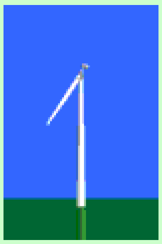
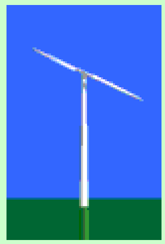
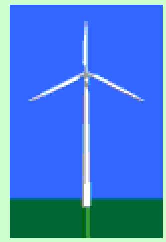






WIND POWER

NATIONAL AEROSPACE LABORATORIES BANGALORE

WIND TURBINE

S. J. Krishna Murthy

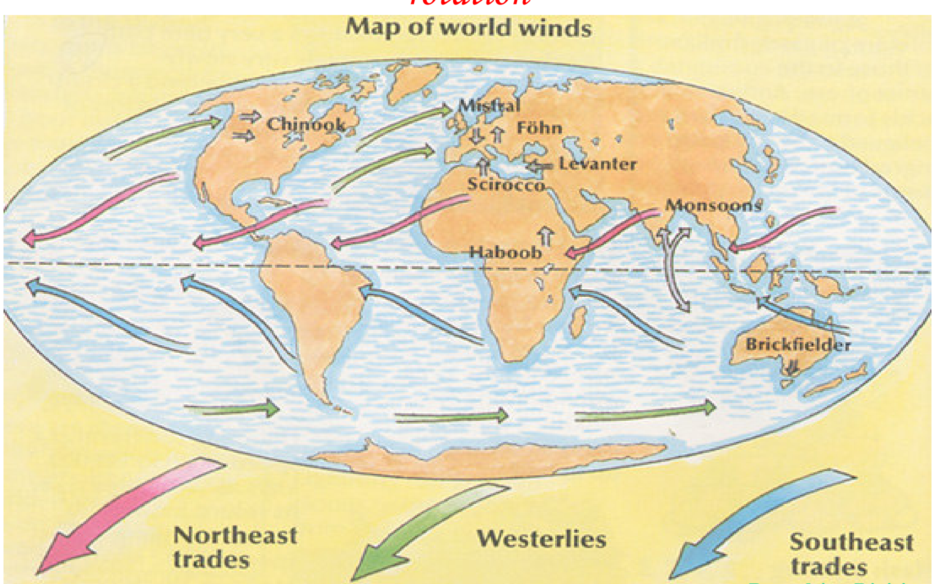
Deputy Director

Propulsion Division

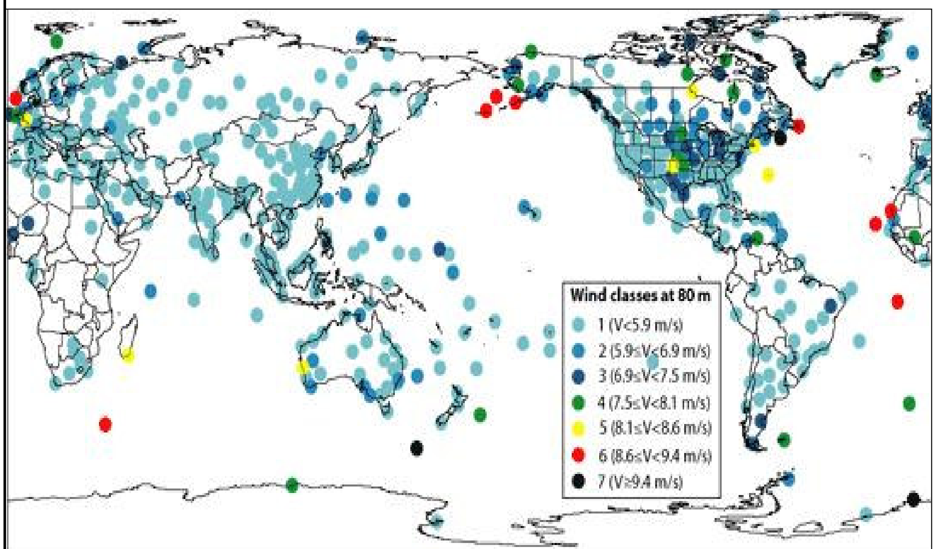
NAL, Bangalore

- **Energy is a major input for the overall socio-economic development of any society.**
- **Prices of the fossil fuels are steeply increasing.**
- **Renewables are expected to play a key role.**
- **Wind energy is the fastest growing renewable.**
- **Wind turbines are up to the task of producing serious amounts of electricity**

Wind generated by uneven heating of earth's surface and rotation



Wind classes : Global Scenario



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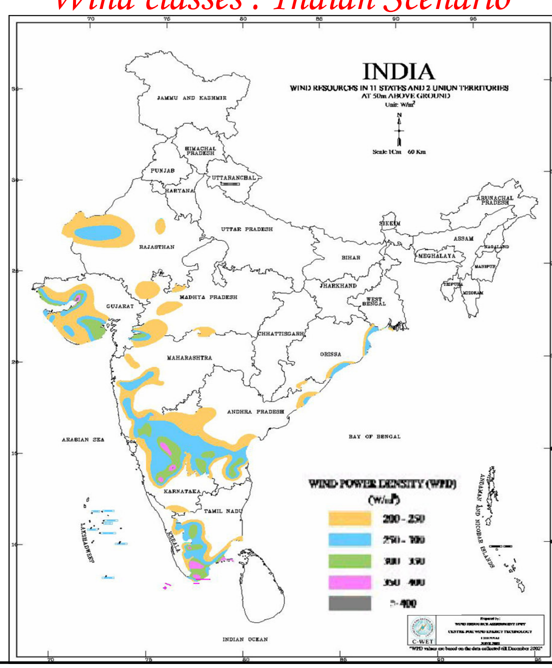
Wind classes : Indian Scenario



