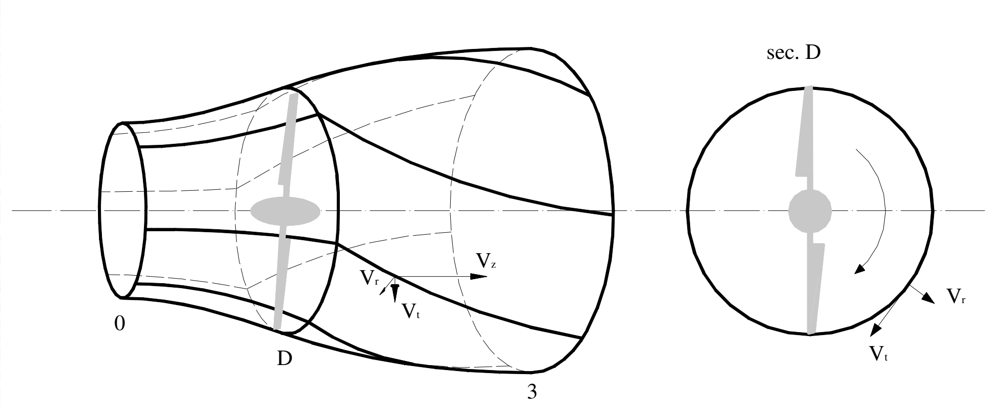
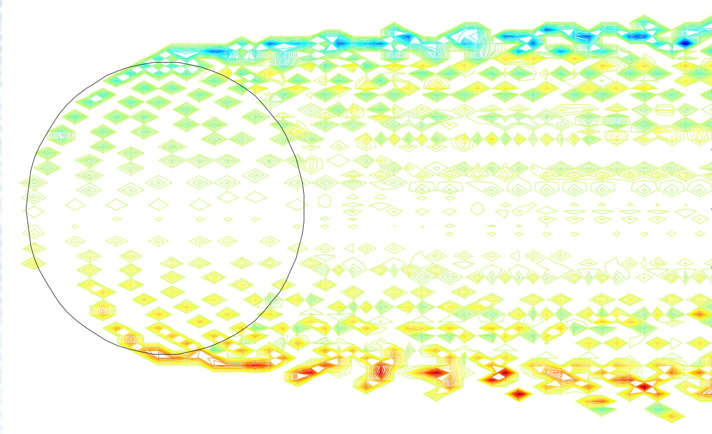
UNIVERSITÁ DEGLI STUDI DI UDINE
Dottorato in Tecnologie Chimiche ed Energetiche

FLUID DYNAMIC MODELLING OF WIND TURBINES





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Udine 21 Maggio 2010

Summary

Introduction

PART I : HAWT analysis

HAWT Fluid dynamics

A turbomachinery approach

Inverse design

Summary

PART II : VAWT analysis

VAWT fluid dynamics

VAWT experimental analysis

VAWT free vortex wake

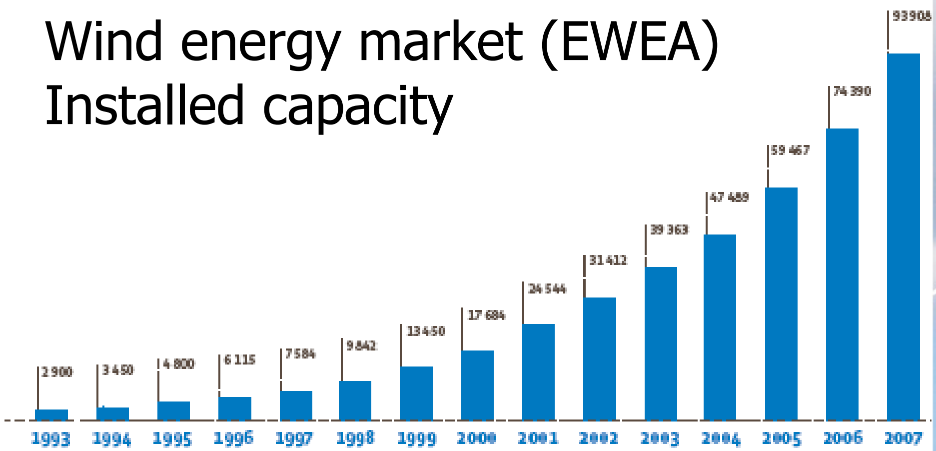
Results and conclusions

Introduction

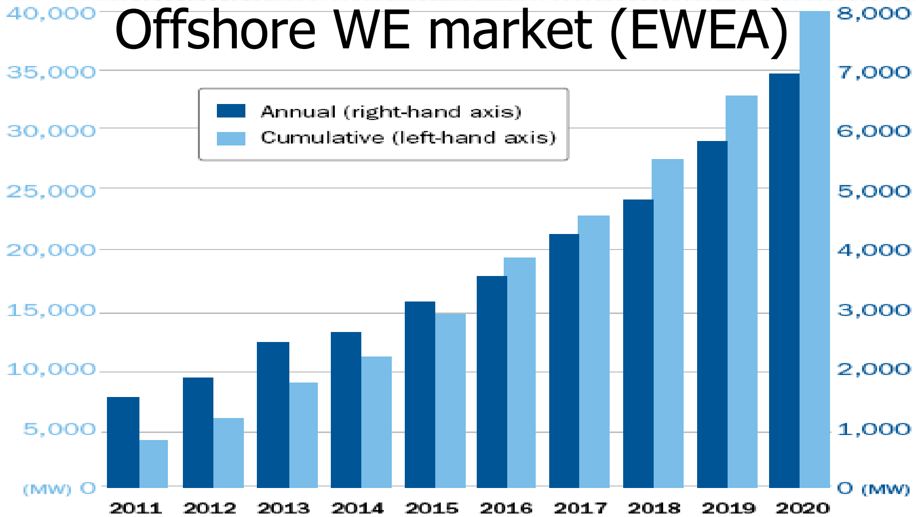
Potenza eolica totale installata nel Mondo dal 1993 (in MW).*

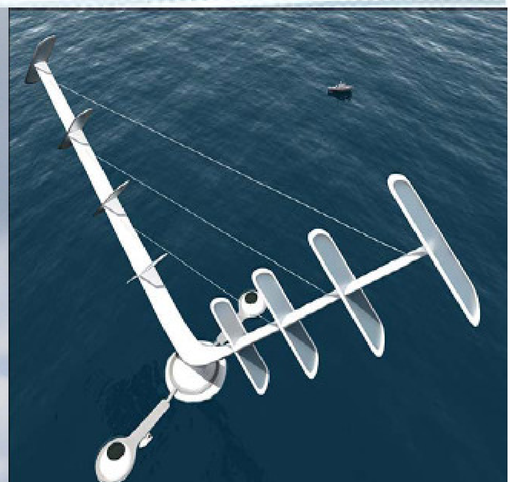
** Stime. Fonte: EurObserv'ER 2009.*

Wind energy market (EWEA)
Installed capacity



Offshore WE market (EWEA)





Aim of the thesis & thesis outline

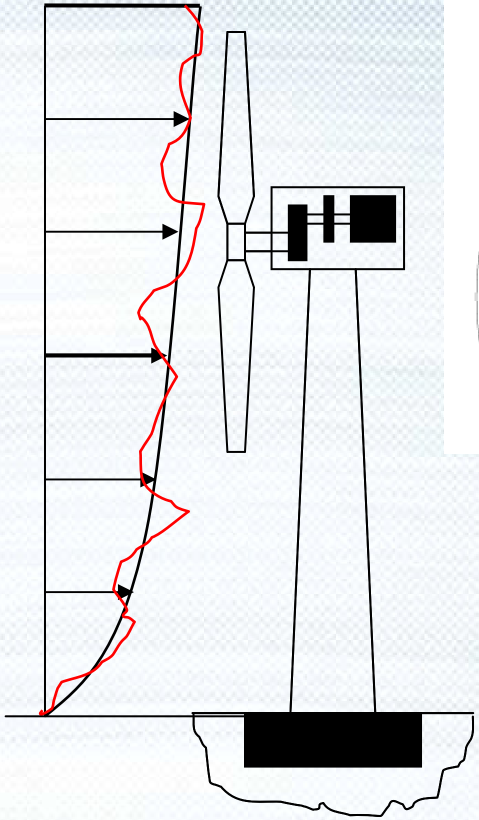
The aim of the thesis is to analyze the fluid dynamic models of wind energy conversion systems, pointing out the limitations of current engineering models and proposing innovative solutions from the design point of view

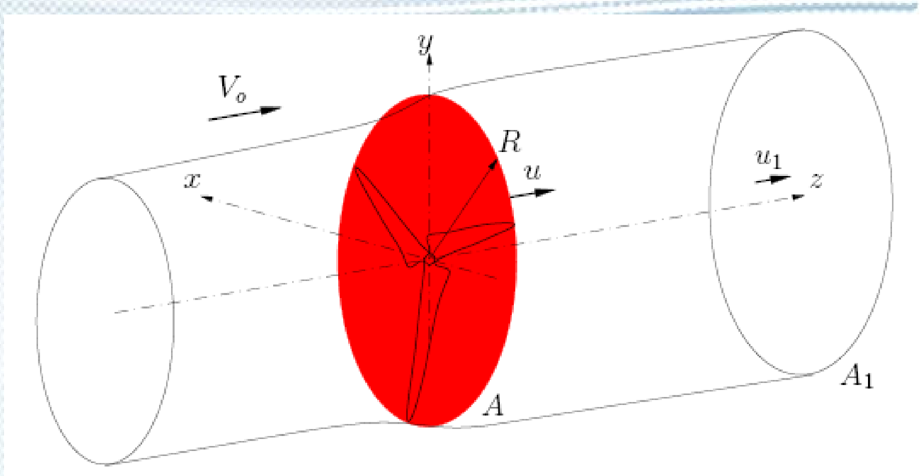
The research activities have been divided in two main parts, following the different rotor – flow interaction characteristics:

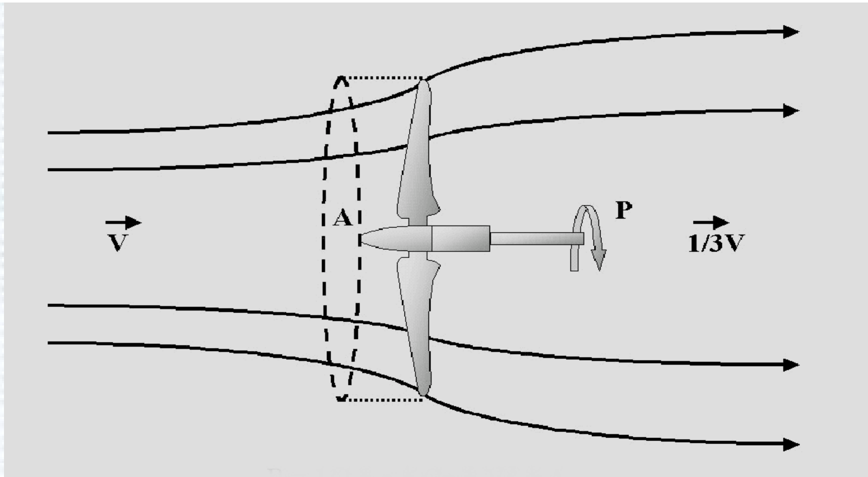
1. Horizontal axis wind turbines - HAWT;
2. Crossflow wind turbines, as vertical axis wind turbines - VAWT.

Part I : HAWT analysis
HAWT fluid dynamics

HAWT fluid dynamics is mainly based on the actuator disk concept







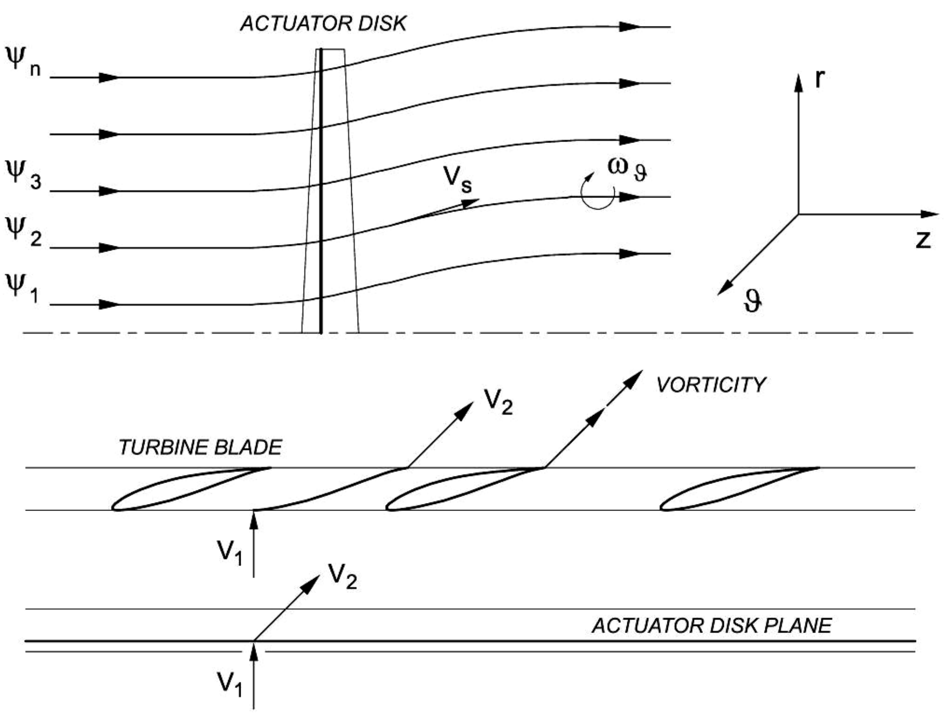
HAWT fluid dynamics
Actuator disk concept

The turbine generates mechanical work from the kinetic energy of the fluid flow

The work exchange between the fluid and the shaft is done by is done by the rotor, which can be modelled as an actuator disk

The bladed rotor can be represented with equivalent forces distribuited over a permeable, immaterial disk

Infinite number of blades
Infinite rotational velocity



HAWT fluid dynamics
Actuator disk – momentum theory

Froude applied for the first time the actuator disk concept to a rotor in open flow.
He applied it with the 1D momentum balance in axial direction

Momentum equation

$$T = \Delta p \cdot A_m = \rho V_{z,3} A_3 \left(V_{z,0} - V_{z,3}\right)$$

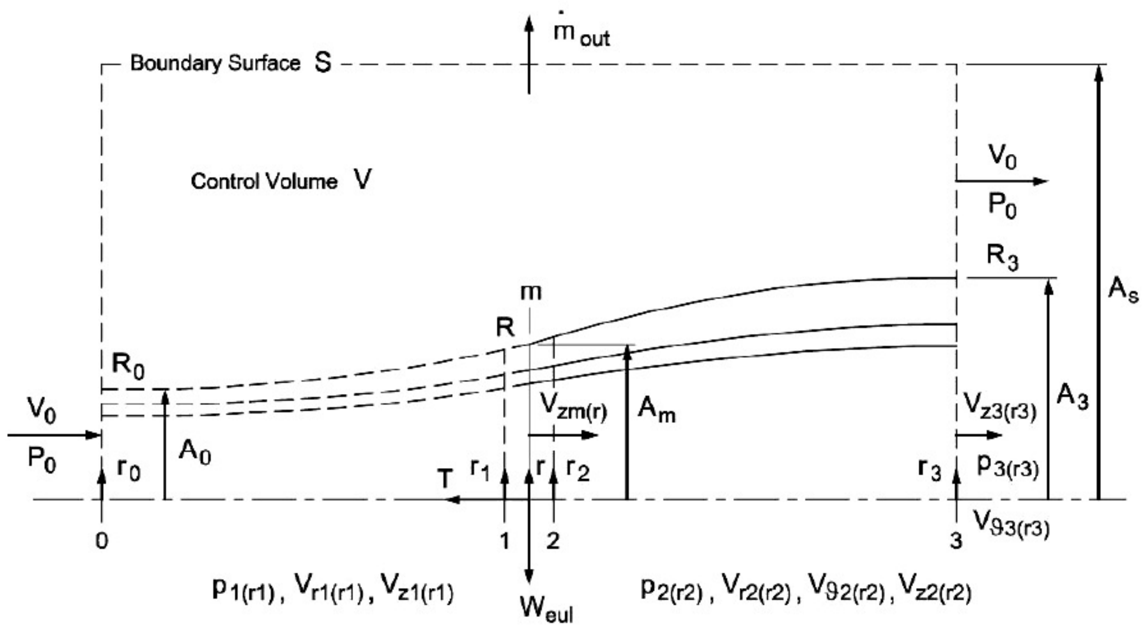
Energy conservation

$$W_{eul} = \frac{\Delta p}{\rho} = \frac{V_{z,0}^2 - V_{z,3}^2}{2}$$

Mass conservation

$$V_{z,m} A_m = V_{z,3} A_3$$

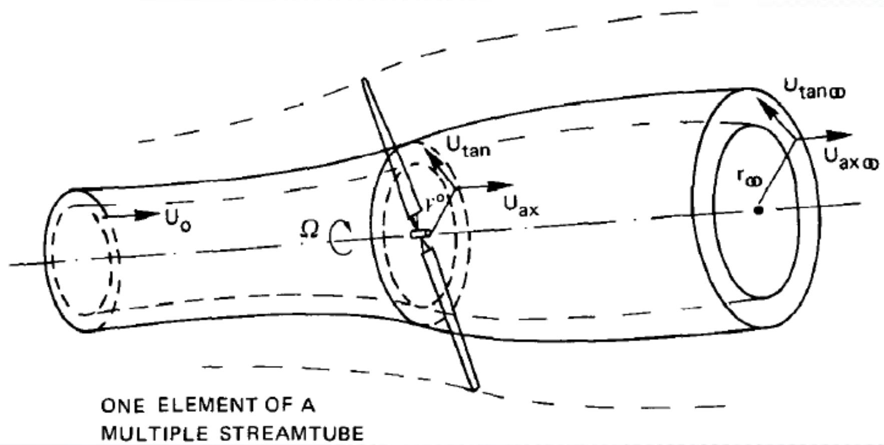
$$V_{z,1} \cong V_{z,2} \cong V_{z,m}$$

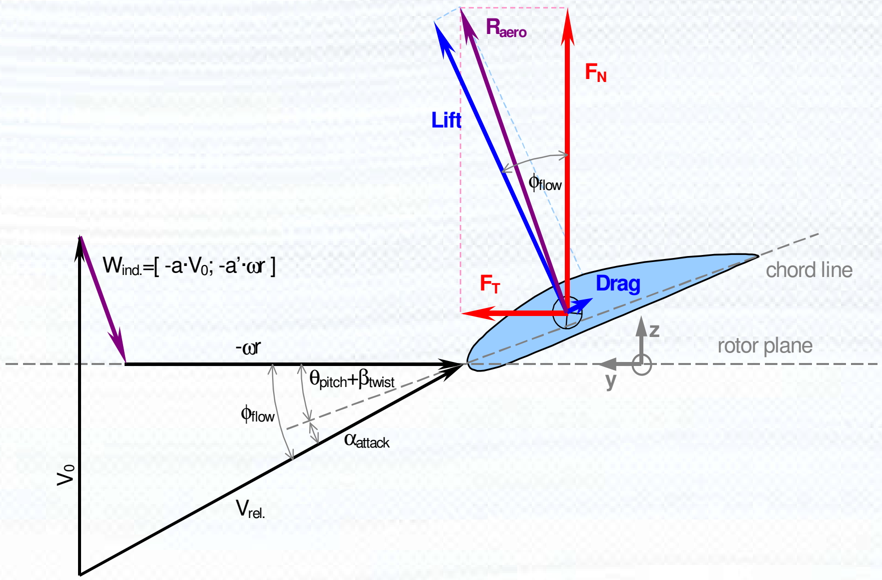


Froude result!

$$V_{z,m} = \frac{V_{z,0} + V_{z,3}}{2}$$

Actuator disk
Blade element – momentum theory





Drzewiecki first applied Froude result dividing the rotor in different annular streamtubes :
Non uniform loading

$$V_{z,m} = \frac{V_{z,0} + V_{z,3}}{2}$$

With the blade element airfoil theory rotor performances can be easily calculated

The annuli interaction is neglected
No swirl flow, (wake expansion?)
Ok lightly loaded rotors

HAWT fluid dynamics
General momentum theory

The general momentum theory should overcome the issues of the swirl flow modelling

Momentum equation : axial | tangential | radial

$$T = \int_{Am} (p_1 - p_2)\, dA = \int_{A3} \left[\rho V_{z,3} (V_{z,0} - V_{z,3}) + (p_0 - p_3) \right] dA$$