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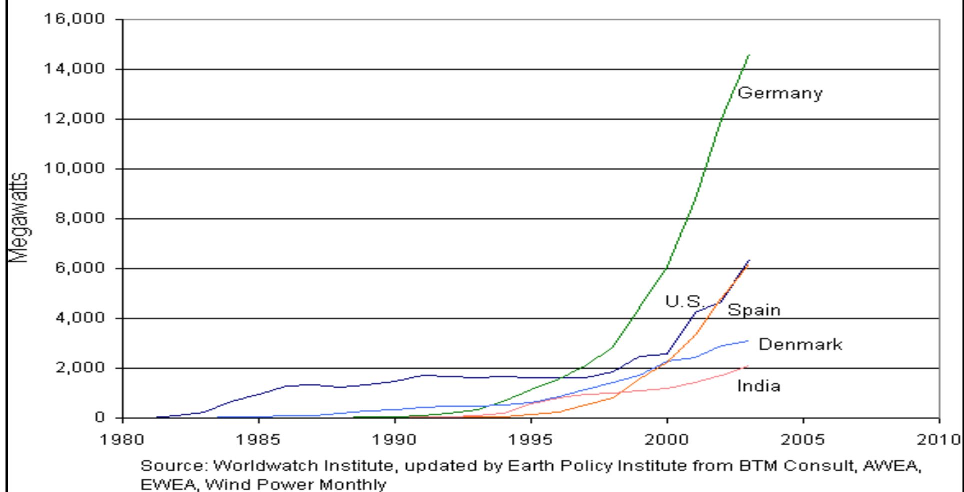
Wind Energy : Global Scenario



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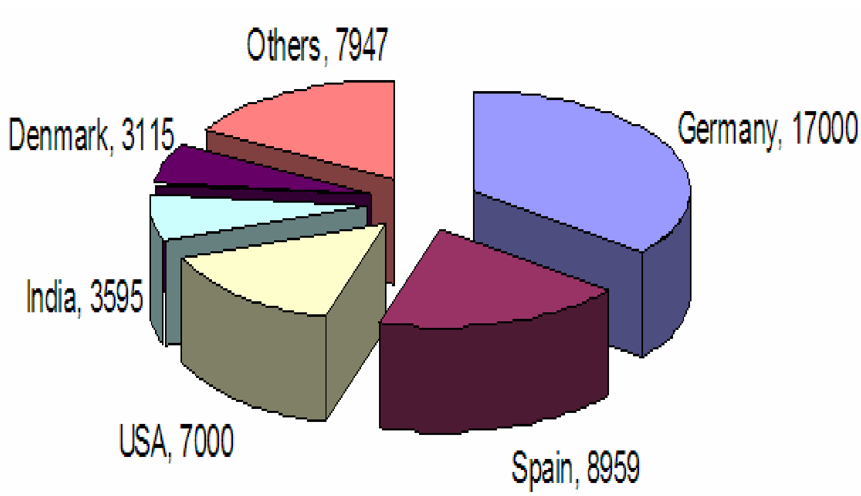
Wind Energy : Global Scenario



Installed Capacity (MW) in 2005

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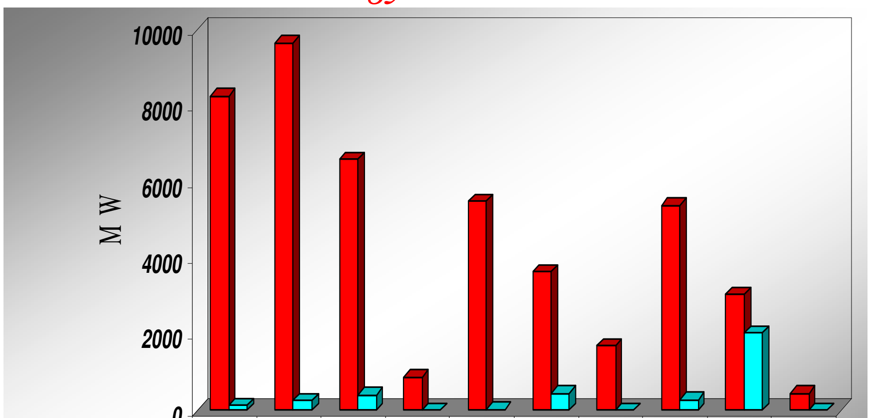
Wind Energy : Indian Scenario



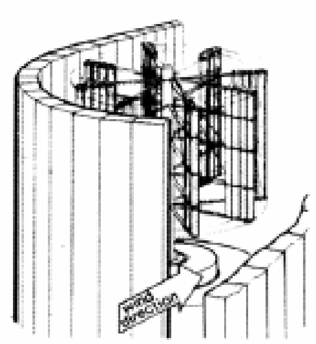
	AP	Gujarat	Karnataka	Kerala	MP	Maharashtra	Orissa	Rajasthan	TN	WB
Gross Potential	8275	9675	6620	875	5500	3650	1700	5400	3050	450
Installed Capacity	120.6	253.53	410.75	2	28.85	456.15	2	284.76	2040.3	1.1

State-wise potential in India (2005)

Propulsion Division

Wind Turbines : Historical Background

- More than 3000 years old Historical Tracking.
- Dates back to 17th Century BC in Babylonian Civilization for irrigation purpose.
- The Persians built windmills in the 7th century A.D.



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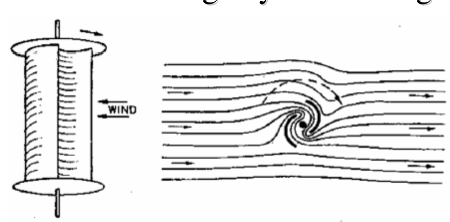
Wind Turbines : Historical Background

- Came to Europe in 13th Century A.D. but development took place only during 18th Century A.D.
- 30,000 *European Windmills* by the end of 19th Century basically used for milling of grains and pumping water.
- The earliest mention of the use of wind power come from the East: **India**, Tibet, Persia and Afghanistan. (1st to 12th century).
- Earlier HAWTs built in 1153 in Turkey.
- Basically used for water pumping, grinding grain, sawing wood and powering tools.
- No significant changes from 12th to later 20th century.

Wind Turbines : Historical Background

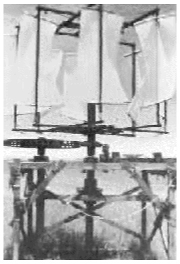
- Early 20th century saw a new design by Finnish engineer S.J.Savonius



- In later 1930 F.M.Darrieus also proposed a new wind mill.

Few Historical Wind Turbines

A 19th-century American version of a vertical-axis windmill

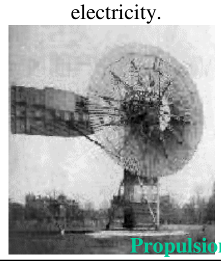


An early sail-wing horizontal-axis mill on the Mediterranean coast

Old Danish wind turbine

A steel-bladed water pumping windmill in the American Midwest (late 1800s)

The Brush Postmill in Cleveland, Ohio, 1888. The first use of a large windmill to generate electricity.