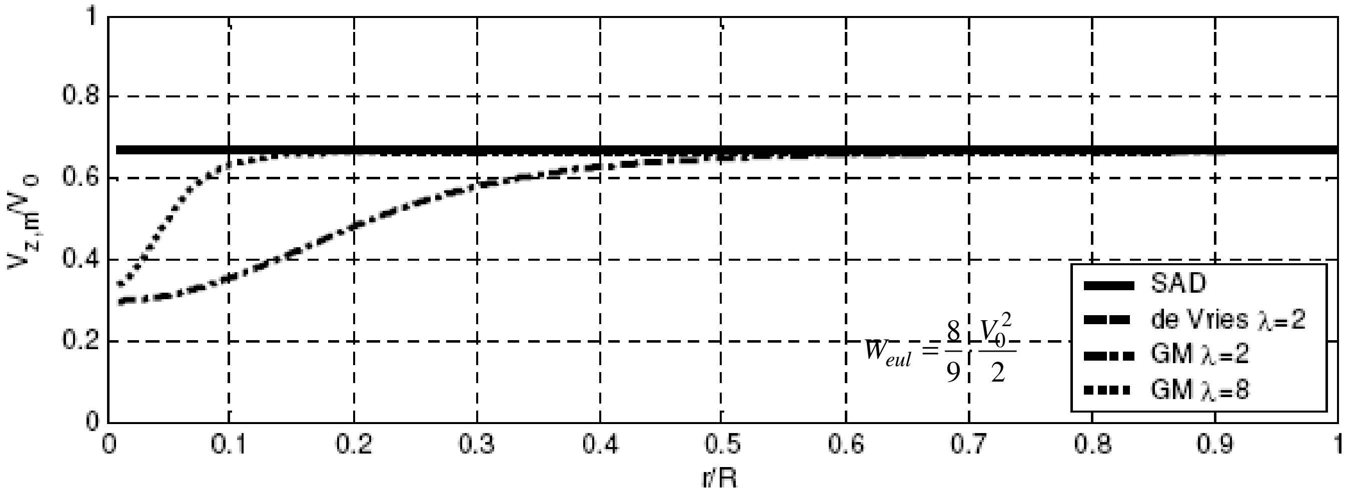
$$M = \int_{A3} \rho V_{\theta,3} V_{z,3} r_3 \, dA$$

$$\frac{p_3 - p_0}{\rho} = \frac{p_3(r_3) - p_3(r_{tip,3})}{\rho} = -\int_{r_3}^{r_{tip,3}} \frac{V_{\theta,3}^2}{\tilde{r}_3} d\tilde{r}_3$$

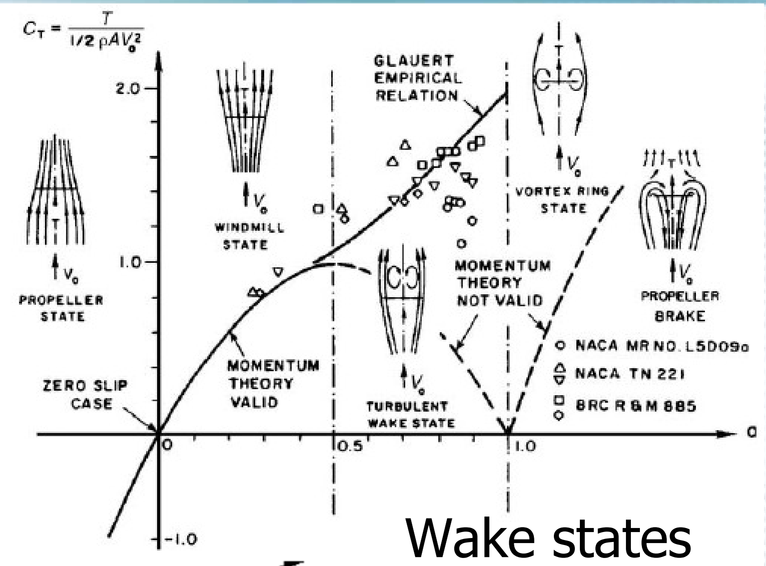
$$\frac{1}{2}\rho \int_{A3} (V_{z,0} - V_{z,3})^2 \, dA = \rho\Omega \int_{A3} V_{z,3} V_{\theta,3} r_3 \left[\frac{1 + 1/2 V_{\theta,3}/\Omega r_3}{V_{z,3}} - \frac{1 + 1/2 V_{\theta,2}/\Omega r}{V_{z,m}} \right] dA$$

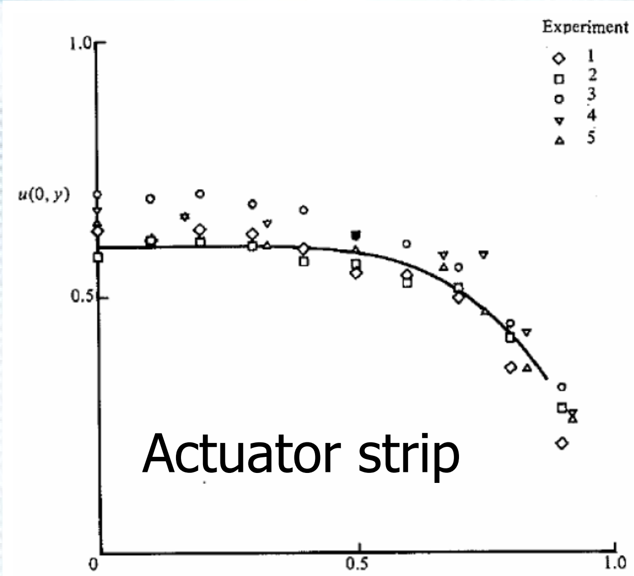
Solutions:
- De Vries
- Differential

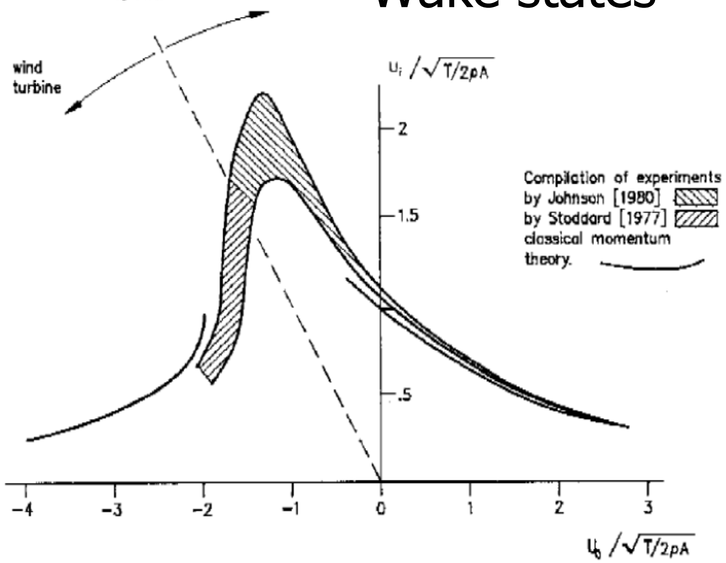
- GM theory is an integral formulation
- It needs the wake solution

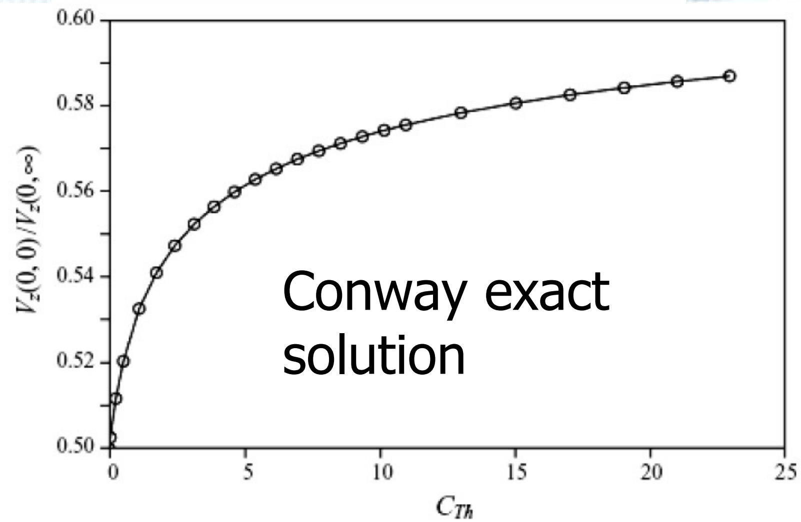


Actuator disk – momentum theory limitations

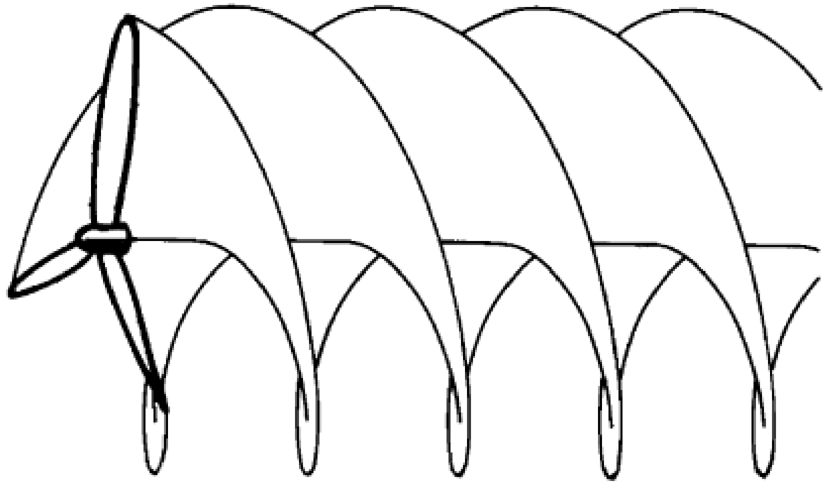








HAWT fluid dynamics
Vortex theory

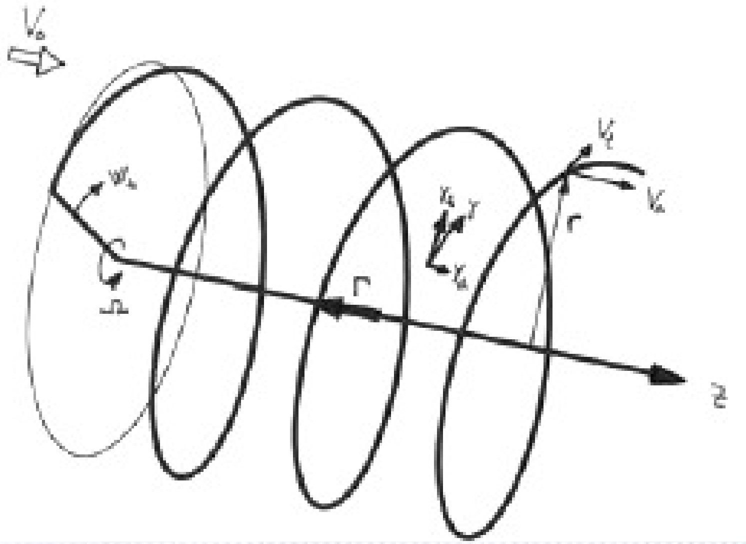


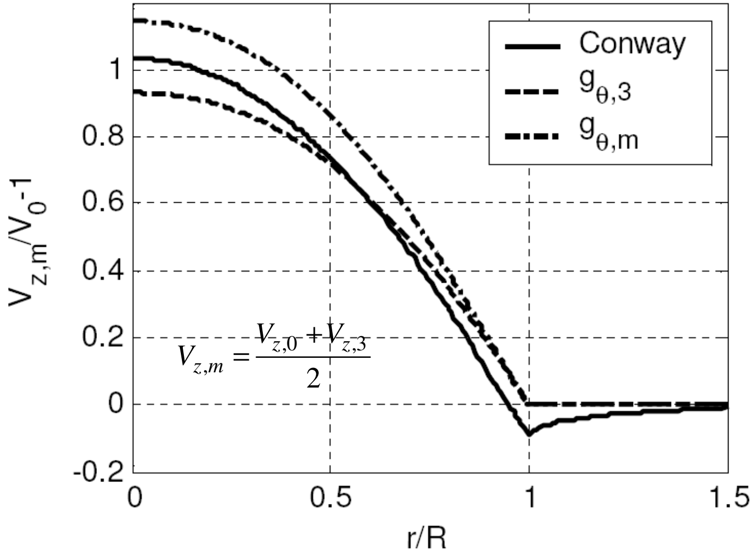
Vortex theory calculates the flow field of the rotor wake by using the fluid dynamic laws of vorticity (Biot-Savart law, Kelvin's theorem, Helmholtz's laws)
Introduced by Joukowski – Betz – Prandtl

Most widespread for propeller analysis and design (both for aerodynamic and marine propellers) and for helicopter rotor performance prediction

- Prescribed vortex wake
- Free vortex wake

Vortex theory
Prescribed vortex wake





Axial velocity

$$d\Gamma = 2\pi \cdot d\left(rV_{\theta,2}\right)$$

$$g_{\theta,m} = \frac{d\Gamma}{2\pi r}\frac{r\Omega + V_{\theta,2}/2}{V_{z,m}}$$

$$g_{\theta,3} = \frac{d\Gamma}{2\pi r_3}\frac{r_3\Omega + V_{\theta,3}}{V_{z,3}}$$

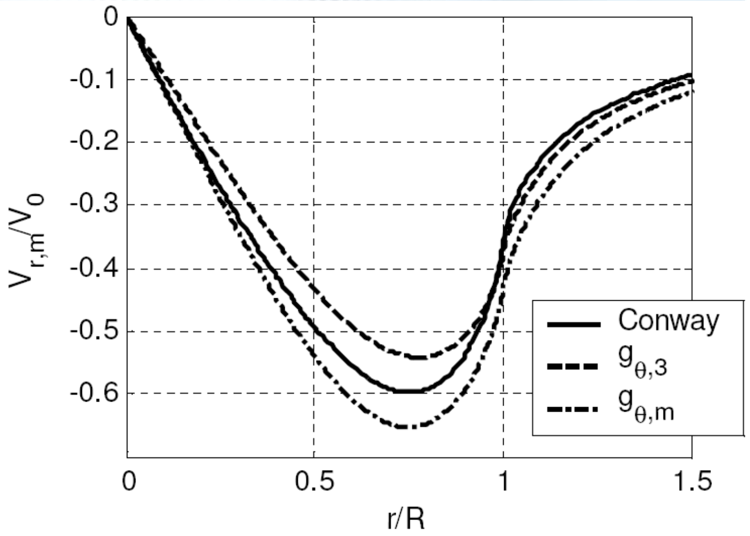
$$v_{z,m} = g_\theta/2 \qquad v_{z,3} = g_\theta$$

Radial velocity

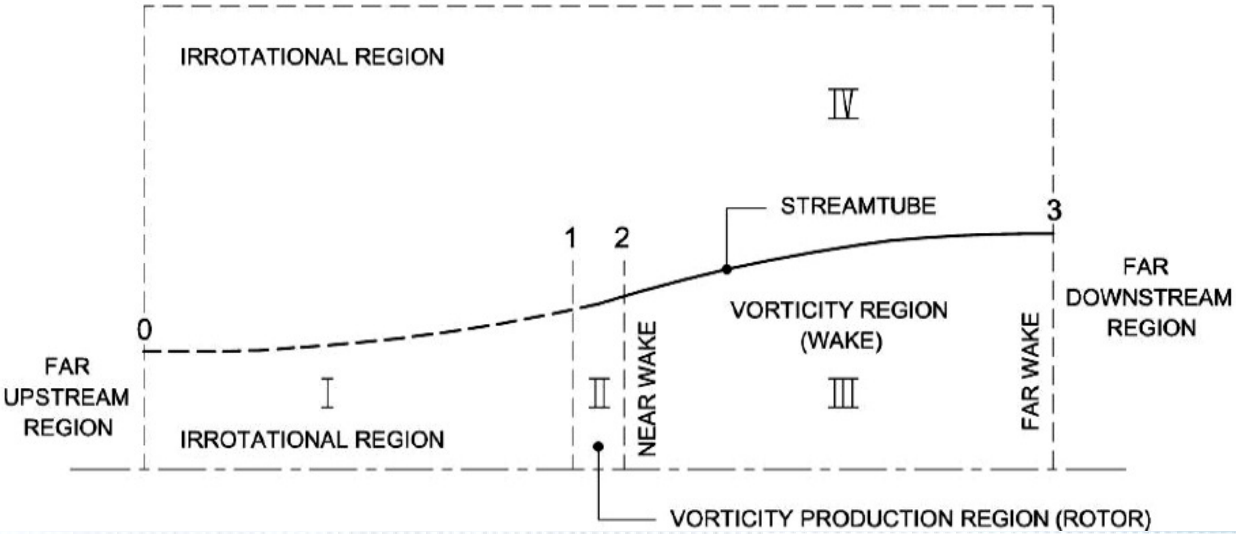
$$V_r\left(r,0\right) = -\frac{1}{r}\int_0^r \tilde{r}\frac{\partial V_z}{\partial z}\left(\tilde{r},0\right)d\tilde{r}$$

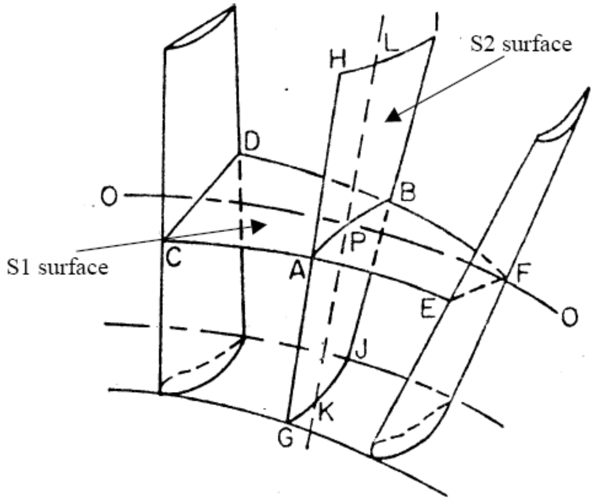
$$\partial V_z/\partial z\left(\tilde{r},0\right) = \frac{g_\theta}{2r} + \frac{g_\theta}{2\pi\left(r-\tilde{r}\right)}\tilde{r}$$

$$\partial V_z/\partial z\left(\tilde{r},0\right) = \frac{g_\theta}{2\pi\left(r-\tilde{r}\right)\tilde{r}^2} - \left(\frac{1}{4} - \frac{1}{2\pi}\right)\frac{g_\theta\left(r-\tilde{r}\right)^2}{\tilde{r}^5}$$



Part I : HAWT analysis
A turbomachinery approach



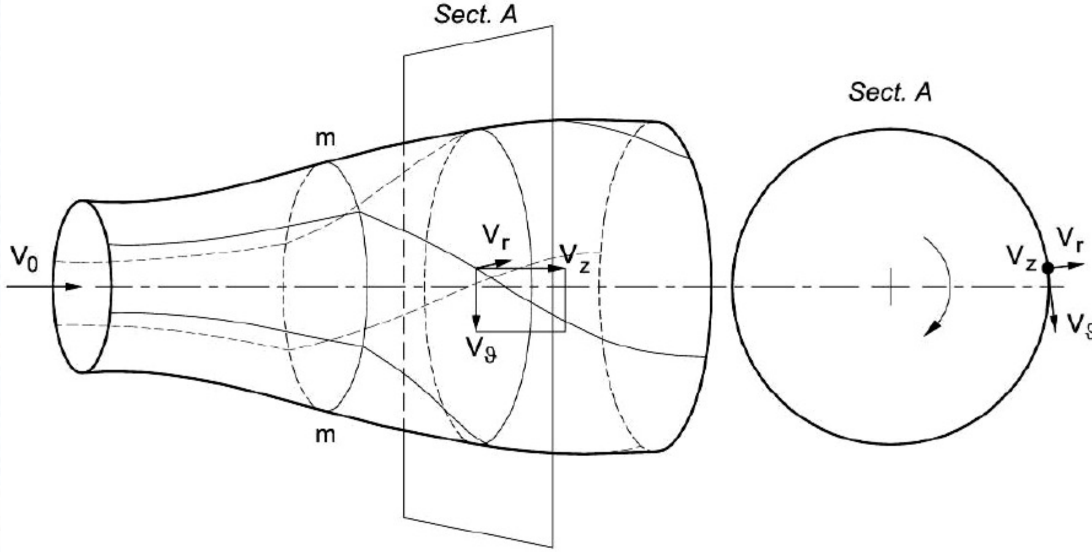


$$\frac{1}{\rho}\frac{\partial p^0}{\partial r} = F_r + \frac{V_\theta}{r}\frac{\partial r V_\theta}{\partial r} - V_z\left(\frac{\partial V_r}{\partial z} - \frac{\partial V_z}{\partial r}\right)$$