Wind Turbines : Evolution

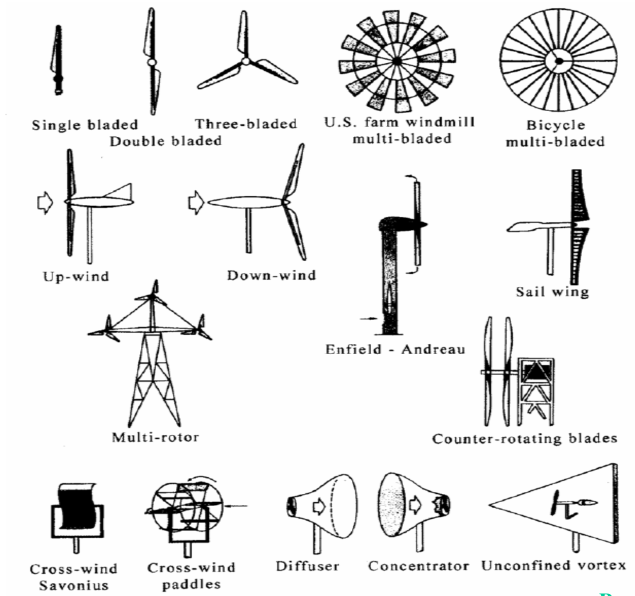
Used for

- Pumping water
- Grinding grain

Mainly used for

- Generating Electricity

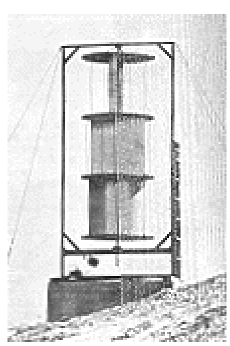
Wind Turbines : Taxonomy



Propulsion Division

Wind Turbines : Taxonomy

Based on Axis of Rotation



Drag Type

Lift Type

Horizontal Axis Wind Turbine

Vertical Axis Wind Turbine

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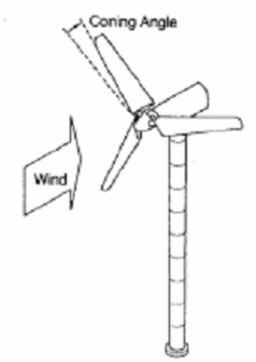
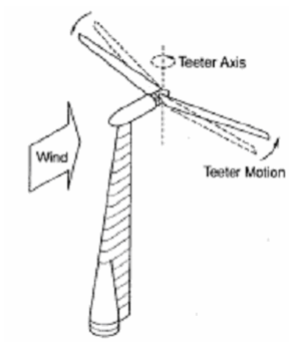
Wind Turbines : Taxonomy

Based on Location of Rotor





Upwind Turbine   Downwind Turbine

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Wind Turbines : Taxonomy

- **Based on technique of power control :**
  - **Pitch regulated Windmill**
  - **Stall regulated Windmill**
    - **a. Active Stall regulated**
    - **b. Passive Stall regulated**
- **Based on hub articulation :**
  - **Teetering hub type**
  - **Rigid hub type**
- **Based on Pitch characteristic :**
  - **Fixed pitch machine**
  - **Variable pitch machine**
- **Based on rotational speed :**
  - **Fixed Speed**
  - **Variable speed**
- **Based on rotor-generator interface :**
  - **Gearbox driven**
  - **Direct driven**
- **Based on Yaw mechanism :**
  - **Forced yaw**
  - **Free yaw**

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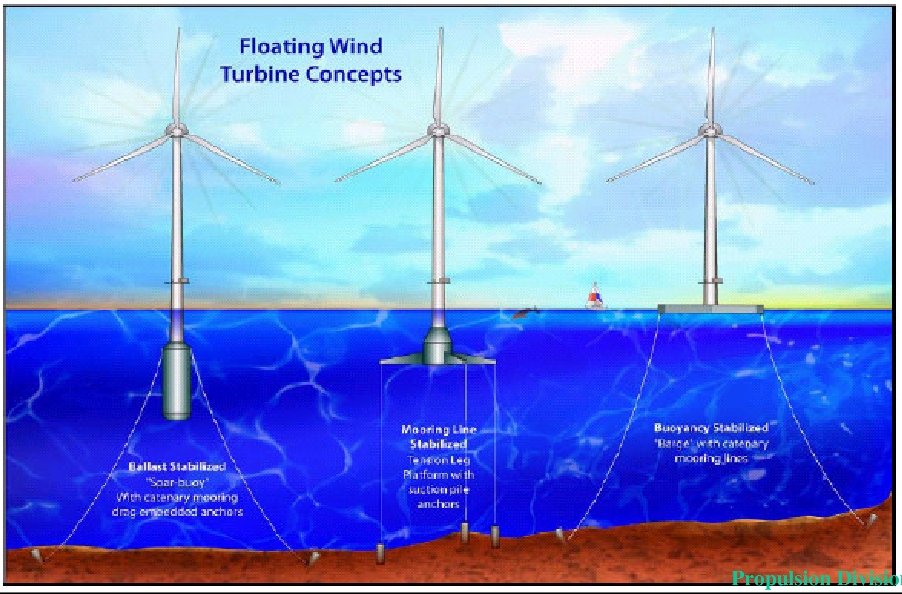
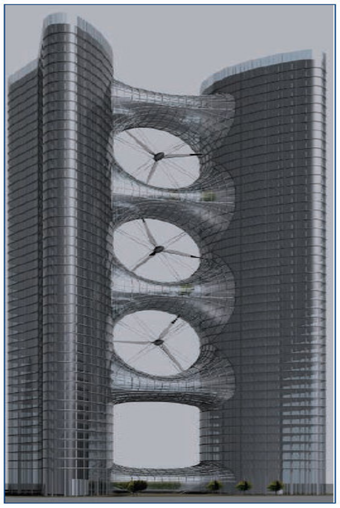
Wind Turbines : New Technologies