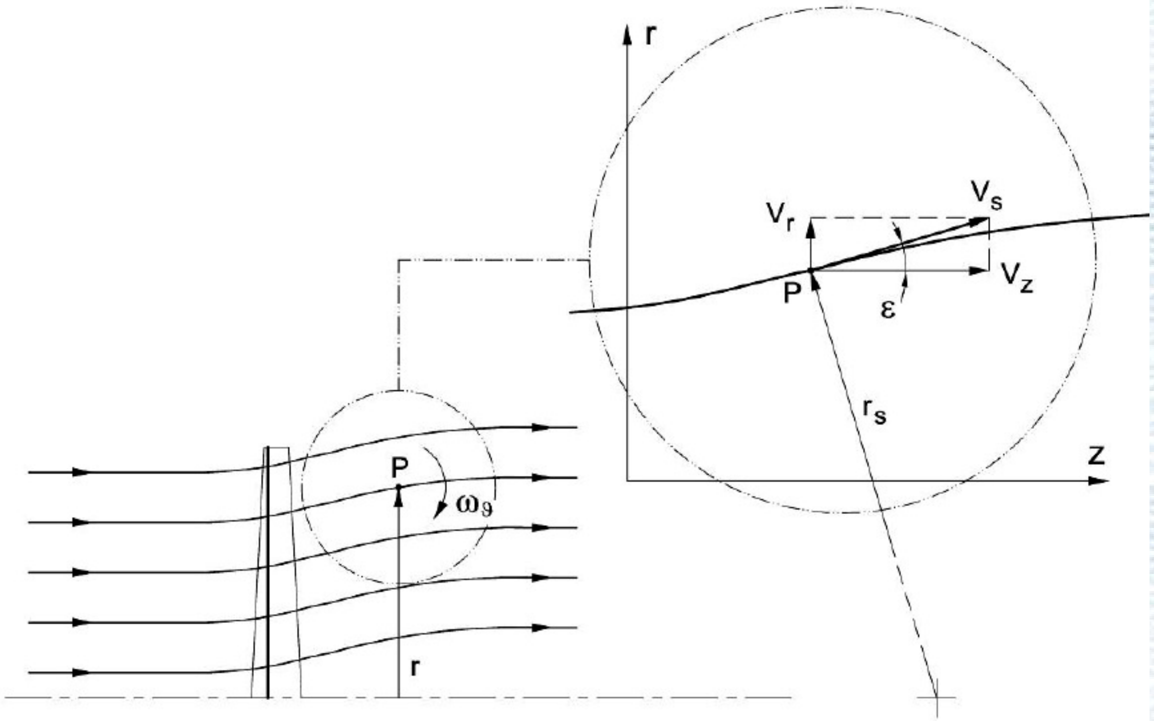
$$V_z\frac{\partial V_\theta}{\partial z} + \frac{V_r}{r}\frac{\partial r V_\theta}{\partial r} = F_\theta$$

$$\frac{1}{\rho}\frac{\partial p^0}{\partial z} = F_z + V_r\left(\frac{\partial V_r}{\partial z} - \frac{\partial V_z}{\partial r}\right) + V_\theta\frac{\partial V_\theta}{\partial z}$$

$$\frac{\partial r V_r}{\partial r} + \frac{\partial r V_z}{\partial z} = 0$$



A turbomachinery approach
Stoke's stream function



$$\omega_\theta = \frac{\partial V_r}{\partial z} - \frac{\partial V_z}{\partial r}$$

$$\frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial z^2} = -r\omega_\theta$$

$$\omega_\theta = V_\theta \frac{d(rV_\theta)}{d\psi} - \frac{r}{\rho}\frac{dp^0}{d\psi}$$

$$\frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial z^2} = 0$$

$$\frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial z^2} = -r\omega_\theta = -rV_\theta \frac{d(rV_\theta)}{d\psi} + \frac{r^2}{\rho}\frac{dp^0}{d\psi}$$

Linearized solution : Horlock actuator disk solution

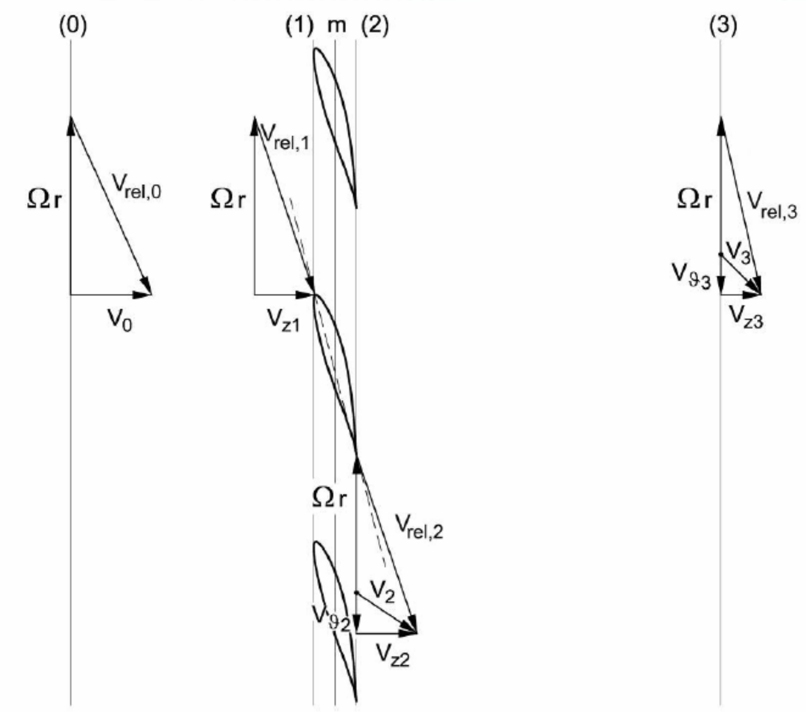
$$\frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial z^2} = -F(r)$$

$$V_z(r,z) = V_{z,0} + \left(\frac{V_{z,3} - V_{z,0}}{2}\right) e^{kz}$$

$$V_r(r,z) = -\frac{1}{r}\int_0^r k\tilde{r}\left(\frac{V_{z,3}(\tilde{r}) - V_{z,0}}{2}\right) e^{kz}\, d\tilde{r}$$

Froude result

A turbomachinery approach
Motion in region II



The flow is determined by

rV_θ p^0

Euler equation

$$\frac{1}{\rho}\left(p_2^0 - p_1^0\right) = \Omega r V_\theta = W_{eul}$$

Wu equation

$$\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{\partial^2\psi}{\partial z^2} = \left[-\frac{\left(p_2^0 - p_1^0\right)/\rho}{\Omega^2} + r^2\right]\frac{1}{\rho}\frac{dp_2^0}{d\psi} = \left(\Omega r^2 - rV_\theta\right)\frac{d\left(rV_\theta\right)}{d\psi}$$

The angular momentum distribution can be assigned

$$V_\theta = k_1 r^n + \frac{k_2}{r} \qquad rV_\theta = k_1 r^{n+1} + k_2$$

Free vortex distribution

$$rV_\theta = const$$

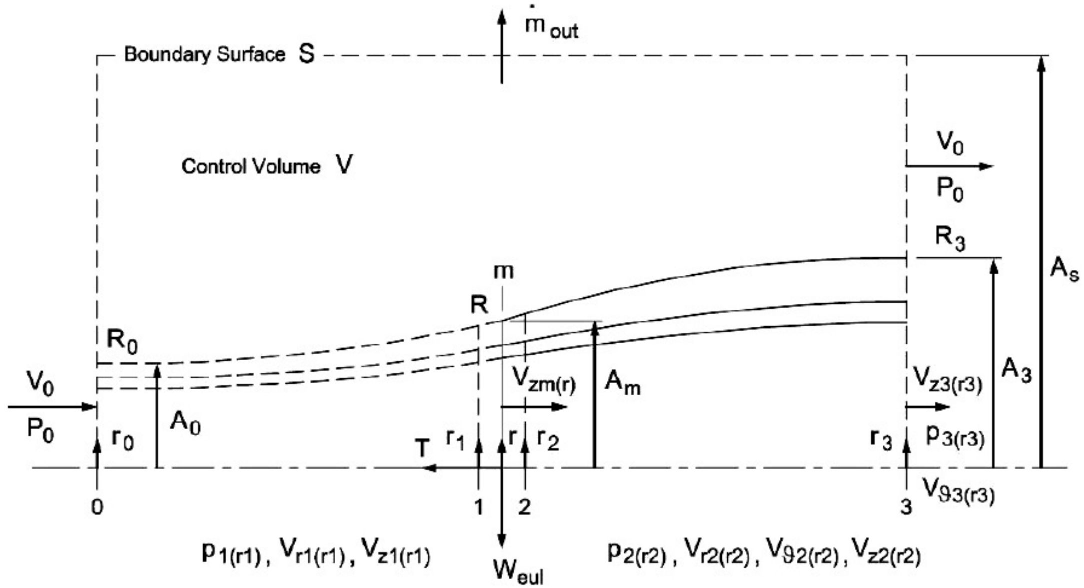
The radial equilibrium theory applied to wind turbines

Radial momentum equilibrium

$$\frac{1}{\rho}\frac{\partial p^0}{\partial r} = F_r + \frac{V_\theta}{r}\frac{\partial r V_\theta}{\partial r} - V_z\left(\frac{\partial V_r}{\partial z} - \frac{\partial V_z}{\partial r}\right)$$

$$\frac{1}{\rho}\frac{dp^0}{dr} = \frac{V_\theta}{r}\frac{d\left(rV_\theta\right)}{dr} + V_z\frac{dV_z}{dr}$$

ISRE



Sections 1 - 2

$$V_z^2 - V_{z,hub}^2 = \frac{2}{\rho}\left(p^0 - p^0_{r,hub}\right) - 2\int_{r,hub}^{r}\frac{V_\theta}{\tilde r}\frac{\partial r V_\theta}{\partial r}d\tilde r + 2\int_{r,hub}^{r} V_z\left(\frac{\partial V_r}{\partial z}\right)_\psi d\tilde r - \left(V_r^2 - V_{r,hub}^2\right)$$

Wu hypothesis

$$\frac{\partial V_{r,1}}{\partial z} = -\frac{\partial V_{r,2}}{\partial z}$$

$$\frac{1}{\rho}\frac{dp_2^0}{dr} = \frac{V_{\theta,2}}{r}\frac{d\left(rV_{\theta,2}\right)}{dr} + 2V_{z,m}\frac{dV_{z,m}}{dr}$$

Wu hypothesis on a streamline

$$\left(\frac{\partial V_{r,1}}{\partial z}\right)_\psi = -\left(\frac{\partial V_{r,2}}{\partial z}\right)_\psi$$

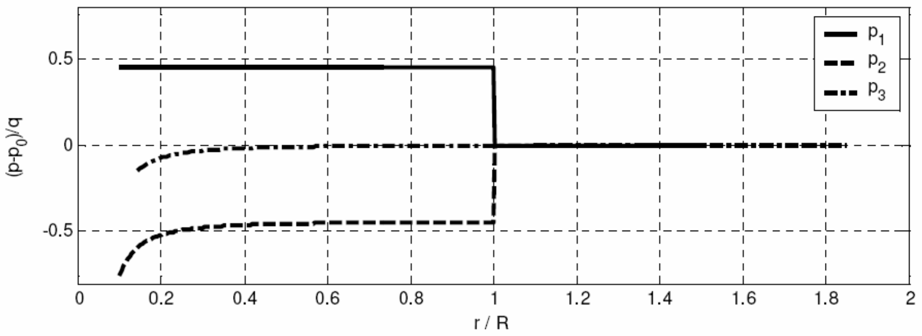
$$\frac{1}{\rho}\frac{dp_2^0}{dr} = \frac{V_{\theta,2}}{r}\frac{d\left(rV_{\theta,2}\right)}{dr} + 2V_{z,m}\frac{dV_{z,m}}{dr} + 2V_{r,m}\frac{dV_{r,m}}{dr}$$

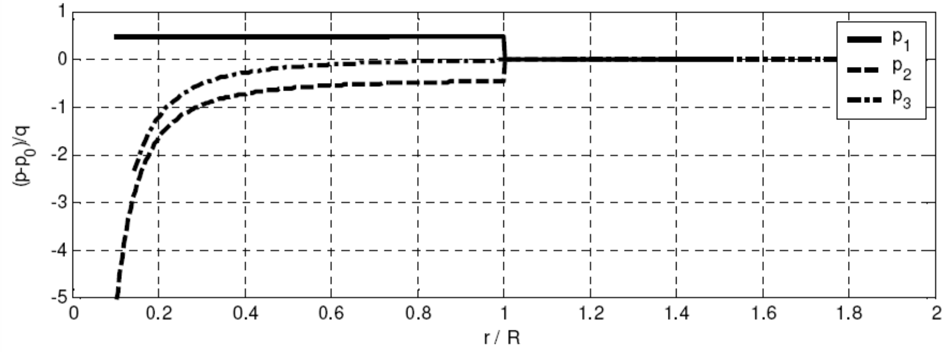
The radial equilibrium theory results and comments

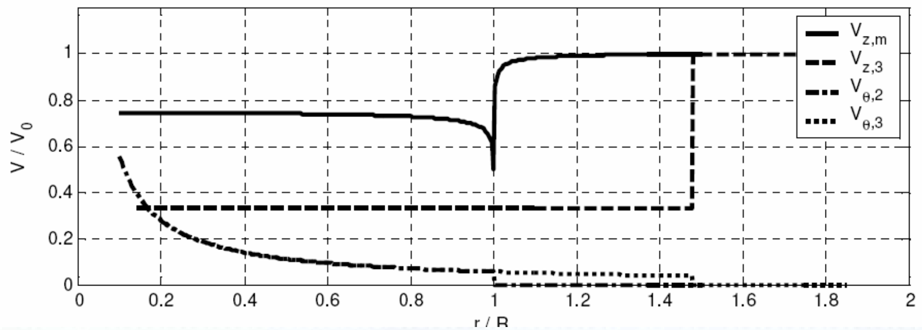
Radial equilibrium solution for a uniformly loaded disk

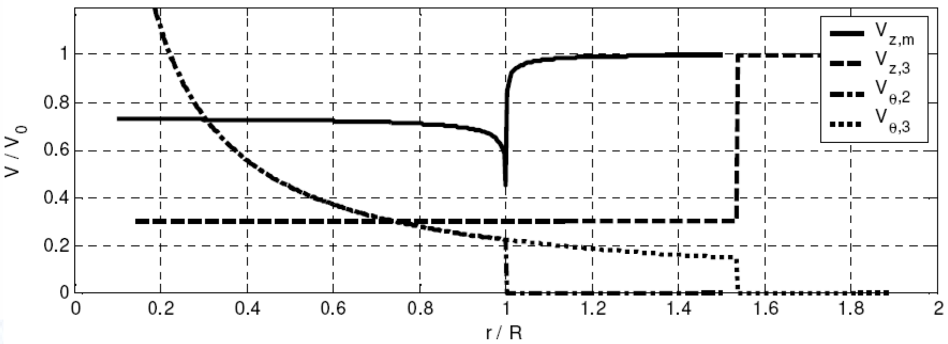
$\lambda = 8$ $\quad W_{eul} = \frac{8}{9} \cdot \frac{V_0^2}{2}$

$\lambda = 2$ $\quad W_{eul} = \frac{8}{9} \cdot \frac{V_0^2}{2}$

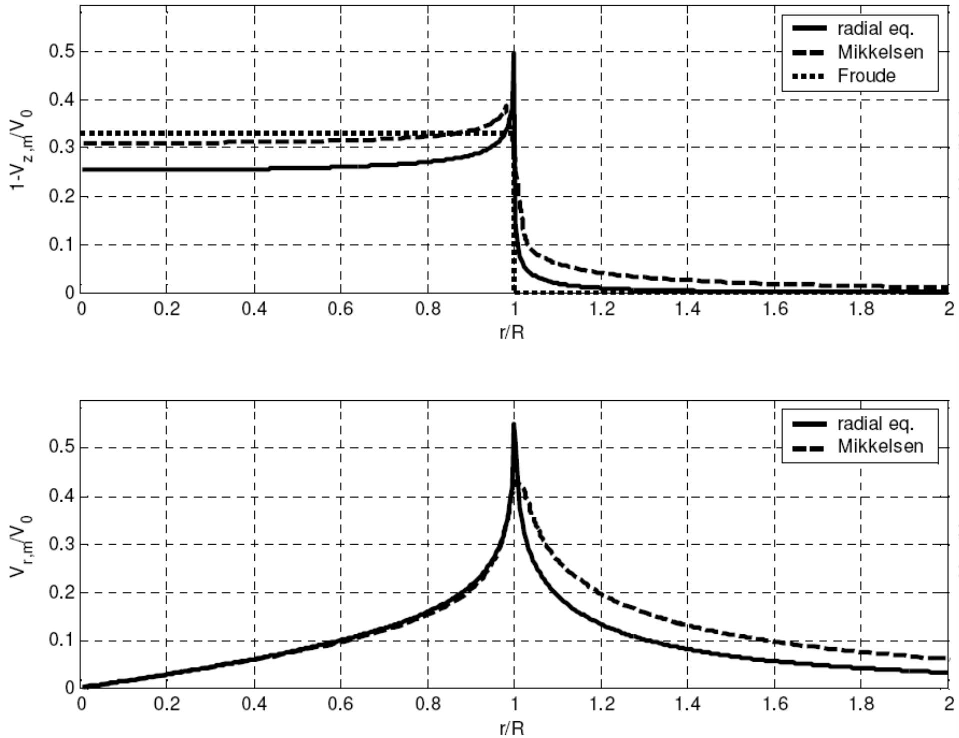


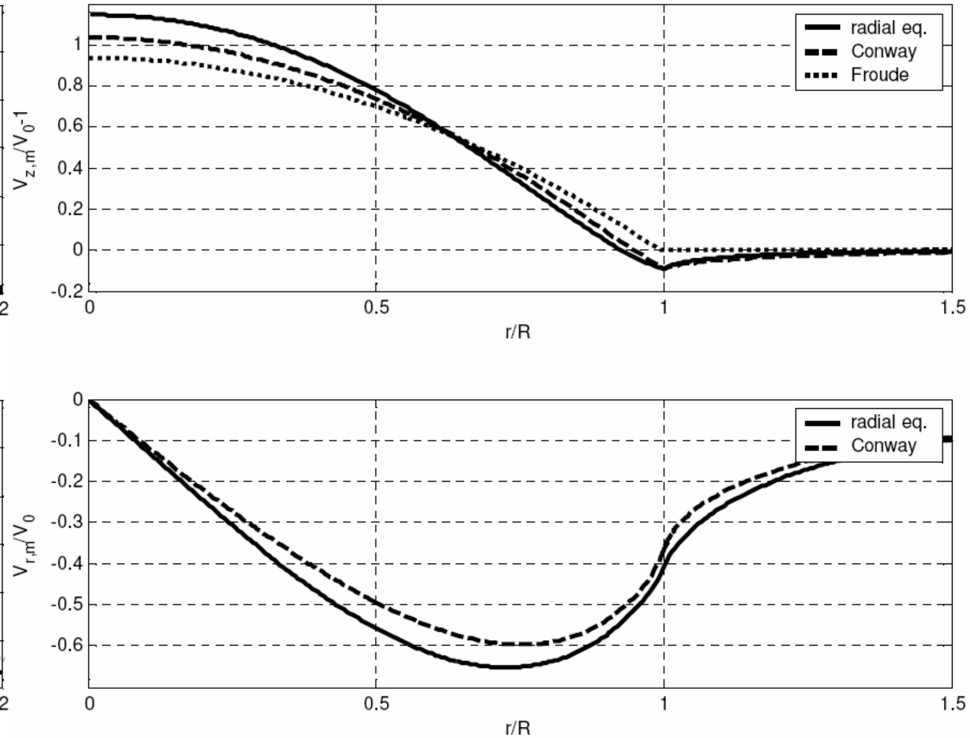






The radial equilibrium theory results and comments



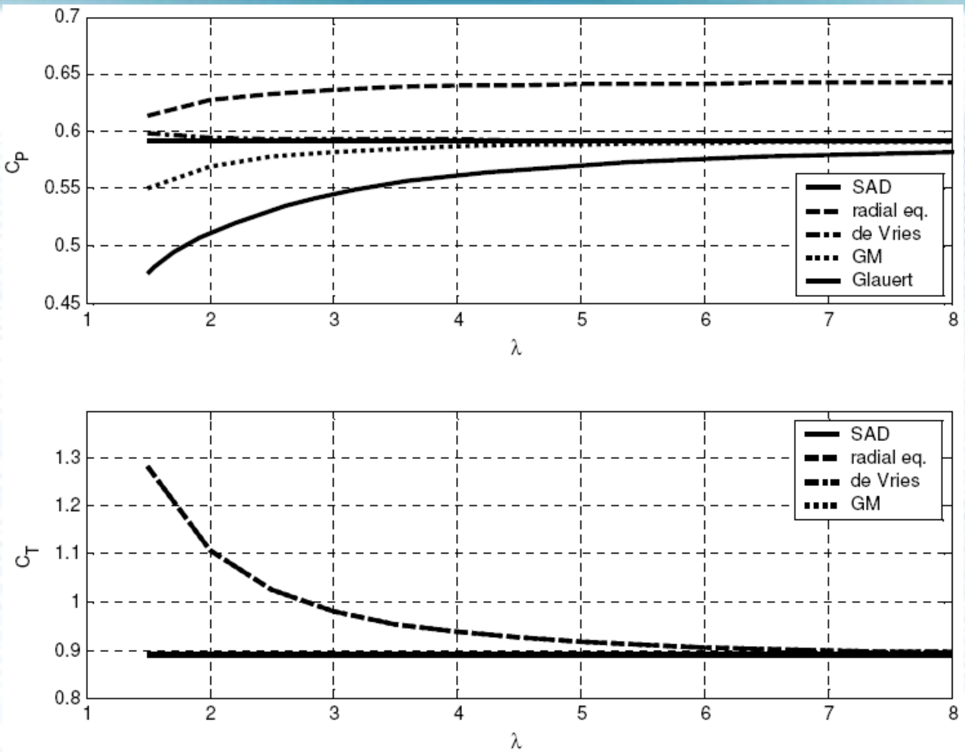


Mikkelsen actuator disk – CFD solution for a uniformly highly loaded disk (wind turbine state)

$$W_{eul} = \frac{8}{9} \cdot \frac{V_0^2}{2}$$

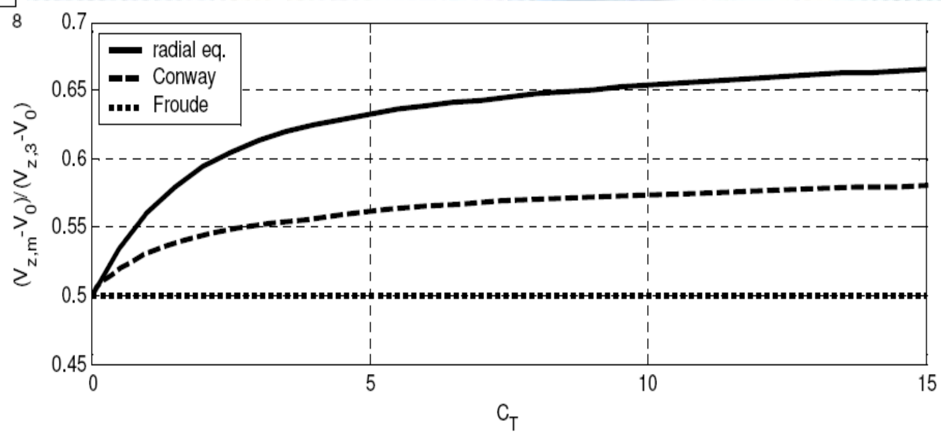
Conway actuator disk – vortex theory exact solution for a (almost) parabolic highly loaded disk (propeller state) C_T = 3.147