Offshore Wind Turbines

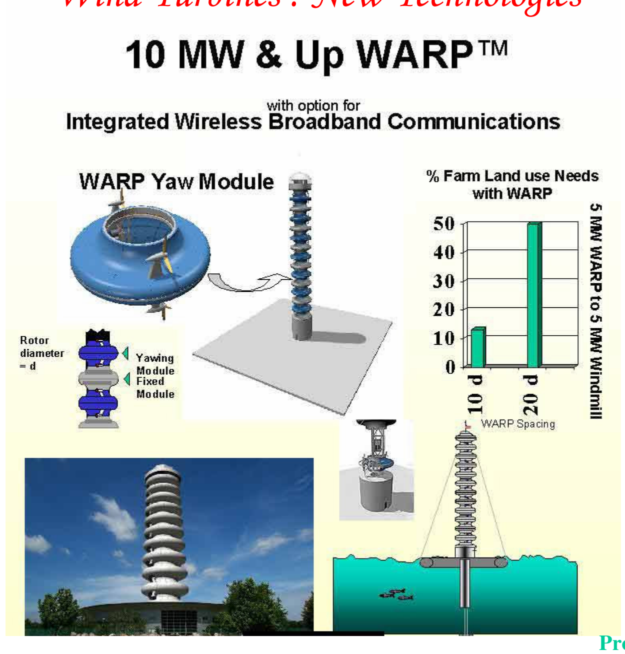


Wind Turbines : New Technologies

Use of Concentrators



Wind Turbines : New Technologies



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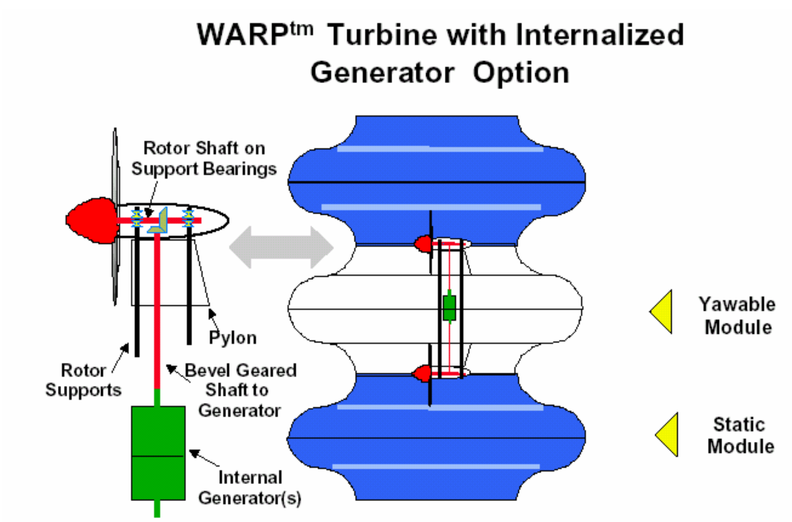
Wind Turbines : New Technologies



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Wind Turbines : New Technologies

Disc type wind turbine

Propulsion Division

Flow of Discussion

- Objectives
- Aerodynamics of Wind Turbine
- Aerodynamic Theories of Wind Turbine
- Aerodynamic Analysis of Wind Turbine
- Analysis of Wind Turbine Using Computational Tools like IMPRANS, CFD-ACE, WTPE, GH – Bladed.
- Conclusion & Future Scopes

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Objectives

- Study of Wind Turbine, its aerodynamics and theories.
- Analysis of an 2 meter Diameter Experimental Stall Regulated Horizontal Axis Wind Turbine.

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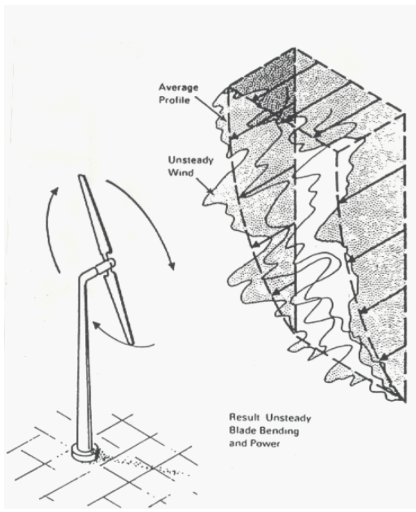
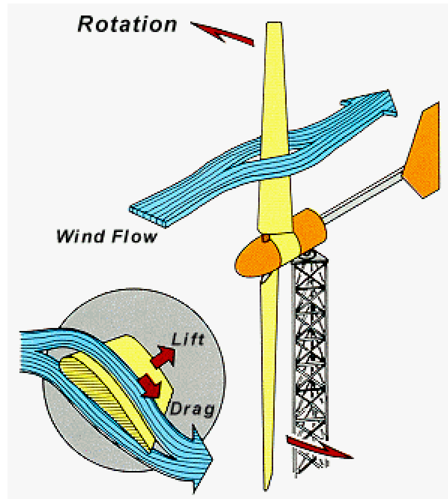
Aerodynamics of Wind Turbine

Aerodynamic Aspects

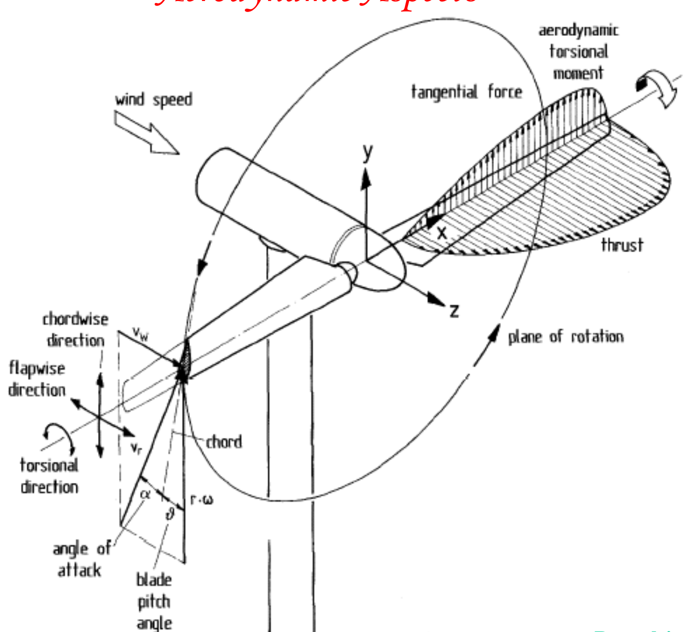
Wind Turbines work in a very unsteady condition



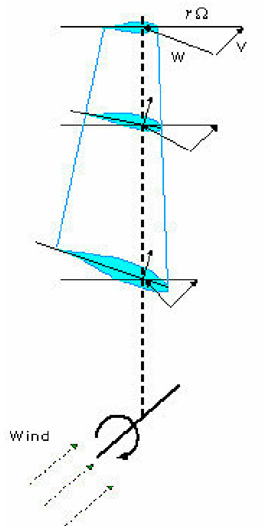


Principles of Wind Turbine Aerodynamic Lift

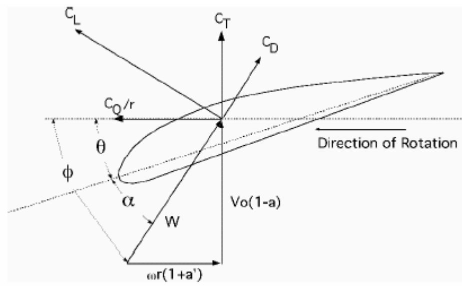
Aerodynamic Aspects



Aerodynamic Aspects



Velocity Triangle



Aerodynamic Forces

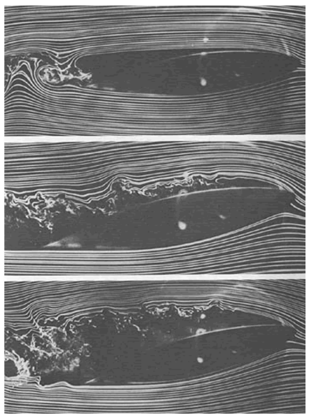
Power control by Aerodynamics

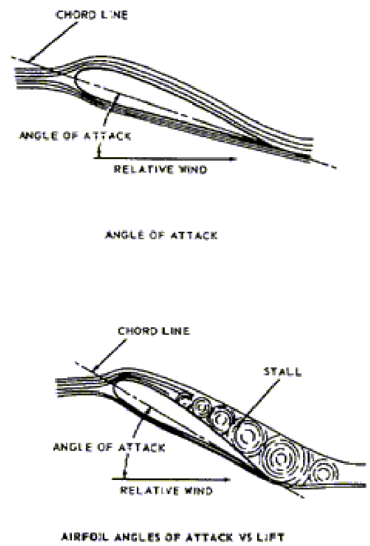
- Stall:
  - fixed blade pitch
  - passive power control by stall effect
  - control parameter: wind speed
- Pitch:
  - blade pitch activated by WT control
  - active power control
  - control parameter: power output, wind speed and rotor speed

Propulsion Division

Power control by Aerodynamics

The Stall Effect





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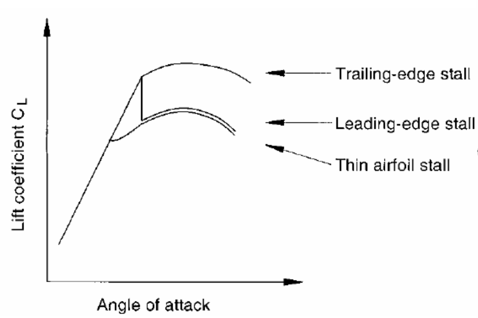
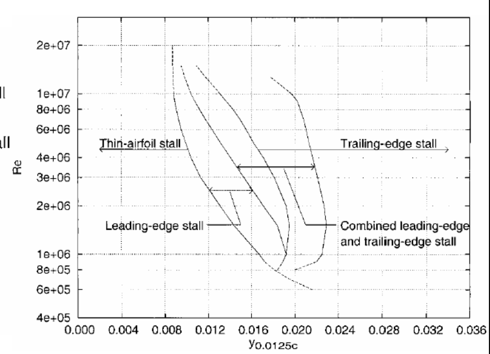
Power control by Aerodynamics

Different Stall Effects





Christian Bak, Helge Aagaard Madsen, Peter Fuglsang and Flemming Rasmussen**, *"Observations and Hypothesis of Double Stall"***, *Wind Energy, Vol – 2, pg 195 – 210, 1999*

Gault D.E., **"A correlation of low-speed, airfoil-section stalling characteristics with Reynolds number and airfoil Geometry"**, *NACA Technical Note 3963*, 1957

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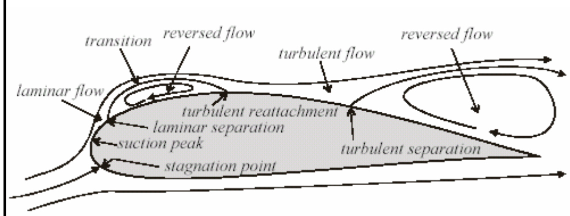
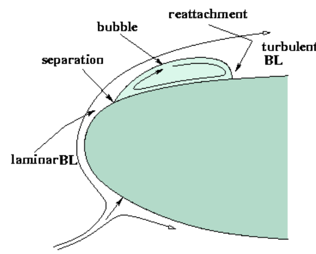
Power control by Aerodynamics