The radial equilibrium theory results and comments



Power and thrust coefficients for the different flow field solution models with a constant work extraction

Conway velocity at the centre of the disk for a propeller



The radial equilibrium theory on a streamline

Radial equilibrium with meridional velocity

$$\frac{1}{\rho}\frac{dp_2^0}{dr}=\frac{V_{\theta,2}}{r}\frac{d\left(rV_{\theta,2}\right)}{dr}+2V_{s,m}\frac{dV_{s,m}}{dr}$$

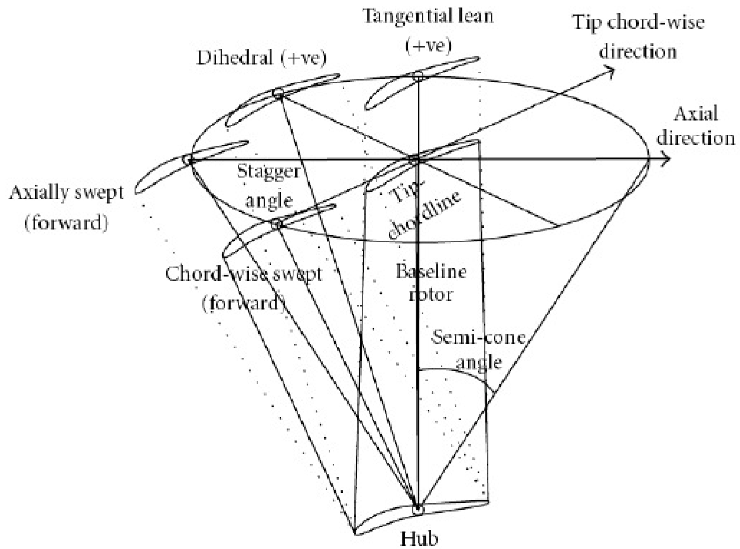
$$V_{s,m}^2=V_{z,m}^2+V_{r,m}^2$$

Denton / Cumpsty approach

$$\frac{1}{2}\frac{\partial}{\partial q}V_s^2=\frac{1}{\rho}\frac{\partial p^0}{\partial q}+V_s\frac{\partial V_s}{\partial s}\sin(\varepsilon+\delta)+\frac{V_s^2}{r_s}\cos(\varepsilon+\delta)-\frac{1}{2r^2}\frac{\partial}{\partial q}\left(r^2V_\theta^2\right)+\frac{V_s}{r}\frac{\partial}{\partial s}(rV_\theta)\tan\gamma+F_d$$

$$\frac{1}{2}\frac{\partial V_s^2}{\partial r}=\frac{1}{\rho}\frac{\partial p^0}{\partial r}+V_s\frac{\partial V_s}{\partial s}\sin\varepsilon-\frac{V_s^2}{r_s}\cos\varepsilon-\frac{1}{2r^2}\frac{\partial}{\partial q}\left(r^2V_\theta^2\right)$$

$$\frac{\partial V_{s,m}^2}{\partial r}=\frac{1}{\rho}\frac{\partial p_2^0}{\partial r}+2V_{r,m}\frac{\partial V_{s,m}}{\partial s}-V_{s,m}^2\cos\varepsilon\left(\frac{1}{r_{s,1}}+\frac{1}{r_{s,2}}\right)-\frac{1}{2r^2}\frac{\partial}{\partial q}\left(r^2V_\theta^2\right)$$



Coning / yaw effects
Turbulence wake state / stall

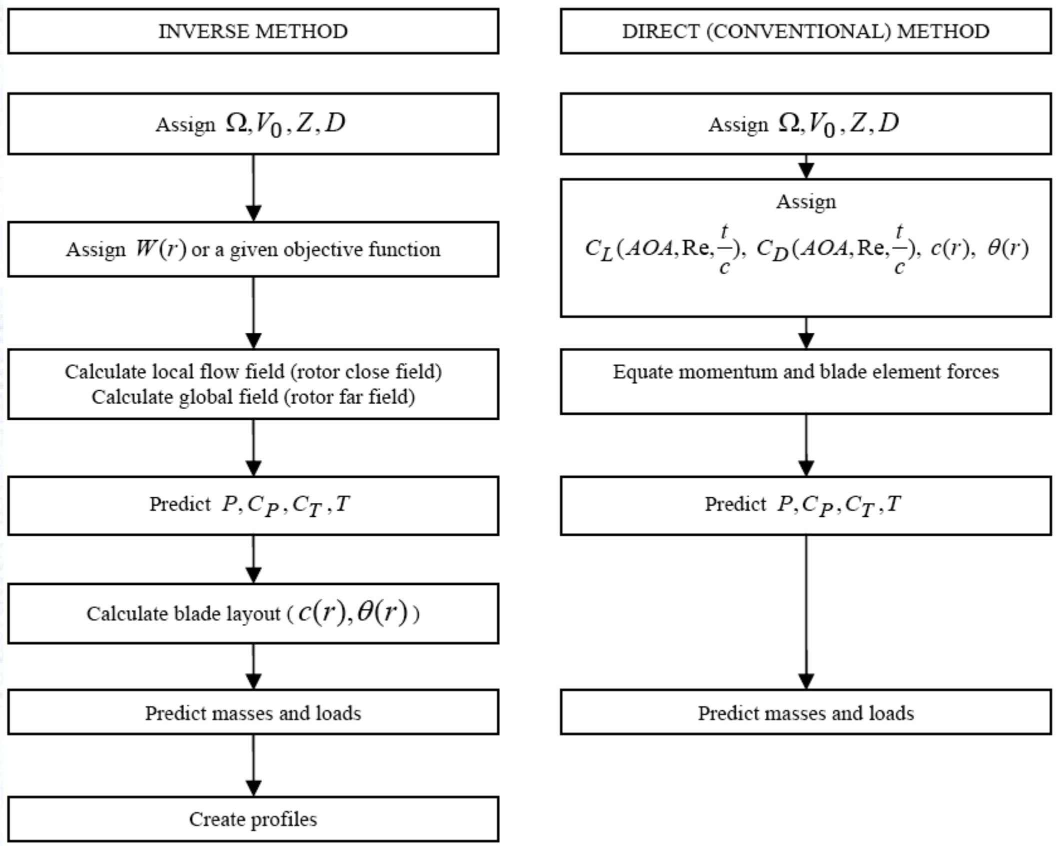
Tip effects
Unsteady dynamics

Considerations on the turbomachinery approach

- The theory handles an expanding and rotating wake.
- Only the disk station has to be solved to obtain the information needed to compute *CP* and *CT.*
- The method is simple and robust also for low tip speed ratios
- Arbitrary disk loading can be analyzed.
- The mathematics involved are comparable with those of the usual actuator disk approaches.
- The actual velocities distribution are qualitatively assessed even though more work has to be carried out to better understand the fluid flow in the neighborhood of the disk and in the wake.
- The radial velocity gradients along the streamlines at the disk have to be better described to reduce the axial velocity overestimation at the disk inner portion.

Part I : HAWT analysis
Inverse Design

Inverse design and direct design methods



The turbine close field structure
The blade architecture

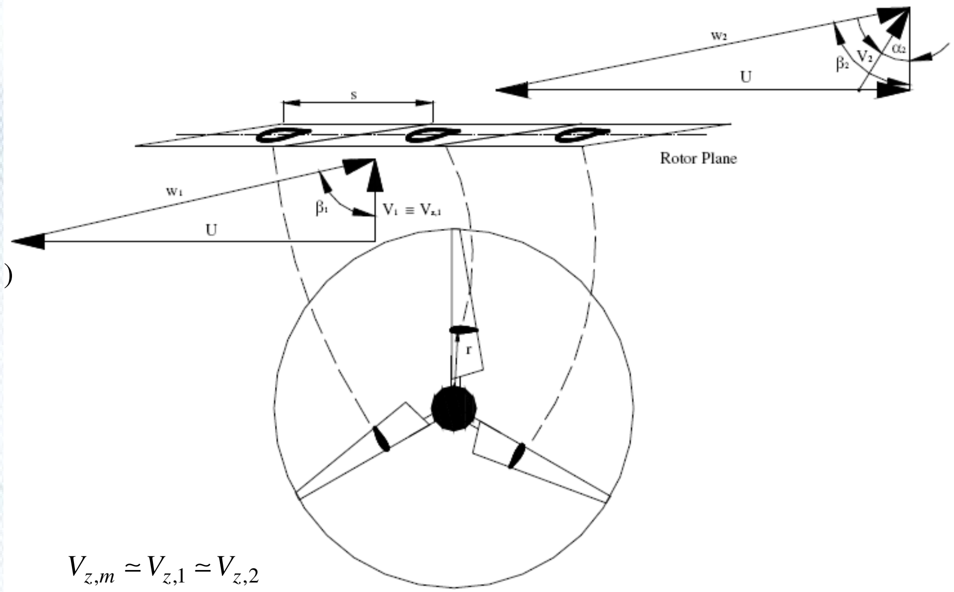
Blade forces

$$F_{\theta,Z} = \rho \cdot V_{z,m} \cdot s \cdot \left(V_{\theta,2} - V_{\theta,1}\right) = \rho \cdot V^2{}_{z,m} \cdot s \cdot \left(\tan\alpha_2 - \tan\alpha_1\right)$$

$$F_{z,Z} = (p_1^0 - p_2^0) \cdot s + \frac{1}{2}\rho \cdot V_{\theta,2}^2 \cdot s$$

$$W_{eul} = U \cdot \left(V_{\theta,2} - V_{\theta,1}\right) = U \cdot V_{z,m} \cdot (\tan\alpha_2 - \tan\alpha_1) = U \cdot V_{z,m} \cdot (\tan\beta_2 - \tan\beta_1)$$

$$W_{eul} = r\omega \cdot \left(k_1 r^n + \frac{k_2}{r}\right)$$



Flow angles

$$\beta_1 = \tan^{-1}\left(\frac{U + V_{\theta,1}}{V_{z,1}}\right) \qquad \beta_m = \tan^{-1}\left(\frac{U + V_{\theta,m}}{V_{z,m}}\right) \qquad \beta_2 = \tan^{-1}\left(\frac{U + V_{\theta,2}}{V_{z,2}}\right)$$

$$V_{z,m} \simeq V_{z,1} \simeq V_{z,2}$$

The blade architecture

$$C_y = \frac{F_y}{F_{y,\max}} = 2 \cdot \frac{s}{c_z}\left(\tan\beta_2 - \tan\beta_1\right)\cos^2\beta_2 \qquad c_z = c \cdot \cos\beta_m \qquad C_L = 2\frac{s}{c}(\tan\beta_2 - \tan\beta_1)\cos\beta_m$$

$$C_y = 0.8$$

Zweifel

$$\theta = \frac{\pi}{2} - \beta_m - \mathrm{sen}^{-1}\left(\frac{C_{L,ID}}{2\pi}\right)$$

$$D_{loc} = \frac{W_{\max} - W_2}{W_{\max}}$$

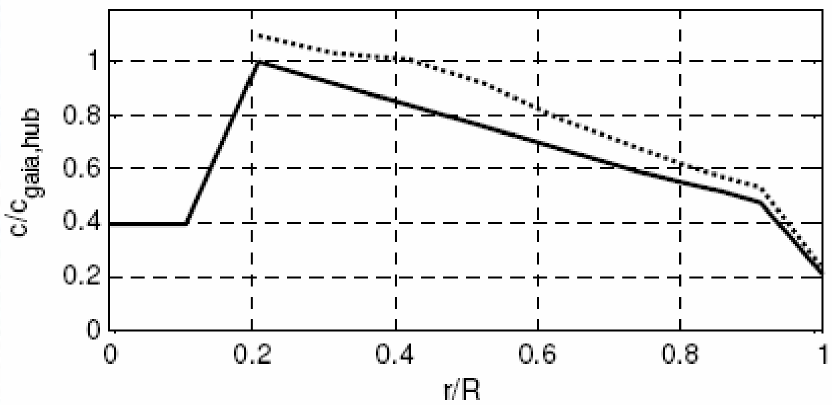
Lieblein

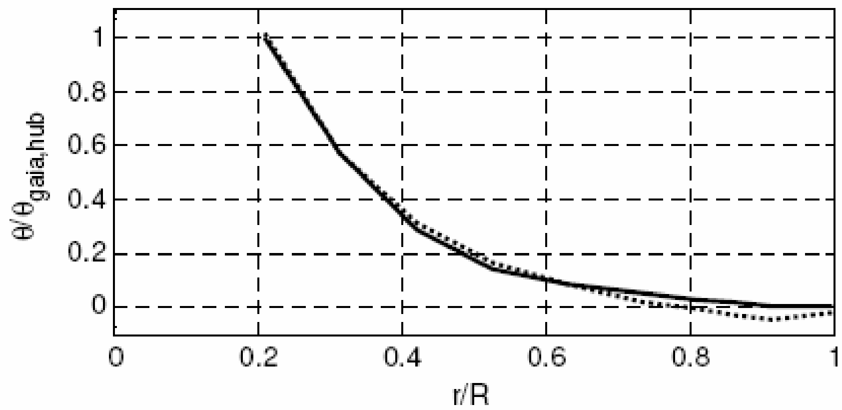
Inverse Design
Results and discussion

Gaia turbine

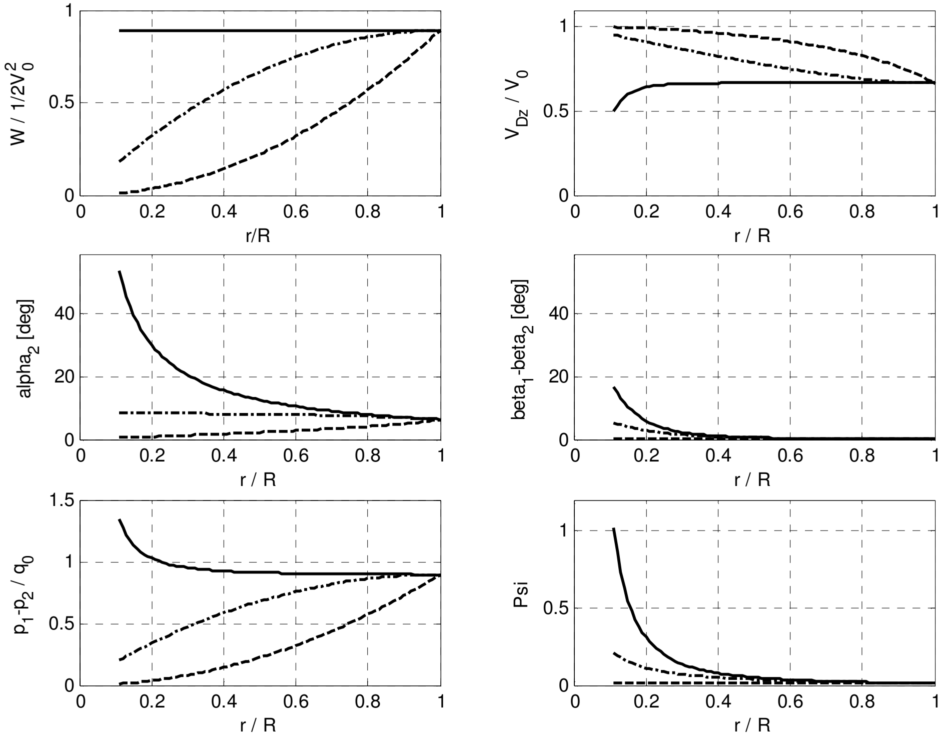
Table 4-2. Main characteristics of GAIA wind turbine.