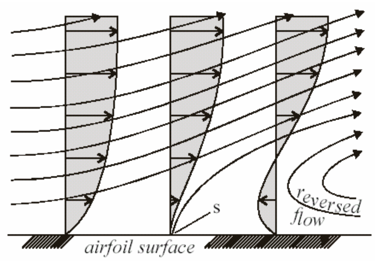
Separation Phenomenon



Qualitative Representation of Separation Types



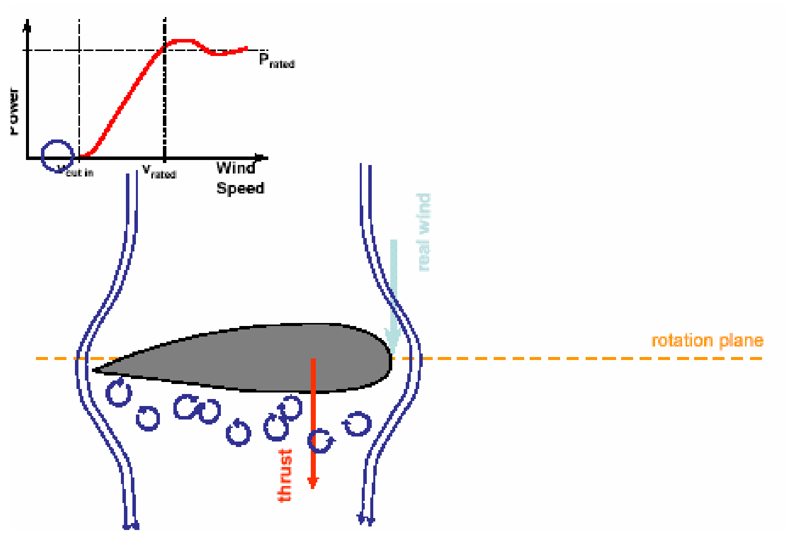
Laminar Separation Bubble



Diagrammatic Representation of the boundary layer flow near separation point

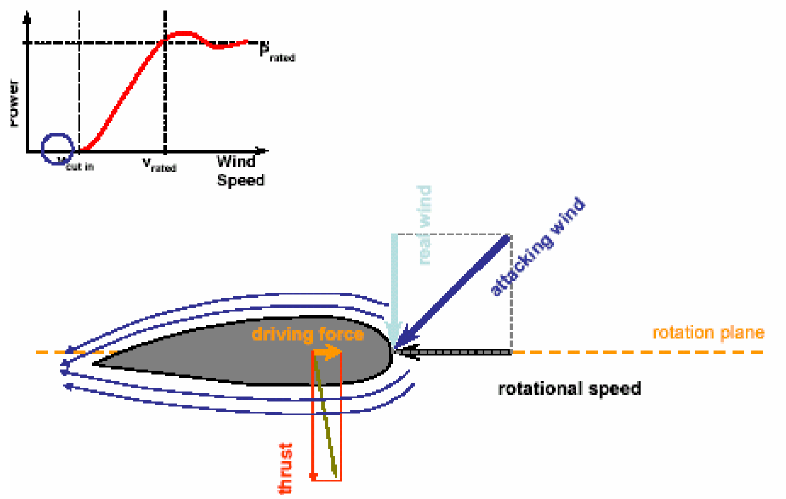
Power control by Aerodynamics

Stall Control



Power control by Aerodynamics

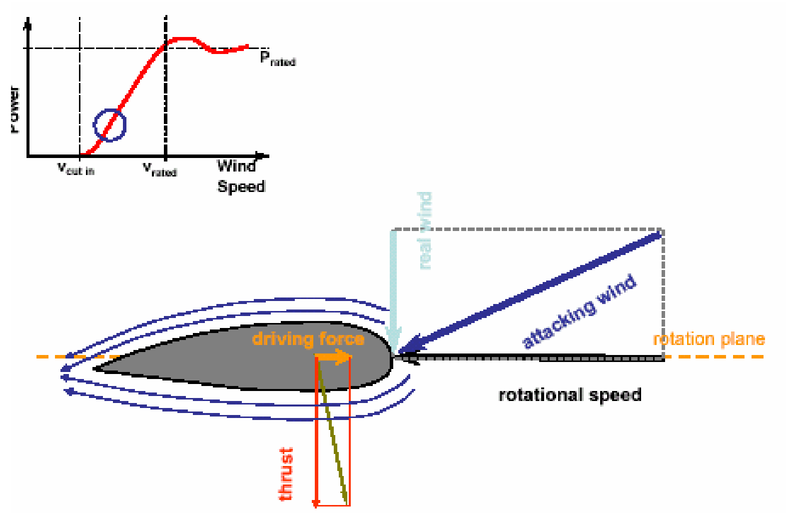
Stall Control



Propulsion Division

Power control by Aerodynamics

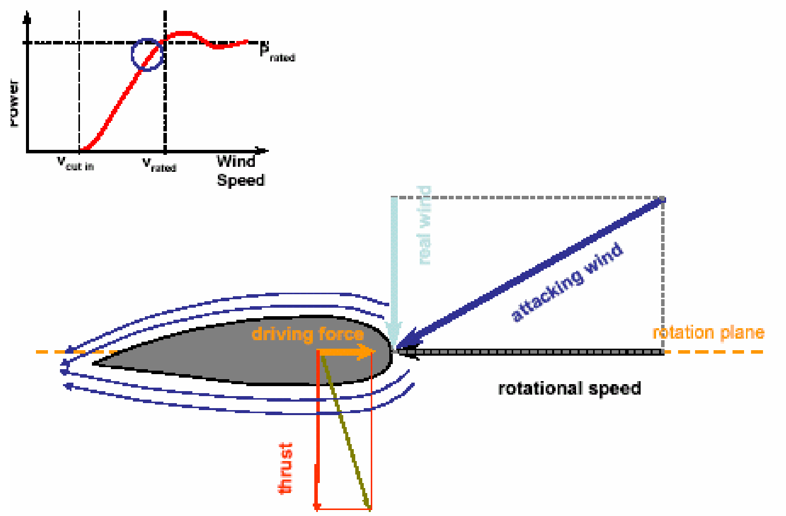
Stall Control



Propulsion Division

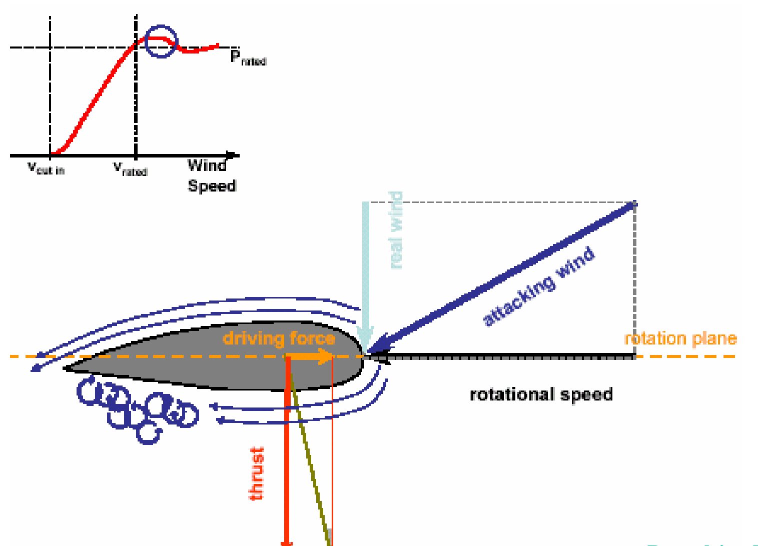
Power control by Aerodynamics

Stall Control



Power control by Aerodynamics

Stall Control



Aerodynamic Theories of Wind Turbine

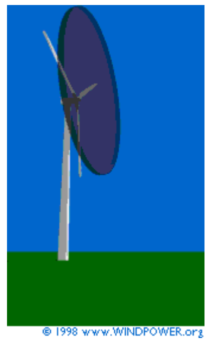
Basic Theories

The Blade Element-Moment Theory - Assumption

Method	Model	Researcher	Year
Momentum	Actuator disk	Betz	1926
	Blade element	Wilson	1974
Vortex wake	Lifting Line	Afjeh	1986
	Lifting surface	Simoes	1990
Local circulation	Elliptic blade	Azuma	1979
Acceleration potential	Pressure perturbation	Van Bussel	1993
CFD	RANS	Duque	1999