Rated power	11 kW
Rotor diameter	13 m
Tower height	18.2 m
Rotors speed	56 rpm



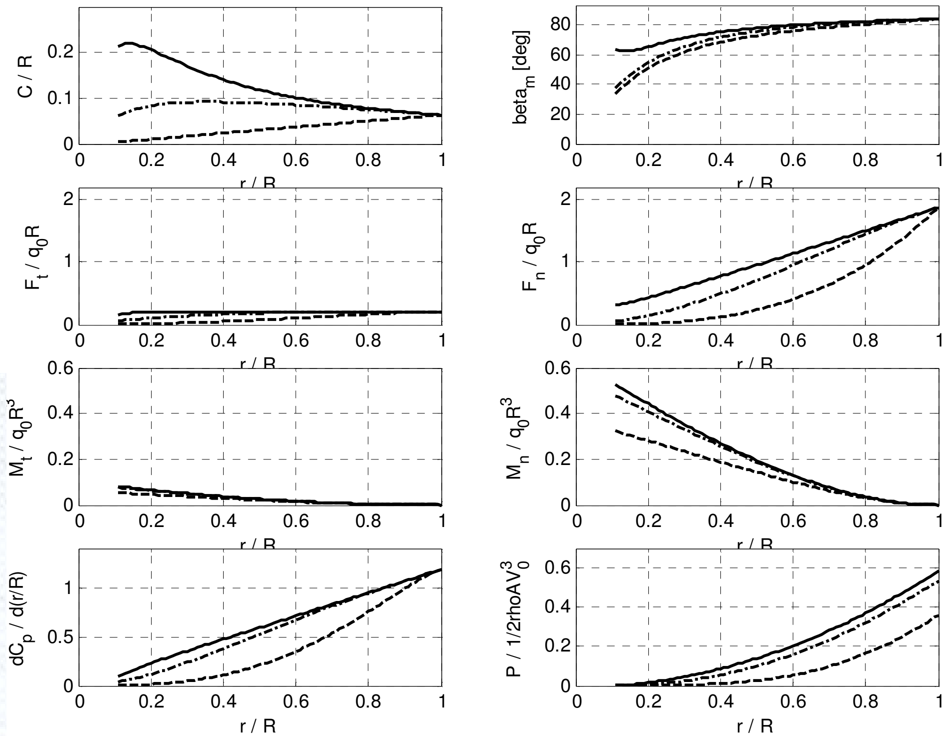


Inverse Design
Results and discussion



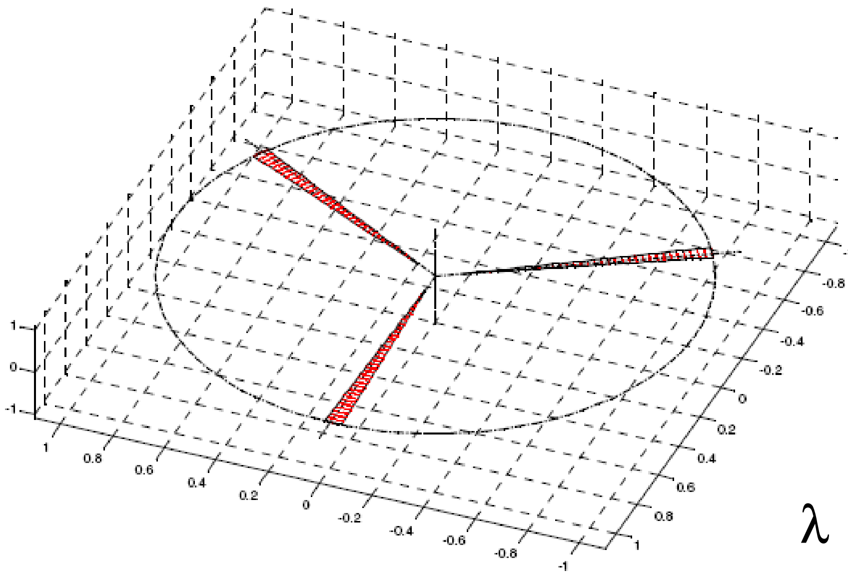
Flow characteristics

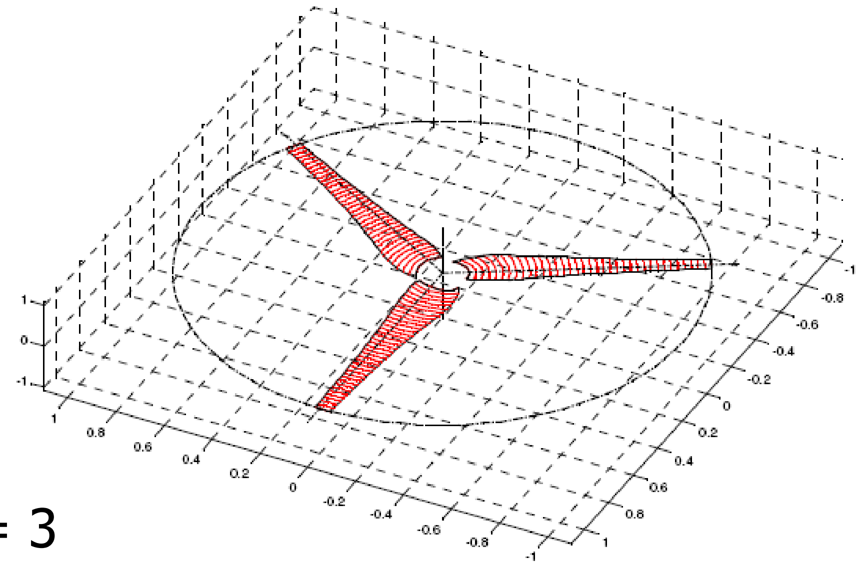
The blade architecture and loads



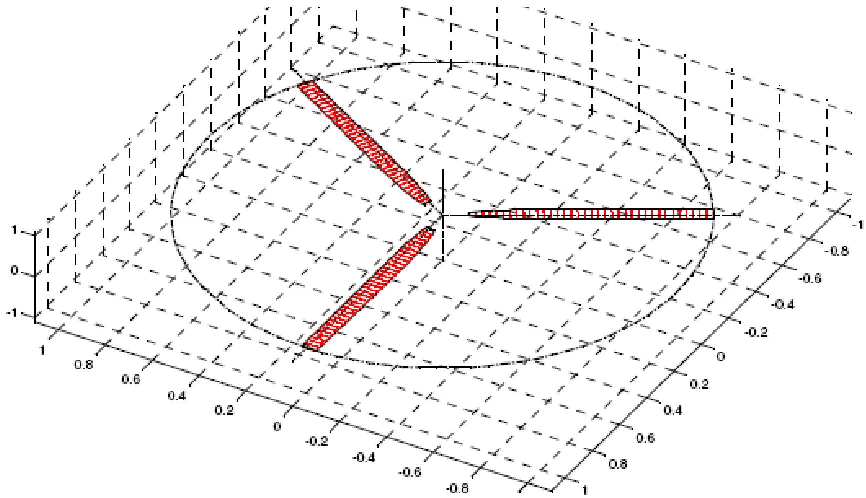
$\lambda = 6$, $Z = 3$

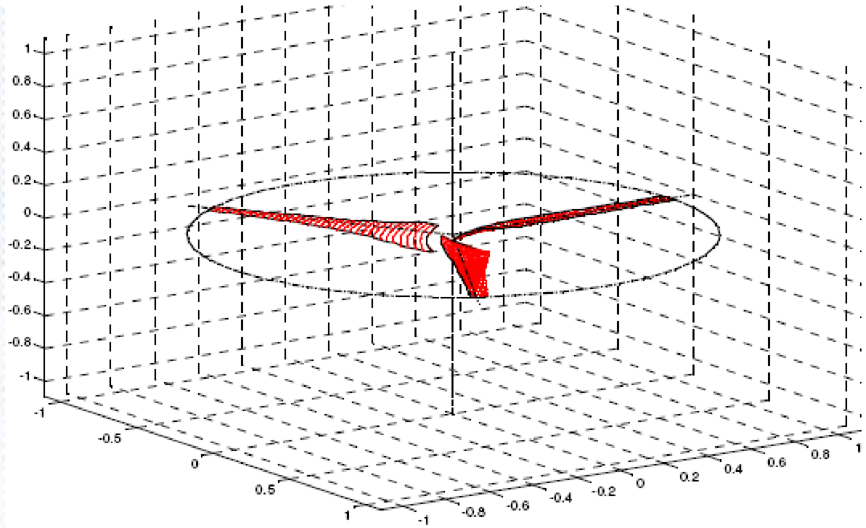
Inverse Design
Results and discussion



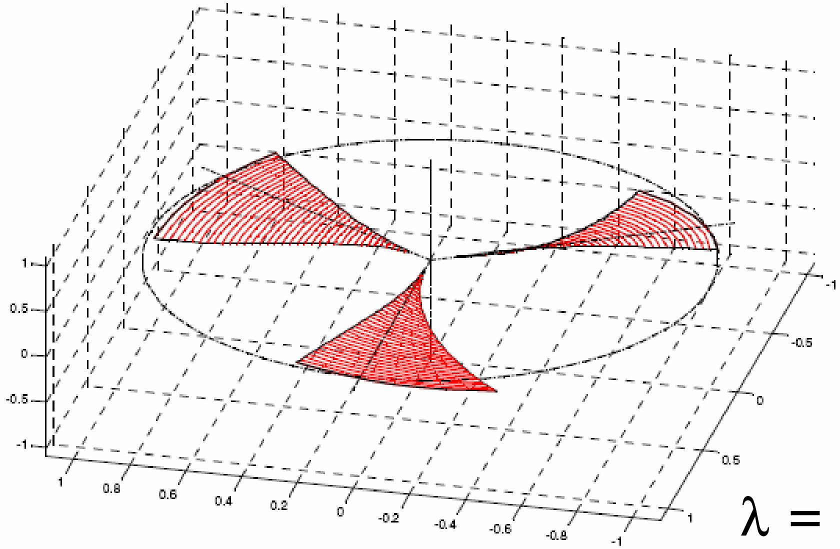


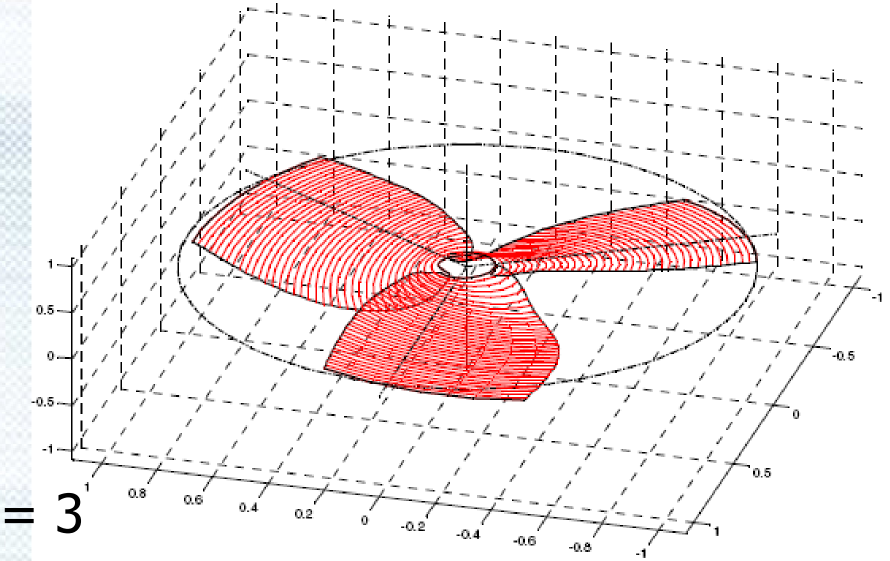
$\lambda = 6$, $Z = 3$



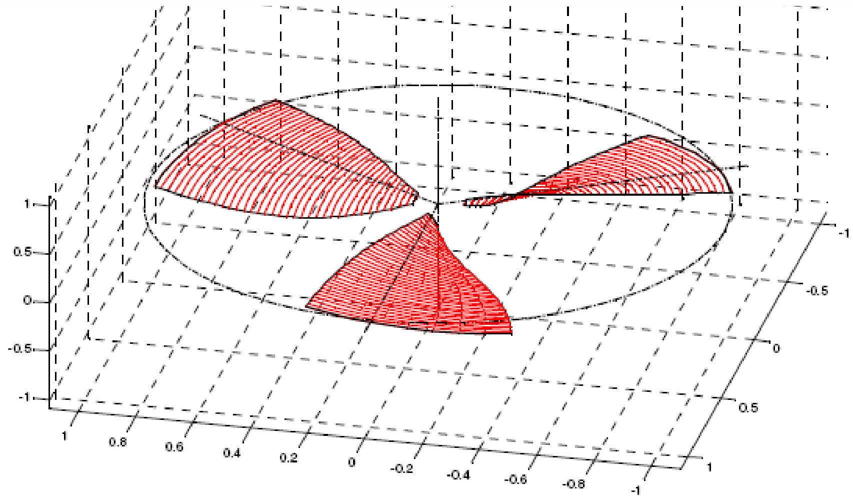


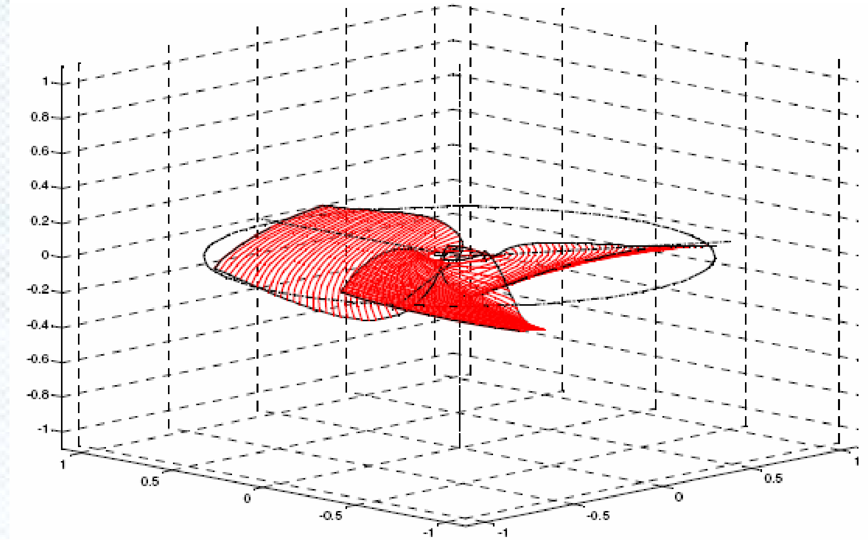
Inverse Design
Results and discussion





$\lambda = 1.5$, $Z = 3$



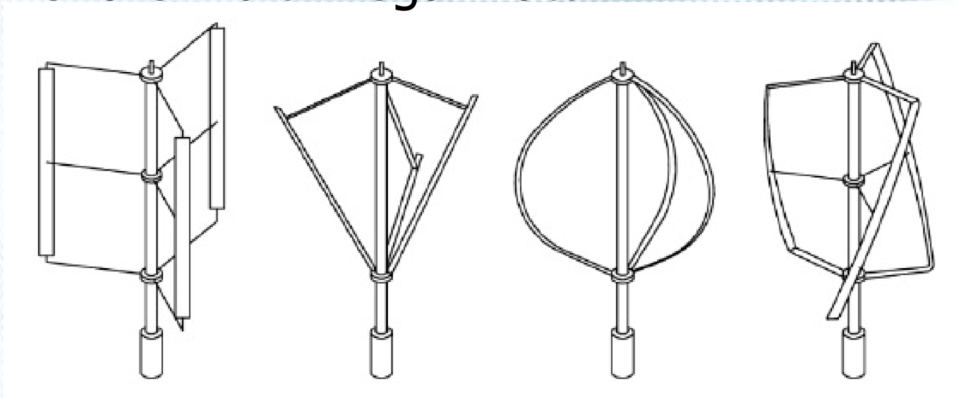


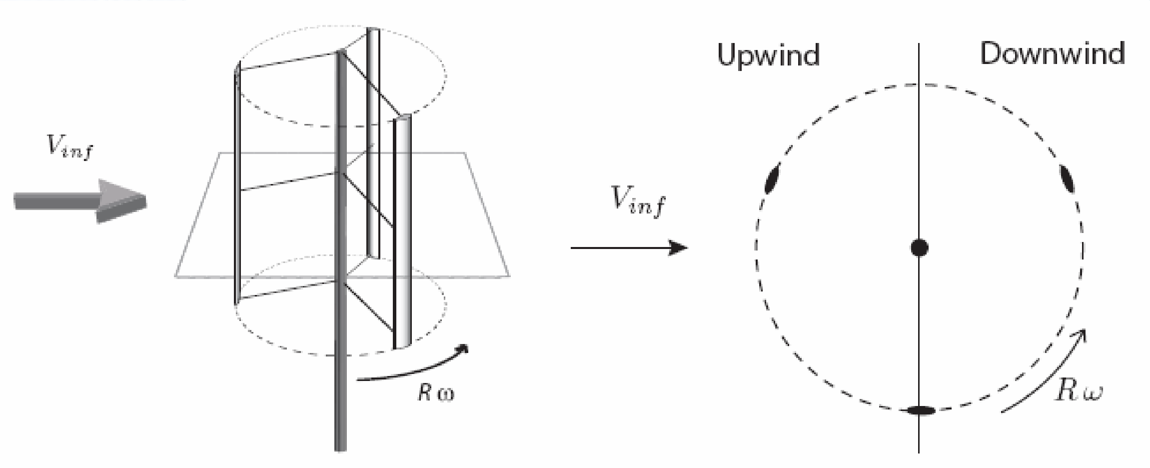
Part II : VAWT analysis
VAWT fluid dynamics

Darrieus eggbeater – Darrieus H/V – Gorlov type

Building environment

Offshore multi Mega Watt





$C_L = \frac{dL}{\frac{1}{2}\rho_0 W^2 c\, dh}$

VAWT fluid dynamics
The double disk BEM for VAWT

Flow characteristics

$$\beta = \tan^{-1}\frac{V \operatorname{sen}\vartheta \cos\delta}{(V\cos\vartheta + \Omega r)\cos\gamma}$$

$$W^2 = \left[(V\cos\vartheta + \Omega r)\cos\gamma\right]^2 + (V \operatorname{sen}\vartheta\cos\delta)^2$$

$$Re = \frac{cW}{\nu_0}$$

$$C_L = \frac{dL}{\frac{1}{2}\rho_0 W^2 c\, dh} \qquad C_D = \frac{dD}{\frac{1}{2}\rho_0 W^2 c\, dh}$$

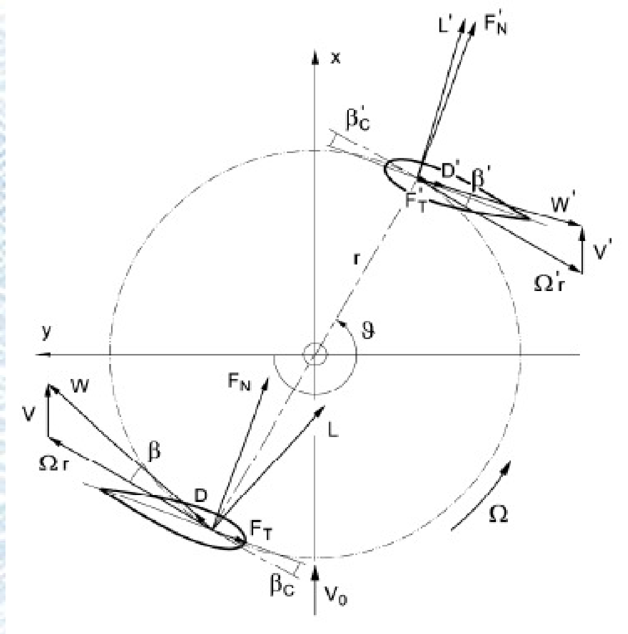
Blade element forces

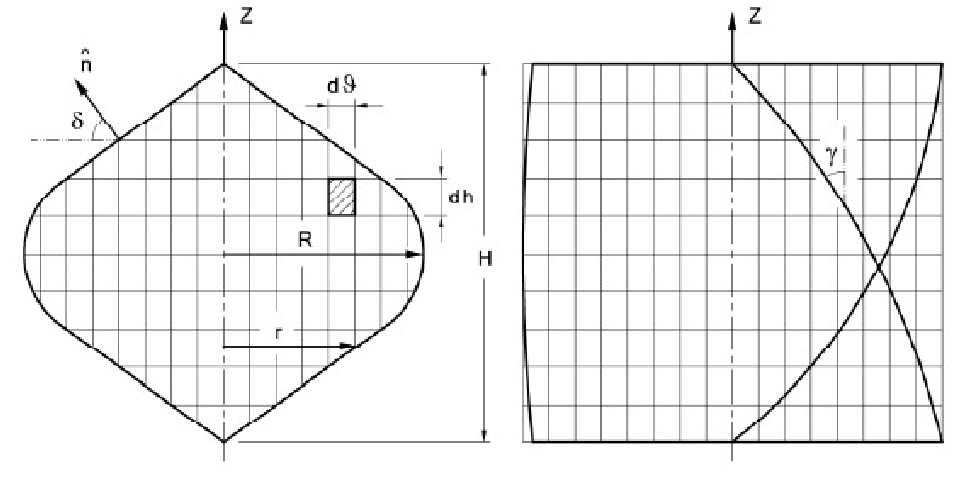
$$C_N = C_L \cos\beta + C_D \sin\beta$$

$$C_T = C_L \sin\beta - C_D \cos\beta$$

$$dF_N = \frac{1}{2}\rho_0 W^2 c \frac{dh}{\cos\delta} C_N$$

$$dF_T = \frac{1}{2}\rho_0 W^2 c \frac{dh}{\cos\delta} C_T$$





Shaft torque/power

$$dM = dF_T\, \Omega$$

$$C_P = \frac{\overline{M}\,\Omega}{\frac{1}{2}\rho_0 A_{sw} V_0^3} = \frac{\frac{1}{N_\vartheta}\int^{N_\vartheta}\int^{B}\int^{L} dM\,\Omega}{\frac{1}{2}\rho_0 A_{sw} V_0^3}$$

VAWT fluid dynamics
The double disk BEM for VAWT

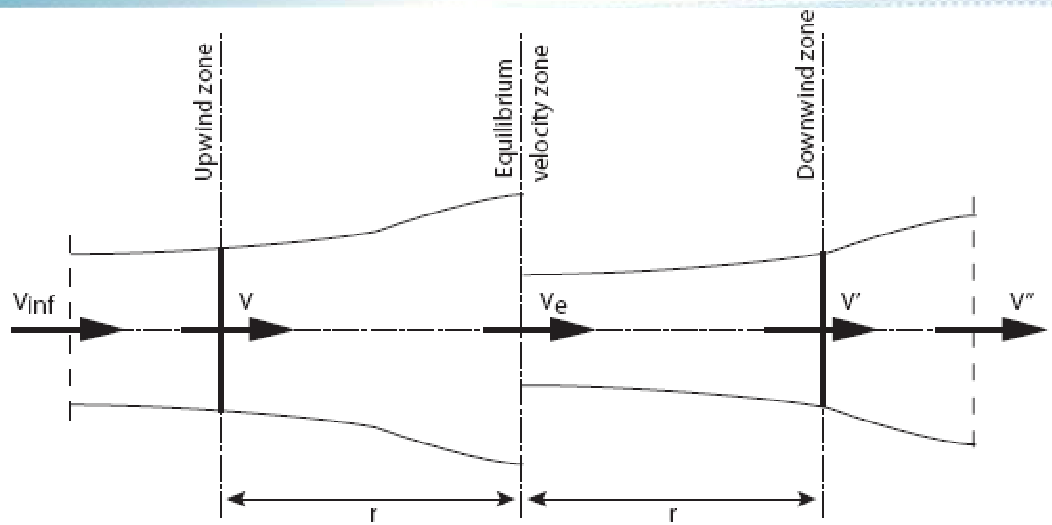
Blade element

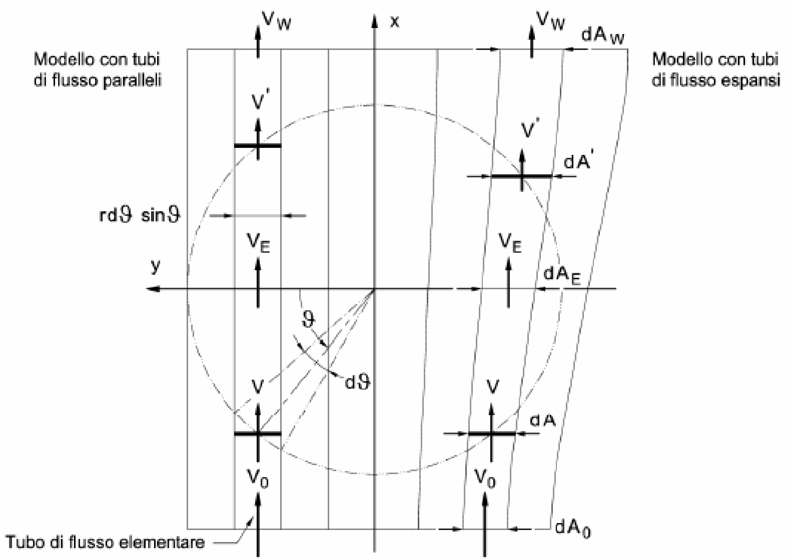
$$dF_x = dF_T \cos\vartheta \cos\beta_c \cos\gamma + dF_N \sin\vartheta \cos\delta$$

$$\overline{dF_x} = B\, 2\frac{\Delta\vartheta}{\pi}\, dF_x$$

$$C_{TH} = \frac{\overline{dF_x}}{\frac{1}{2}\rho_0 V_0^2 dA_s}$$

$$dA_s = dh\, r\, d\vartheta\, \sin\vartheta$$





Momentum theory

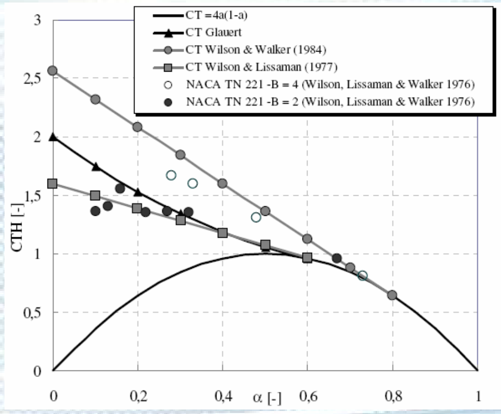
$$\alpha = \frac{V}{V_0}$$

$$dF_x = 2\rho\, dA_s V(V_0 - V)$$

$$C_{TH} = \frac{dF_x}{\frac{1}{2}\rho V_0^2 dA_s} = \frac{2\rho\, dA_s V(V_0 - V)}{\frac{1}{2}\rho V_0^2 dA_s} = 4\alpha(1-\alpha)$$

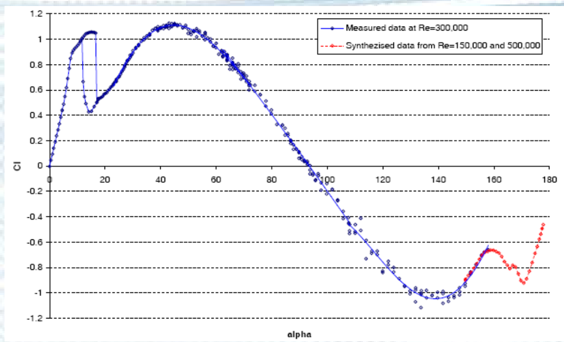
The double disk BEM for VAWT Corrections

Glauert correction $C_{TH} = \frac{26}{15}(1-\alpha) + \frac{4}{15}$

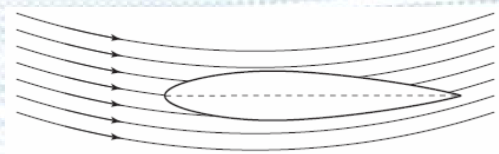


Tip losses

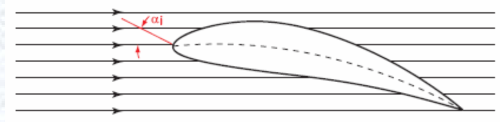
Post stall airfoil performance correction



Flow curvature



Dynamic stall

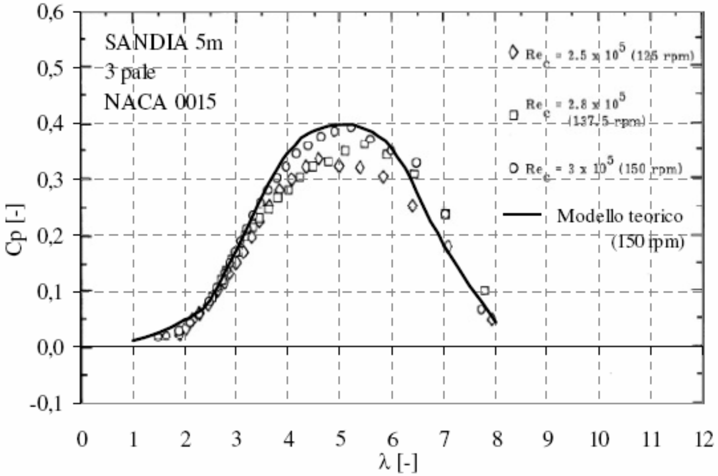


Streamtubes expansion

VAWT fluid dynamics
Validation and results

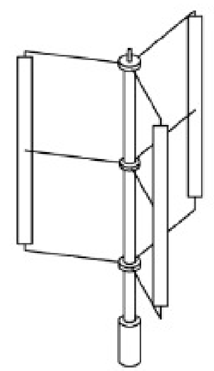
Sandia 5m
Darrieus
3blades
NACA0015

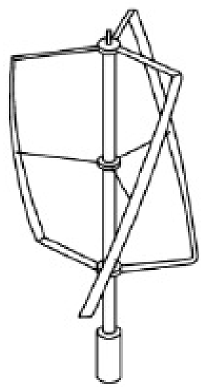
H	5,1 m
D	5,0 m
c	0,152 m
Airfoil	NACA0015
Solidity	0,1



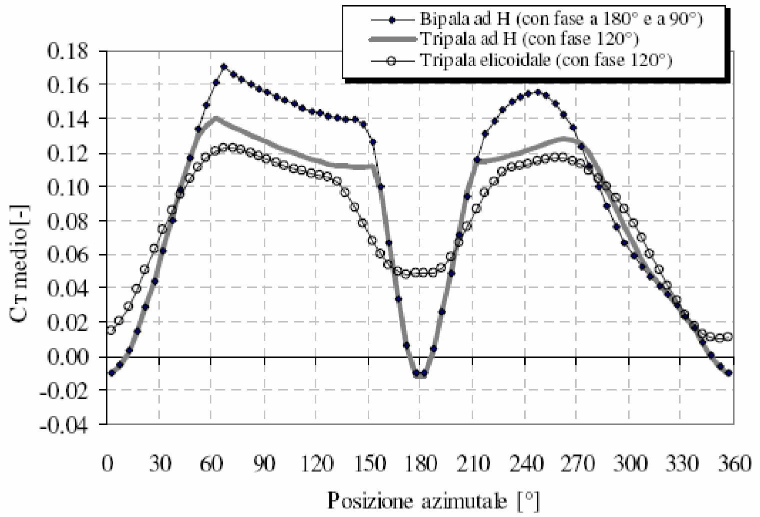
Four geometric characteristics

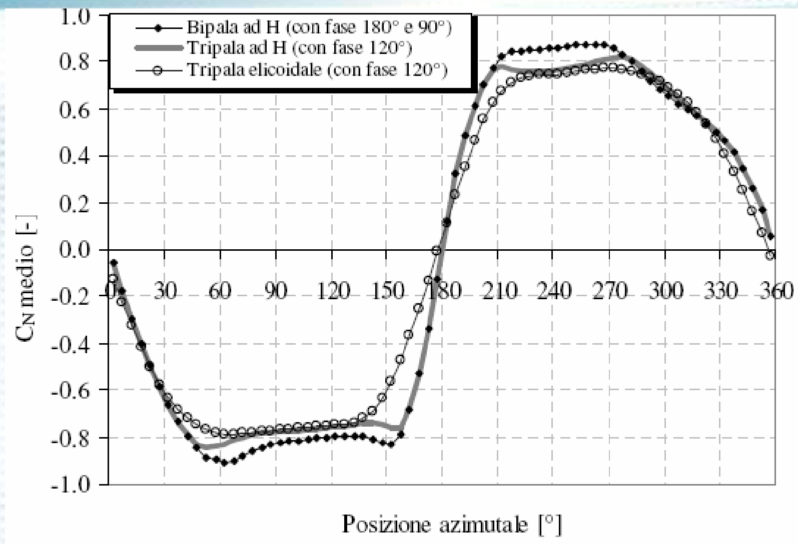
	A	B	C	D
H	2,5 m	2,5 m	2,5 m	2,5 m
D	1,8 m	1,8 m	1,8 m	1,8 m
c	0,148 m	0,148 m	0,099 m	0,092 m
Airfoil	NACA0018	NACA0018	NACA0018	NACA0018
Blade geometry	Straight blade ($\gamma = 0°$)	Straight blade ($\gamma = 0°$)	Straight blade ($\gamma = 0°$)	Helicoidal blade ($\gamma = 20{,}51°$)
Blades number	2	2	3	3
Blades spacing	180°	90°	120°	120°
Solidity	0,166	0,166	0,166	0,166





VAWT fluid dynamics
Validation and results





Blade tangential and normal force coefficients

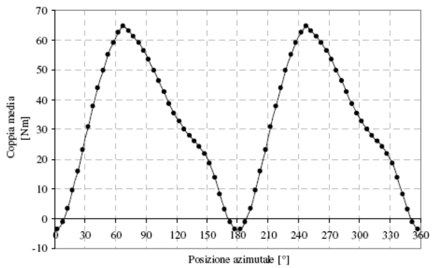
Shaft forces and torque
Mean value and fluctuations

	A	B	C	D
Torque $_{mean}$	32,14 Nm	32,14 Nm	28,83 Nm (-10%)	27,19 Nm (-15%)
R $_{Torque}$	2,13	0,97 (-54%)	0,57 (-73%)	0,32 (-82%)
Fx $_{mean}$	204 N	204 N	194 N (-5%)	193 N (-5%)
R $_{Fx}$	1,80	0,42 (-77%)	0,35 (-80%)	0,35 (-80%)
Fy $_{mean}$	-24,4 N	-24,4 N	-20,0 N (-18%)	-16,2 N (-34%)
R $_{Fy}$	-19,5	-9,3 (-52%)	-4,7 (-76%)	-3,9 (-80%)

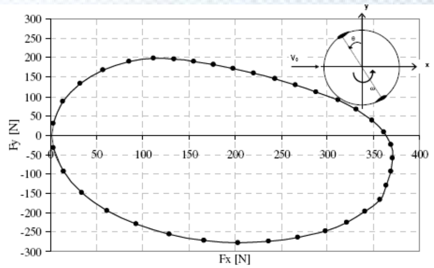
$$R = \frac{Value_{max} - Value_{min}}{Value_{mean}}$$

VAWT fluid dynamics
Validation and results

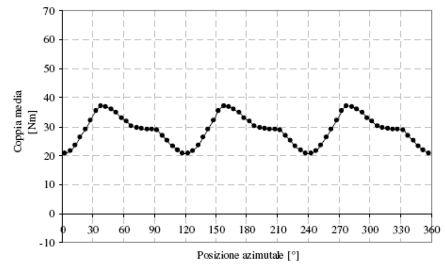
Shaft torque and forces diagrams



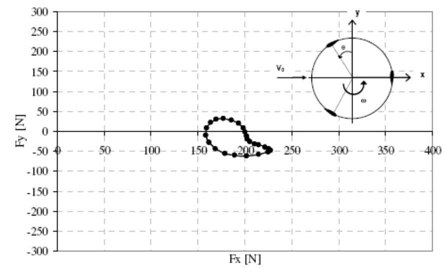
A1



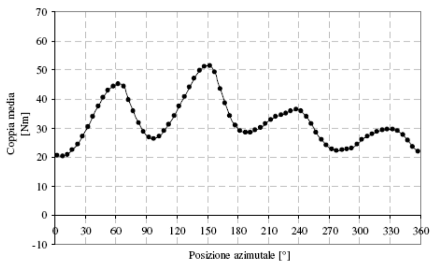
A2



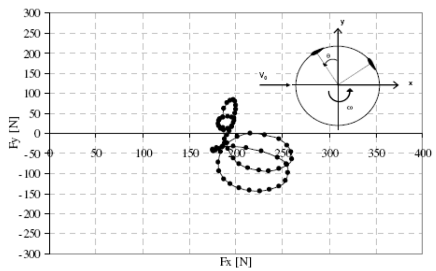
C1



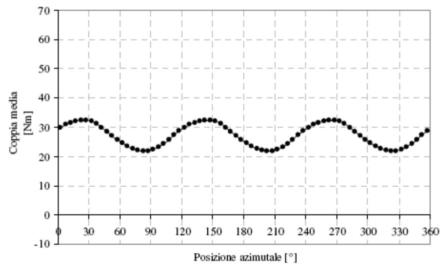
C2



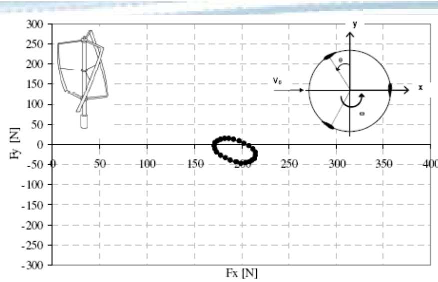
B1



B2



D1



D2

2-bladed presents the best power performance
3-bladed presents lower forces fluctuations
3-bladed Gorlov type presents the lowest fatigue loads (complex geometry)
2-bladed a 90° reduces the loads fluctuations but needs rotor balancig

VAWT fluid dynamics
Limitations of VAWT BEM codes

- The circular path is simplified in two actuator disks
- The momentum equilibrium is applied only in axial direction
- The axial expansion is generally neglected or not correctly/completely implemented
- The turbulent wake state correction is taken from HAWT corrections
- No (or weak) interaction between streamtubes
- Tip losses correction is of doubtful application for VAWT
- Complex geometry not resolvable from a fluid dynamic point of view
- Unsteady fluid dynamic effects are of difficult implementation

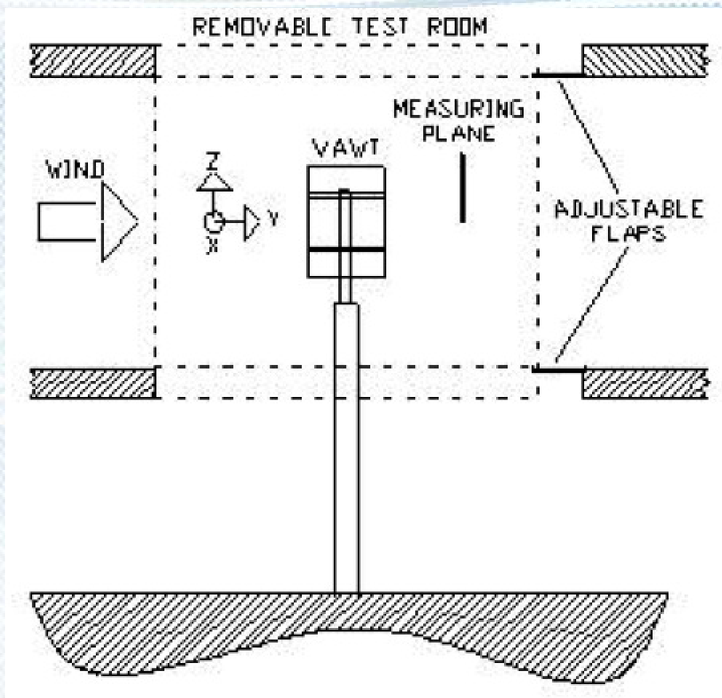
Part II : VAWT analysis
VAWT experimental analysis

VAWT experiments in controlled conditions

The Politecnico di Milano Large Wind Tunnel

High speed test section: 4x3.84m
Wind speed up to 55m/s
Possibility to work in open/close test section

2 different rotor prototypes designed by Tozzi Nord Wind Turbines:
PDF1 – research purpose
PDF3 – commercial turbine



The turbines layout and the instrumentations

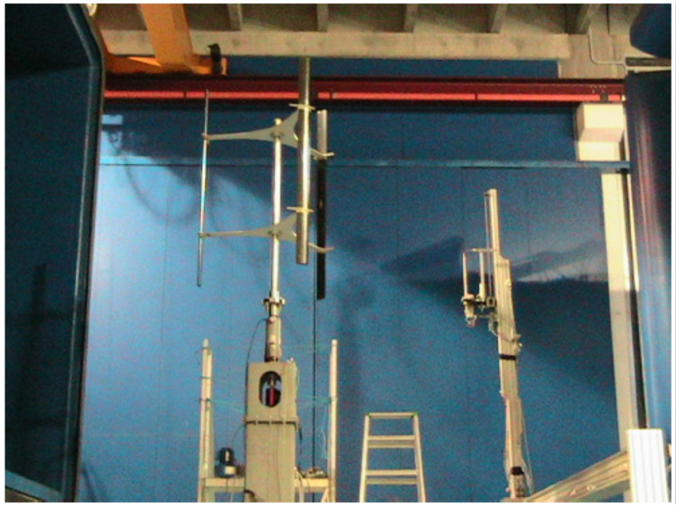
PDF1
3 Blades
H = 1.46m
D = 1.03m
NACA0021
Solidity 0.25
Rotor position
Torque
Support loads

PDF3
3 Blades - Gorlov
H = 2.5m
D = 1.78m
P = 1.5kW
H(tower) = 3.5m
Rotor position
Torque (electric)
Support loads