Basic Theories

The Actuator Disk Theory

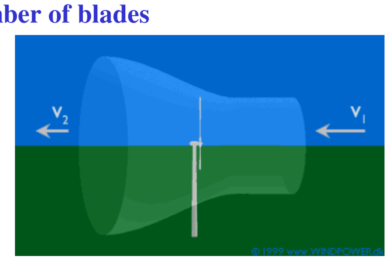


Propulsion Division

Basic Theories

The Actuator Disk Theory - Assumptions

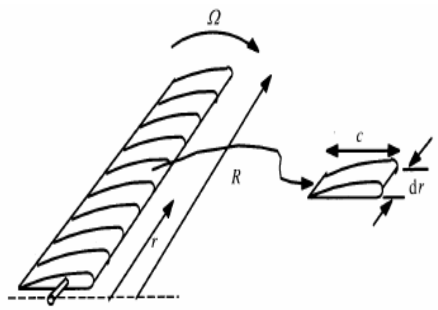
- **Homogenous, Incompressible, steady state fluid flow.**
- **No frictional drag.**
- **The pressure increment or thrust per unit area is constant over the disk.**
- **The rotational component of the velocity in the slipstream is zero.**
- **There is continuity of velocity through the disk.**
- **An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



Propulsion Division

Basic Theories

The Blade Element-Moment Theory



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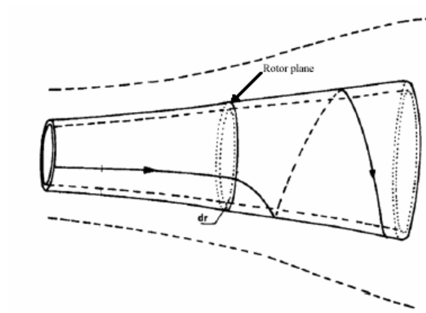


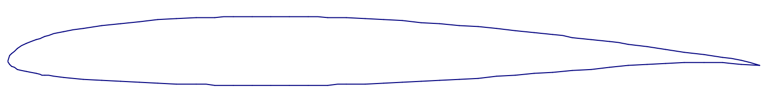
Basic Theories

The Blade Element-Moment Theory - Assumption

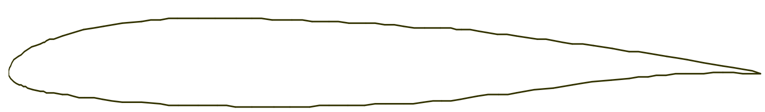
- **Individual *streamtubes* can be analyzed independently of the rest of the flow.**
- ***Spanwise flow* is negligible.**
- **Axisymmetric flow**
- **Thrust force is equivalent to change in Axial Momentum**
- **Torque is equivalent to change in Angular Momentum**

Aerodynamic Analysis of Wind Turbine

Numerical Investigation of Aerofoil Characteristics



• Aerofoil used for last 2 stations at Tip: NASA LS(1) 0413 MOD



•Aerofoil used for next 3 stations from hub : NASA LS(1) 0417 MOD

• Aerofoil used for first 5 stations from hub : NASA LS(1) 0421 MOD

Propulsion Division

Analysis by BEMT

- Define sectional parameters namely local radius r m, radius ratio μ_r, chord ratio c/R, local chord c m, and blade twist angle β degree for all sections along the blade, free-stream wind velocity, U_∞ m/s, rotor angular velocity Ω rad/s.
- Assume induction factors a and a' initially zero.
- Calculate axial flow velocity and tangential flow velocity at the blade plane of rotation and hence resultant relative velocity w m/s as follows :

$$U_d = U_\infty(1-a) \;\;\&\;\; U_t = \Omega r(1+a')$$

$$\text{Henceforth, } w = \sqrt{U_\infty{}^2(1-a)^2 + \Omega^2 r^2(1+a')}$$

- Calculate flow angle φ degree as follows :

$$\varphi = \tan^{-1}\left\{\frac{U_\infty(1-a)}{\Omega r(1+a')}\right\}$$

- Calculate angle of attack α degree as defined below and interpolate the values of C_L and C_D from the airfoil data.

$$\alpha = \varphi - \beta$$

Propulsion Division

Analysis by BEMT

- Calculate lift-to drag ratio, axial force coefficient, C_x and tangential force coefficient C_y as follows

$$C_x = C_l \cos\varphi + C_d \sin\varphi \;\;\&\;\; C_y = C_l \sin\varphi - C_d \cos\varphi$$

- Calculate local solidity σ_r as follows

$$\sigma_r = Bc/2\pi\mu_r R$$

- Calculate a and a' given by

$$a = \frac{g_1}{1+g_1} \qquad \text{and} \qquad a' = \frac{g_2}{1-g_2}$$

$$\text{where } g_1 = \frac{\sigma_r}{4\sin^2\varphi}\left\{C_x - \frac{\sigma_r C_y^2}{4\sin^2\varphi}\right\} \;\;\&\;\; g_2 = \frac{\sigma_r C_y}{4\sin\varphi\cos\varphi}$$

Above steps have to be iterated until a stable value of angle of attack and hence forth a and a' are arrived at.

Propulsion Division

Analysis by BEMT

- The elemental thrust force on the blade annulus is given by,

$$\frac{dT}{dr} = 4\pi\rho U_\infty^2 a(1-a)r$$

- The elemental torque on the blade annulus is given by,

$$\frac{dQ}{dr} = 4\pi\rho U_\infty(\Omega r a')(1-a)r^2$$

- The elemental power contribution is calculated using the formula

$$\frac{dP_a}{dr} = \Omega\left(\frac{dQ}{dr}\right)$$

- The thrust coefficient of rotor at particular wind speed is calculated using

$$C_T = \frac{T}{\frac{1}{2}\rho U_\infty^2 \pi R^2}$$

- The power coefficient of the rotor at particular wind speed is calculated using

$$C_P = \frac{P_a}{\frac{1}{2}\rho U_\infty^3 \pi R^2}$$

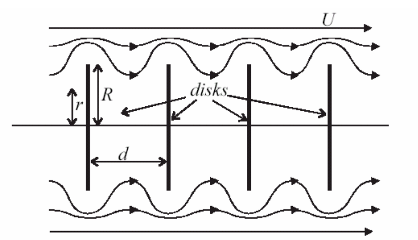
- The torque coefficient of the rotor at particular wind speed, is calculated using