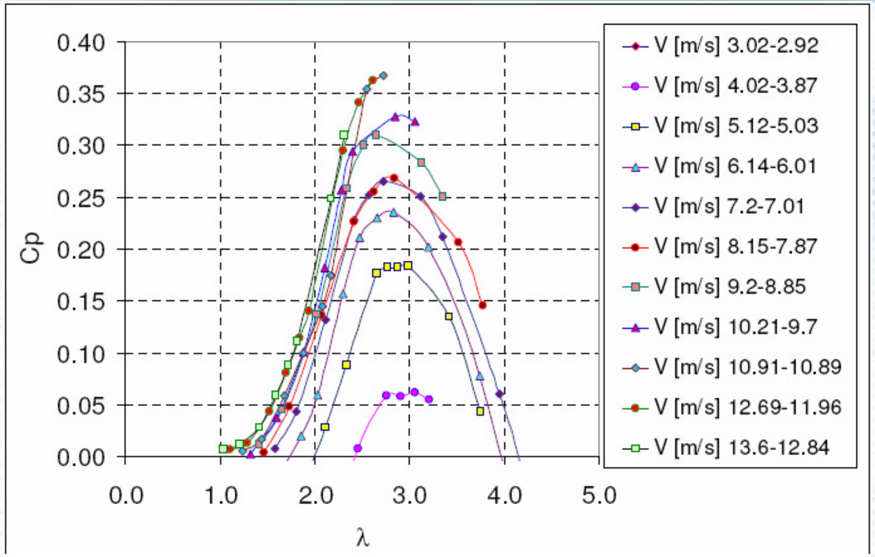
Aerodynamics

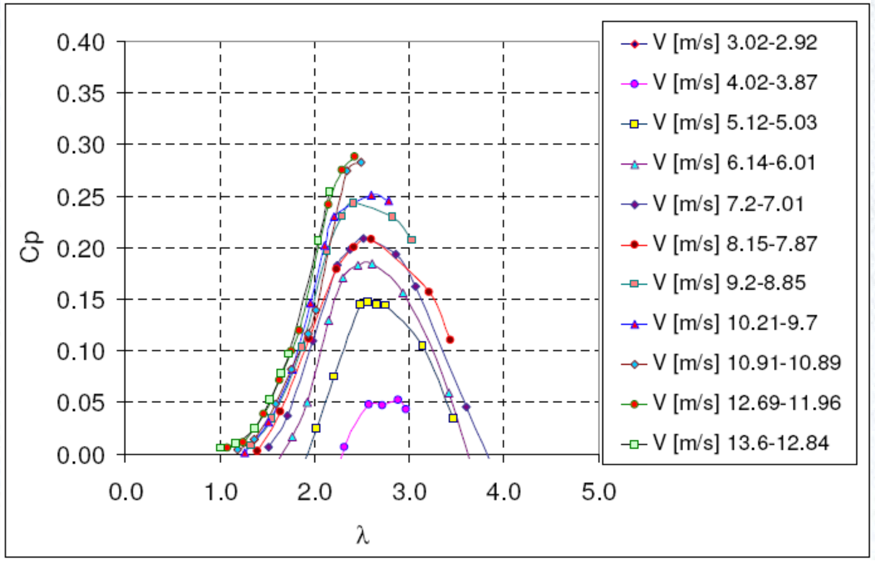
Directional pneumatic 5 holes probe

Single sensor hot wire anemometer



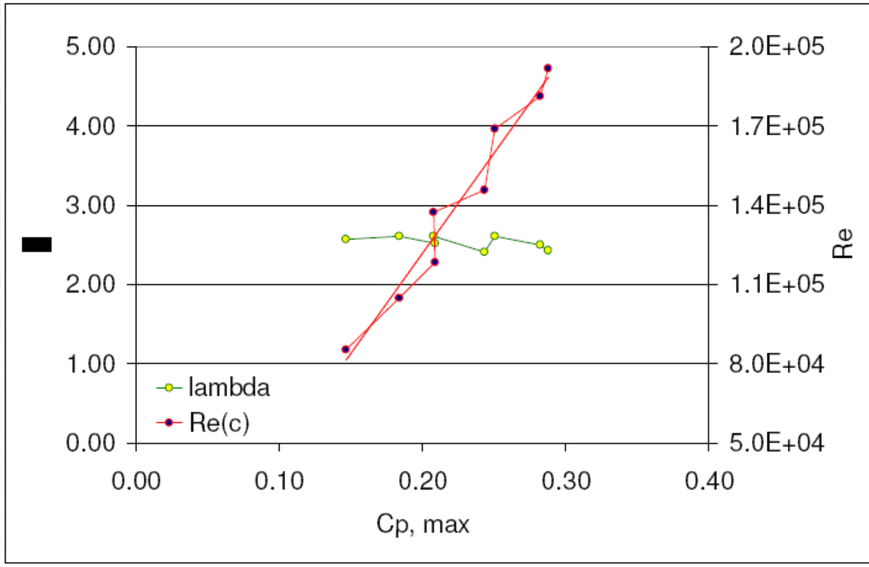
VAWT experimental analysis PDF1 rotor - Performance



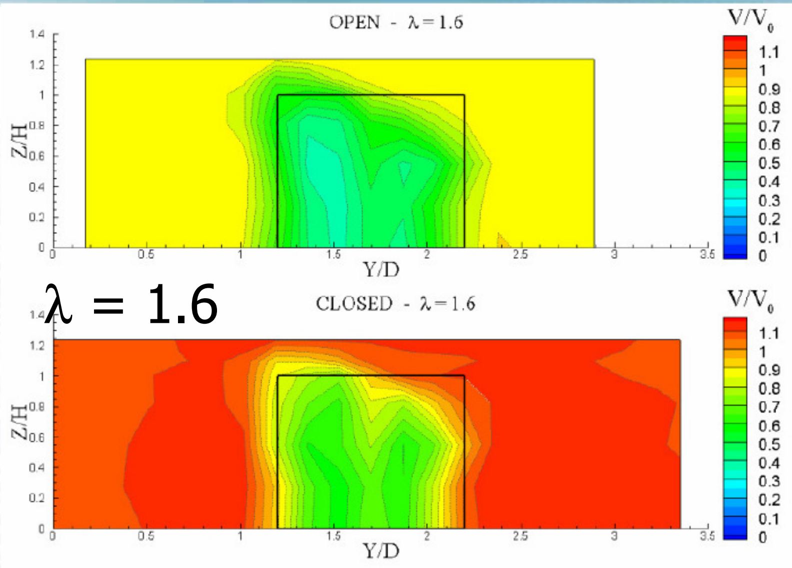


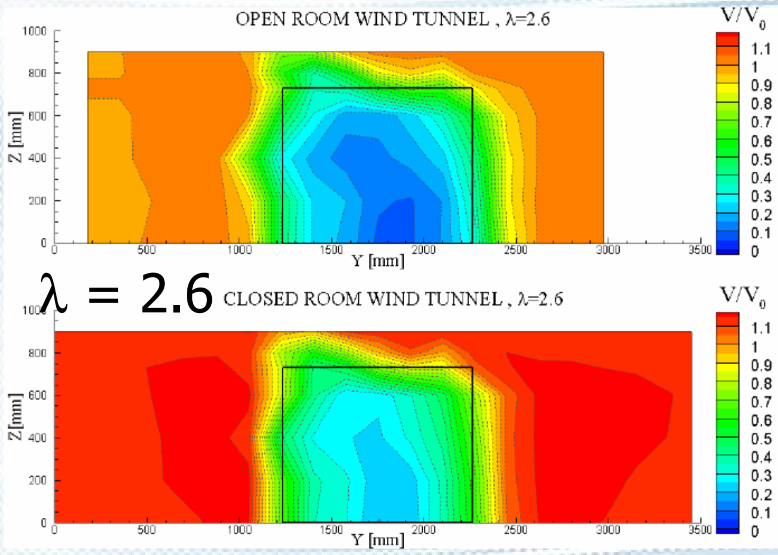
Blockage : 0.097 close test section
Blockage effects up to 20-30% for C_P and 10-20% for C_T

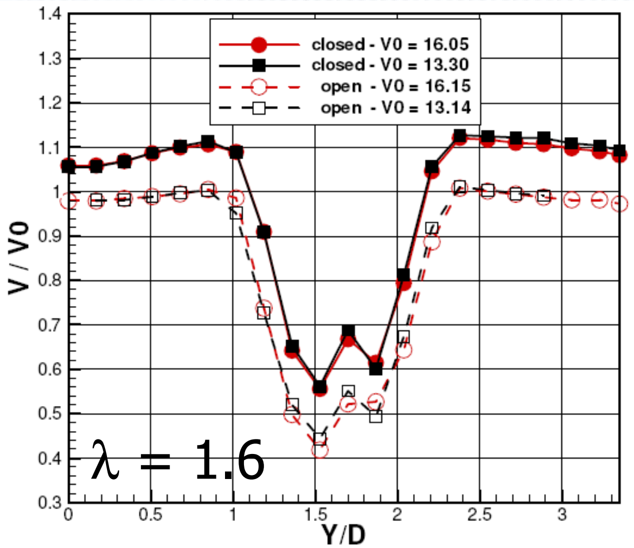
Reynolds numbers very important on power performance for Re < 200000



VAWT experimental analysis
PDF1 rotor - Aerodynamics



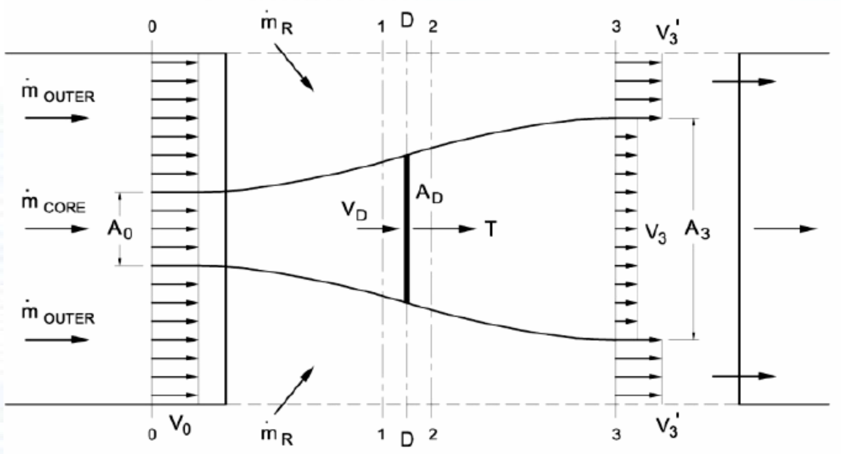




Wake non symmetric and deformed turnwise (in particular at low tip speed ratios)

In closed wind tunnel there is an higher velocity due to blockage effects

VAWT experimental analysis
PDF1 rotor - Aerodynamics

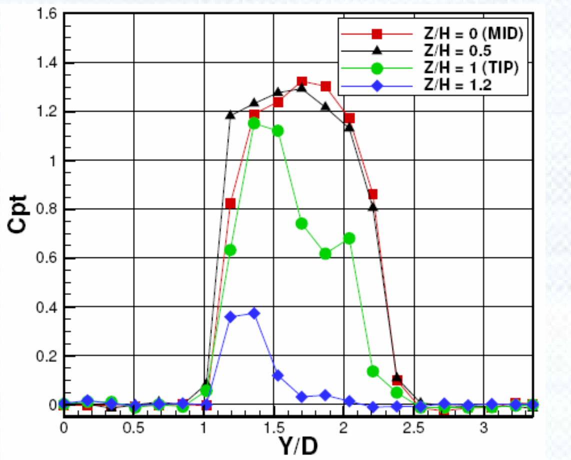


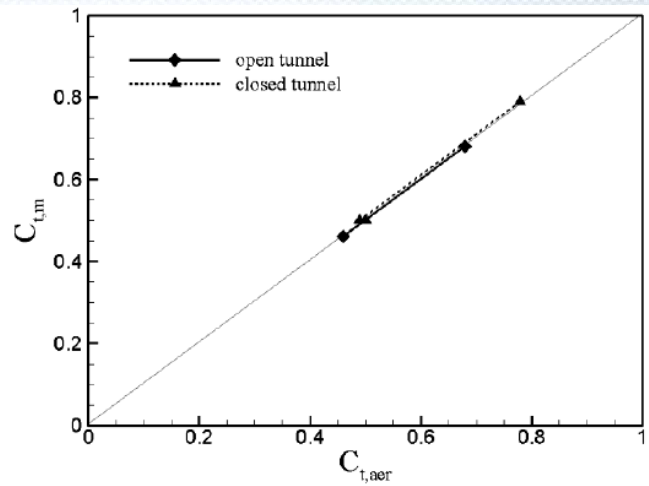
Wind tunnel blockage

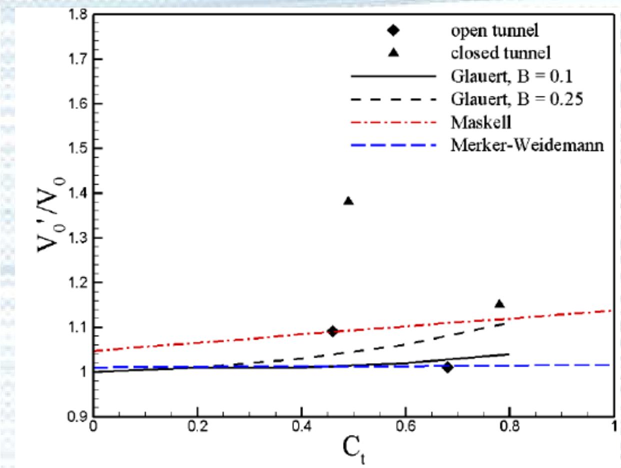
$$T = A_D\left[\left(p_0 + \frac{1}{2}\rho V_0^2 - \frac{1}{2}\rho V_D^2\right) - \left(p_3 + \frac{1}{2}\rho V_3^2 - \frac{1}{2}\rho V_D^2\right)\right]$$

$$\frac{V_0^{'}}{V_0} = \frac{V_D}{V_0} + \frac{C_T}{4\dfrac{V_D}{V_0}}$$

1D momentum theory doesn't seem the best model for blockage effects

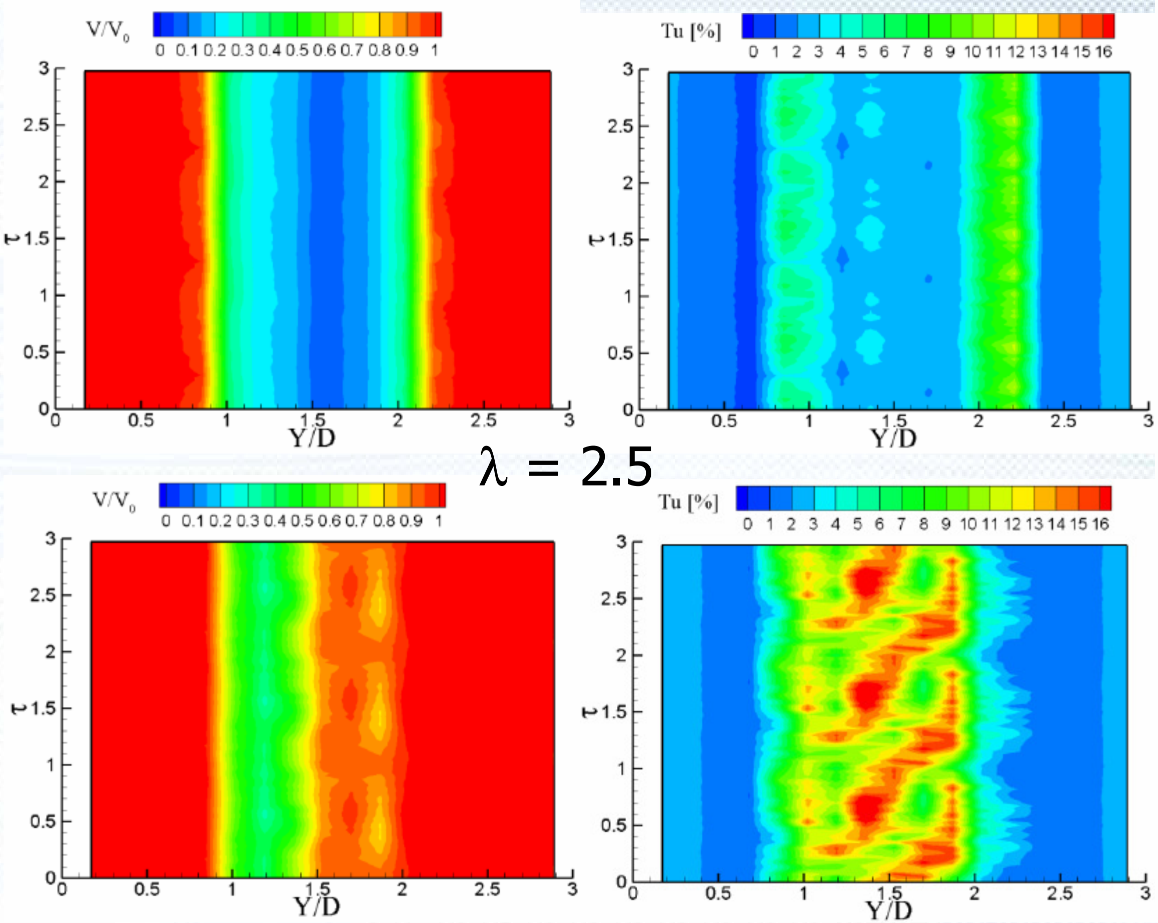


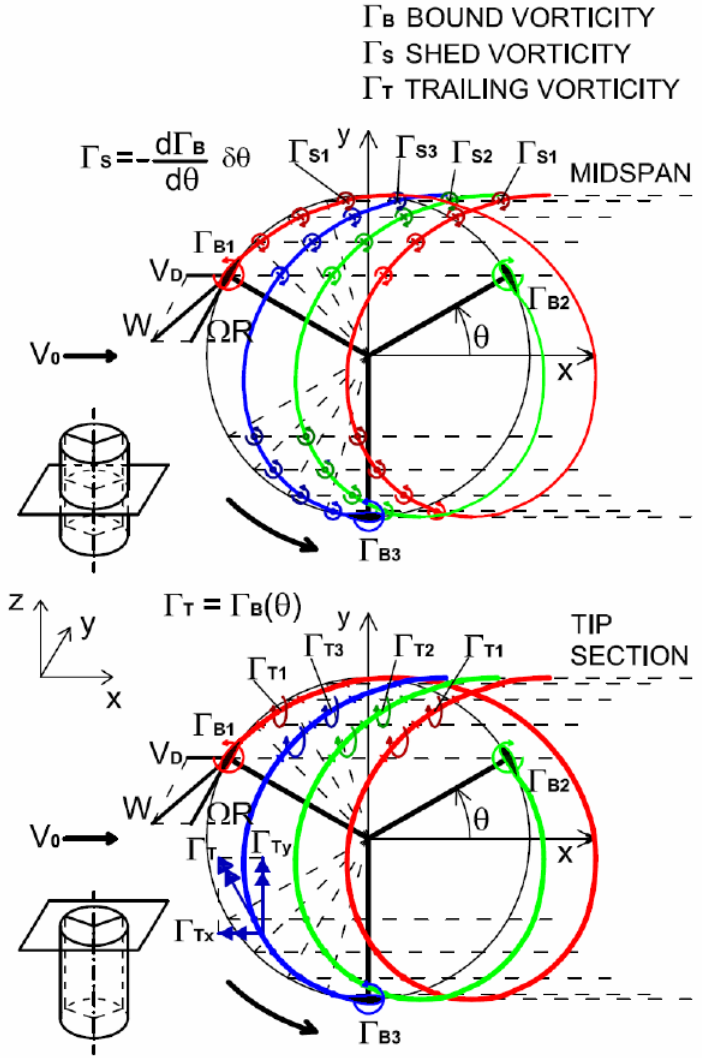




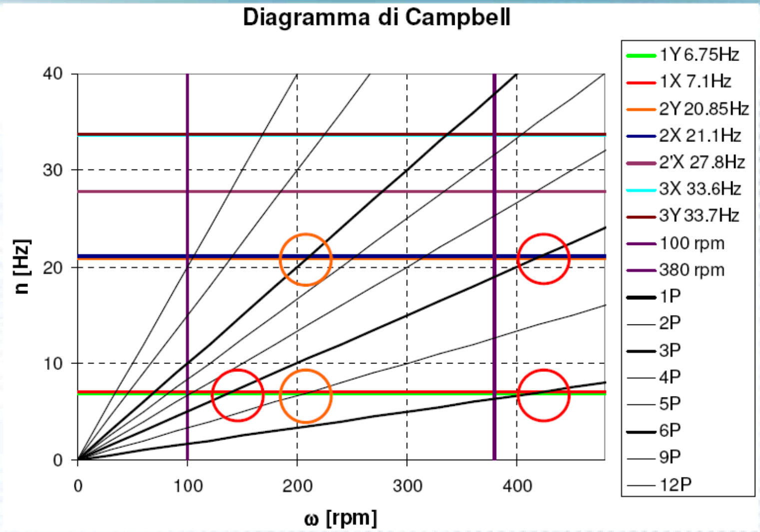
VAWT experimental analysis
PDF1 rotor - Aerodynamics

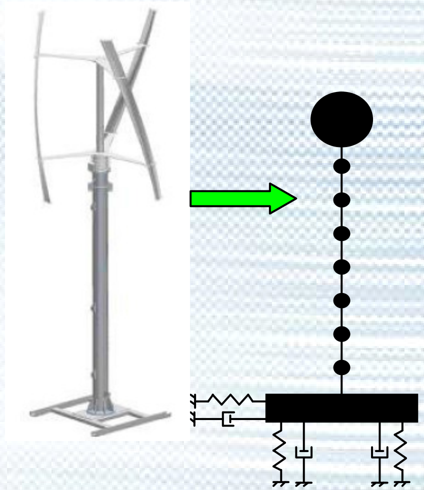
Unsteady flow field

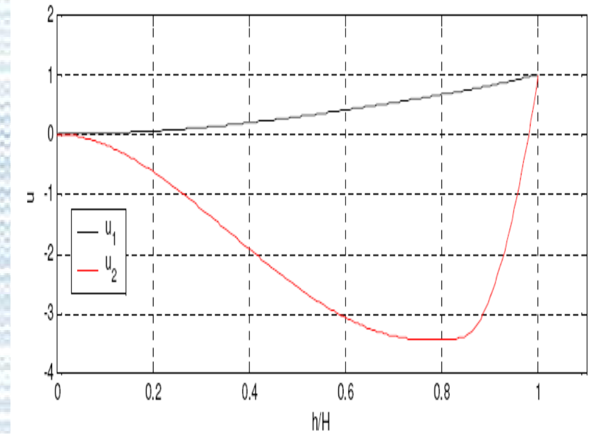


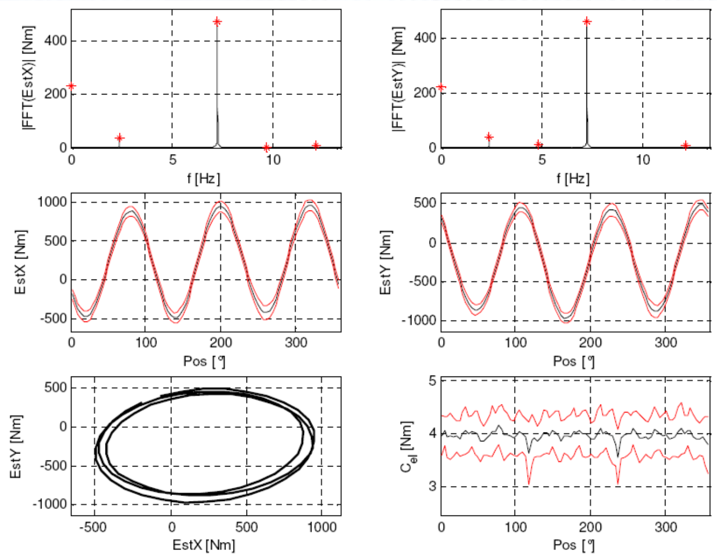


VAWT experimental analysis
PDF3 rotor - Dynamics

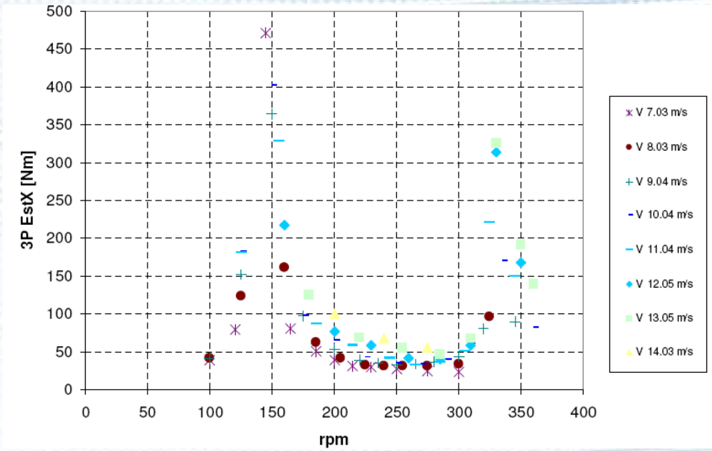




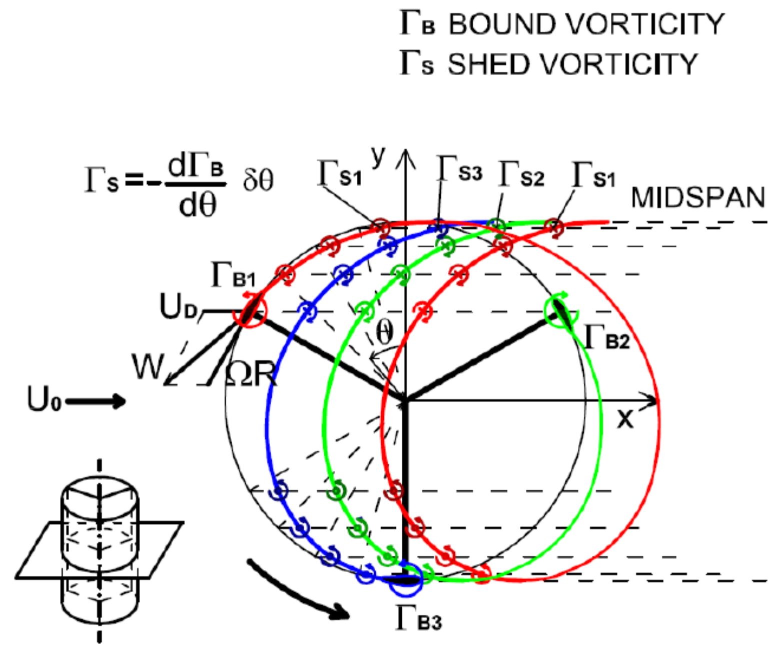




Dynamic analysis and modelling



Part II : VAWT analysis
2D Free vortex wake



Bound and shed vorticity

$$L = C_l \frac{1}{2}\rho W^2 c = \rho W \Gamma_B \qquad \Gamma_B = \frac{1}{2} C_l W c \qquad \delta\Gamma_S = -\frac{d\Gamma_B}{d\theta}\delta\theta$$

Induced velocitites (Biot-Savart)

$$u = -\frac{\Gamma}{2\pi}\frac{(y-y_0)}{(x-x_0)^2+(y-y_0)^2+h^2} \qquad v = \frac{\Gamma}{2\pi}\frac{(x-x_0)}{(x-x_0)^2+(y-y_0)^2+h^2}$$

Flow characteristics

$$W^2 = \left[\Omega R + (U_0+u_C)\cos(\theta) + v_C\sin(\theta)\right]^2 + \left[(U_0+u_C)\sin(\theta) - v_C\cos(\theta)\right]^2$$

$$\phi = \tan^{-1}\frac{(U_0+u_C)\sin(\theta) - v_C\cos(\theta)}{\Omega R + (U_0+u_C)\cos(\theta) + v_C\sin(\theta)}$$

$$\alpha = \phi - \beta$$

Shed vortex position

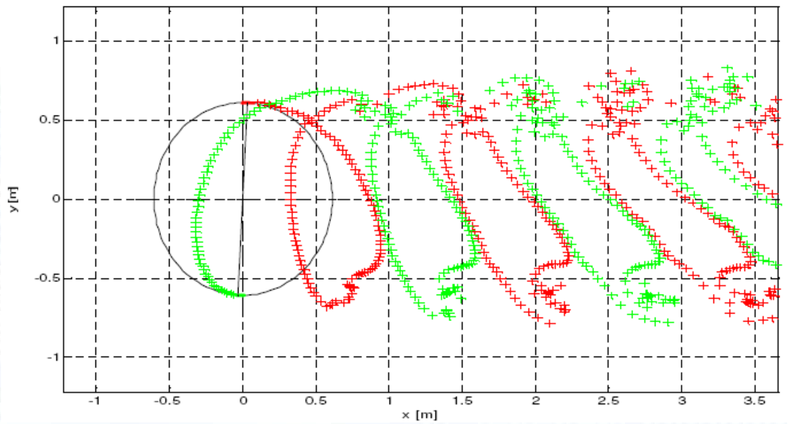
$$\tilde{x}_{S,i} = x_{S,i-1} + \left(U_0 + u_S\left(x_{S,i-1}, y_{S,i-1}\right)\right)\cdot dt$$

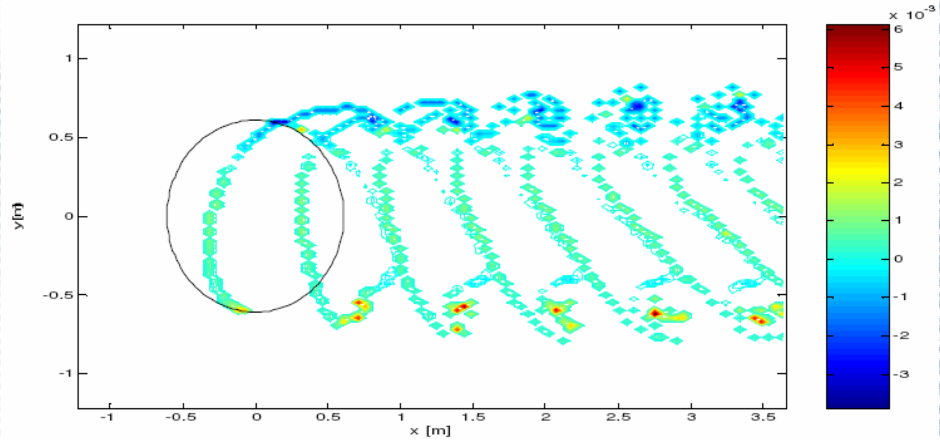
$$\tilde{y}_{S,i} = y_{S,i-1} + v_S\left(x_{S,i-1}, y_{S,i-1}\right)\cdot dt$$

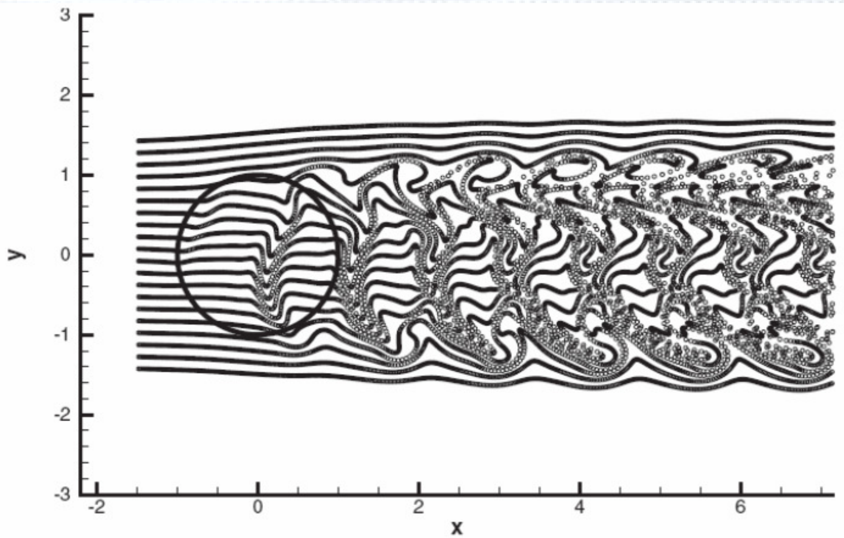
$$x_{S,i} = x_{S,i-1} + \left[U_0 + 0.5\cdot\left(u_S\left(\tilde{x}_{S,i}, \tilde{y}_{S,i}\right) + u_S\left(x_{S,i-1}, y_{S,i-1}\right)\right)\right]\cdot dt$$

$$y_{S,i} = y_{S,i-1} + 0.5\cdot\left(v_S\left(\tilde{x}_{S,i}, \tilde{y}_{S,i}\right) + v_S\left(x_{S,i-1}, y_{S,i-1}\right)\right)\cdot dt$$

VAWT 2D Free vortex wake Validation and results



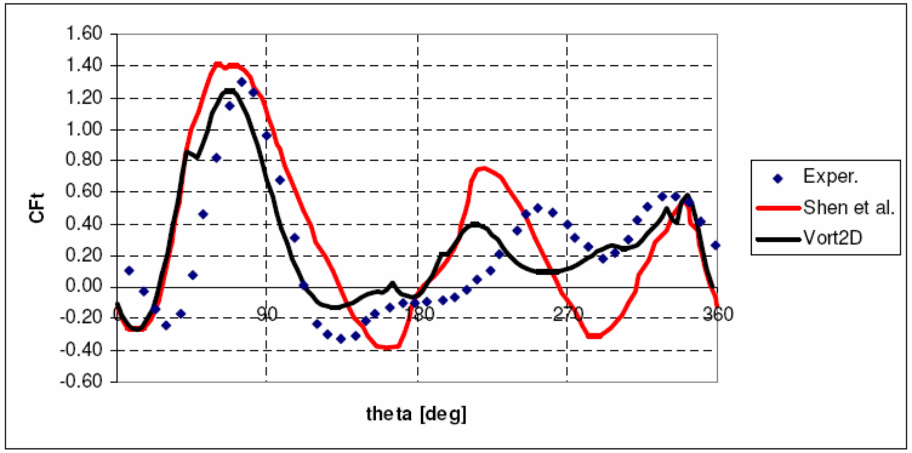


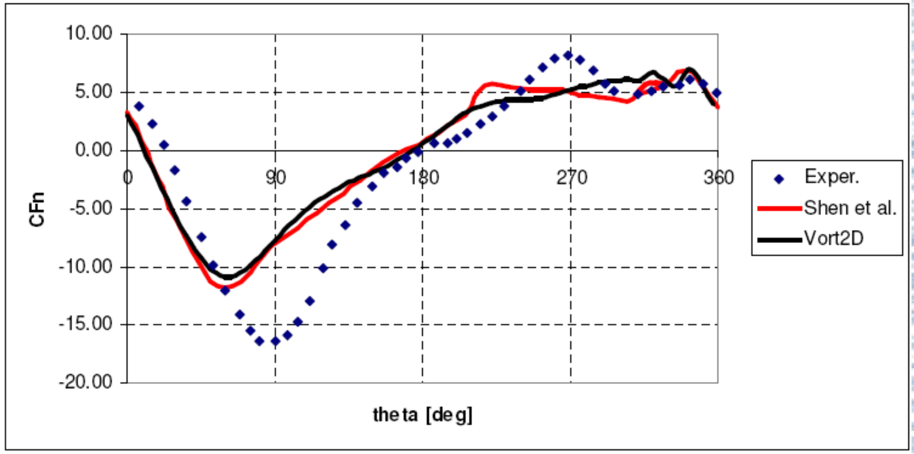


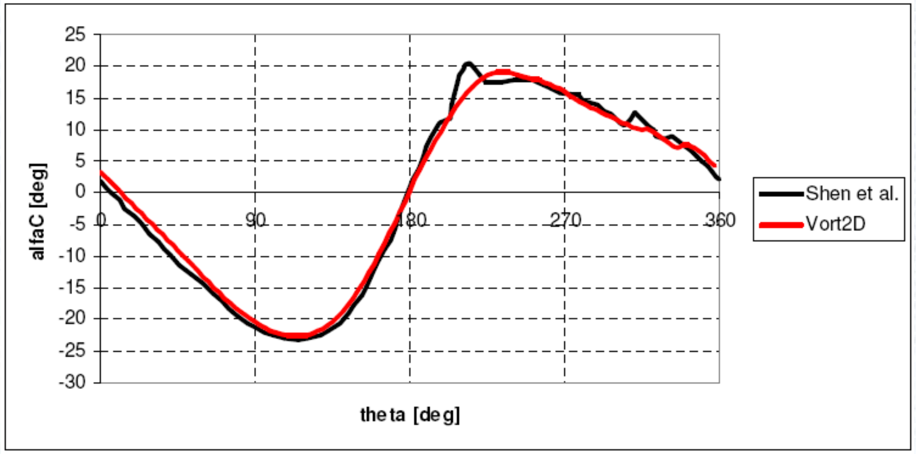
Comparison with Shen et al. actuator surface – CFD computations of a 2-bladed rotor

- Flow characteristics are qualitatively well assessed
- Viscosity is quite important

VAWT 2D Free vortex wake
Validation and results

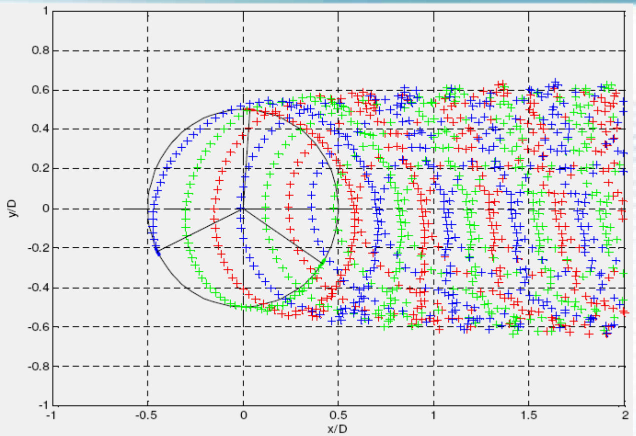


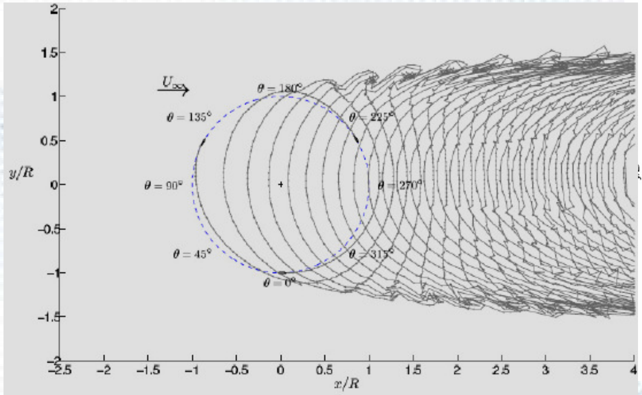


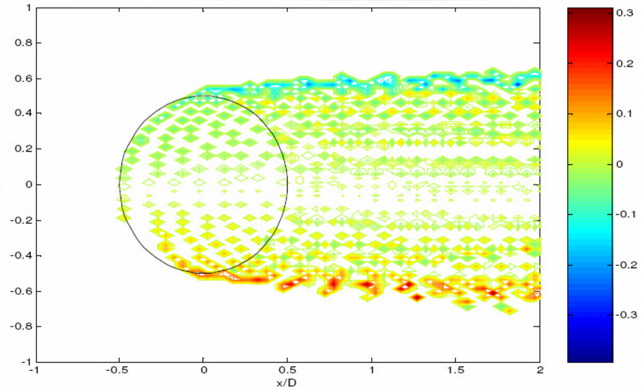


- The angle of attack is well reproduced
- Airfoil database are very important
- Normal force coefficient peak not well reproduced: dynamic stall model to be improved

Validation and results
Ferreira panel model



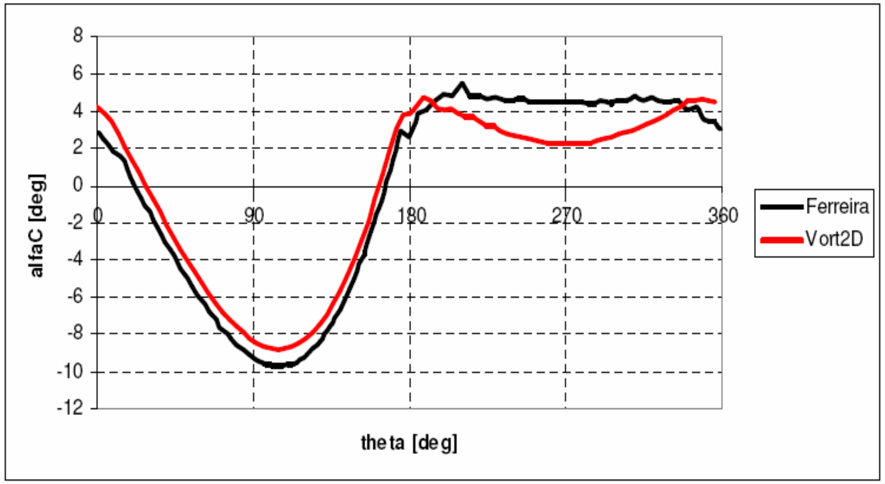


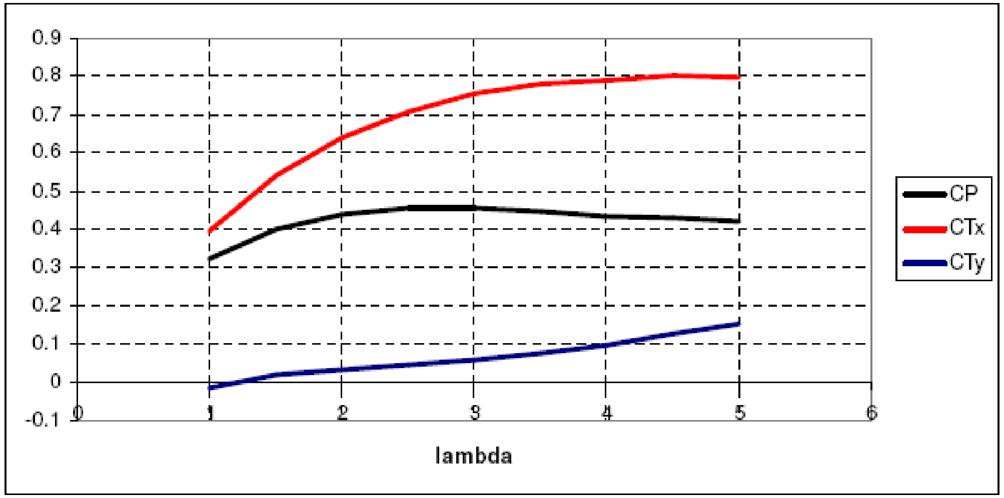


The angle of attack is reproduced sufficiently well

The efficiency seems slightly lower than HAWT

Drag!





Conclusions - HAWT

- HAWT analysis : actuator disk – momentum theory
- Shortcomings : swirl flow, wake expansion, tip effects
- General momentum theory can't overcome these issues
- Turbomachinery approach
- Radial equilibrium
- Radial equilibrium in meridional flow
- Turbomachinery approach + inverse design
- Innovative dsign should be found

Conclusions - VAWT

- VAWT complex 3D geometry, working in his own wake
- VAWT analysis : double moultiple streamtubes – BEM model
- DMS-BEM limitations
- 2D free vortex wake
- Airfoil database + DS + tip correction
- Slightly lower efficiency
- Blockage effects and Reynolds numbers
- 1D momentum theory is not suited for VAWT - unsteady
- Structural dynamics : aeroelastic codes + free wake codes

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