$$C_Q = \frac{C_P}{\lambda}$$

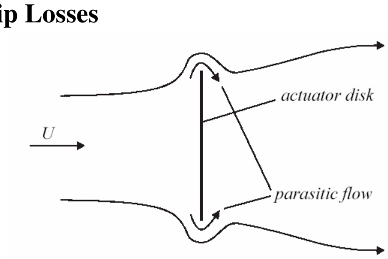
Propulsion Division

Analysis by BEMT

Hub-Tip Losses



Prandtl's solid disk model



Parasitic flow around the actuator disk

The Hub-Tip Loss factor is defined as

$F=F(t)xF(h)$

Factor $F(t)$ is the loss factor at tip portion and $F(h)$ is the loss factor at hub portion. They are defined as :

$$F(t) = \left(\frac{2}{\pi}\right)\left(\arccos(e^{-f_t})\right) \quad \text{where } f_t = \left(\frac{B}{2}\right)\left(\frac{R_{tip}-r}{r\sin\phi}\right)$$

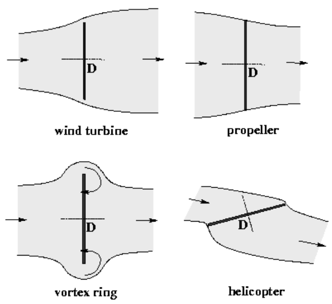
&

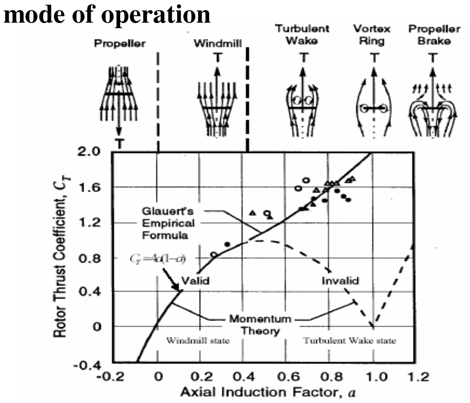
$$F(h) = \left(\frac{2}{\pi}\right)\left(\arccos(e^{-f_h})\right) \quad \text{where } f_h = \left(\frac{B}{2}\right)\left(\frac{r-R_{root}}{R_{root}\sin\phi}\right)$$

Propulsion Division

Analysis by BEMT

Common mode of operation





For $a \leq 0.3539$, $H = 1.0$

For $a > 0.3539$, $H = \dfrac{4a(1-a)}{(0.6+0.61a+0.79a^2)}$

Propulsion Division

Analysis by BEMT

Hence g_1 and g_2 are re-defined as follows :

$$g_1 = \frac{\sigma_r}{4F\sin^2\phi}\left\{C_x - \frac{\sigma_r C_y^2}{4\sin^2\phi}\right\}\cdot H$$

&

$$g_2 = \frac{\sigma_r C_y}{4F\sin\phi\cos\phi}$$

Taken from :
Bossanyi E. A., *"GH Bladed Theory Manual"*, Version 3.6, GH Partners Ltd., UK, December, 2003

Propulsion Division

Analysis by WTPE

- Input parameters:
  - Blade radius
  - Operational parameters
  - Number of blades
  - Blade cone angle, (included)
  - Hub cut-out
  - Prandtl Tip loss switch, (included)
  - Wind shear exponent
  - Normalized tower height
  - Number of sections along the blade, (10)
  - Blade chord ratio and twist distribution
  - Airfoil characteristics, (Tunnel tested, Literature)
  - Shaft tilt angle, (included)
  - Blade pitch, (Fixed pitch)

Analysis by WTPE

- Output parameters:

  Non-dimensional Performance Parameters
  - Thrust coefficient
  - Torque coefficient
  - Power coefficient
  - Aerodynamic efficiency

  Rotor Parameters
  - Aerodynamic Thrust
  - Aerodynamic Torque
  - Aerodynamic Moment
  - Aerodynamic Power

  These output data are obtained for specified range of Tip speed ratio or free stream wind velocity.

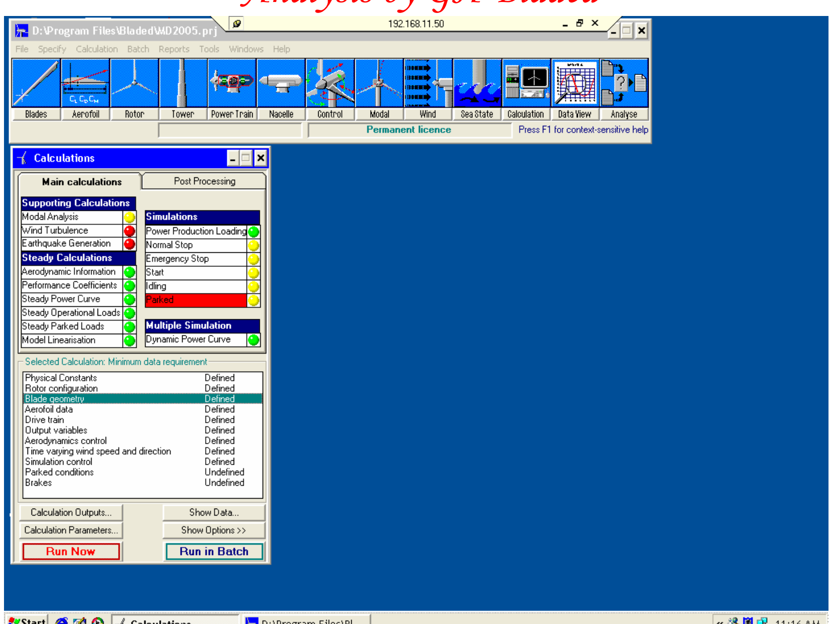
- The blade span-wise aerodynamic information is not available from WTPE program.

Analysis by GH-Bladed

- Commercial software for design and analysis of HAWTs with different configurations including present case.
- **Pre-processing data**
  - Blade geometry including pitch axis
  - Airfoil characteristics with Re and t_{max}/c
  - Rotor configuration
  - Operational parameters
  - Aerodynamic tolerance
  - Prandtl hub and tip loss
  - Wake treatment models
  - Wind shear and tower shadow effects
  - Power control strategy

Propulsion Division

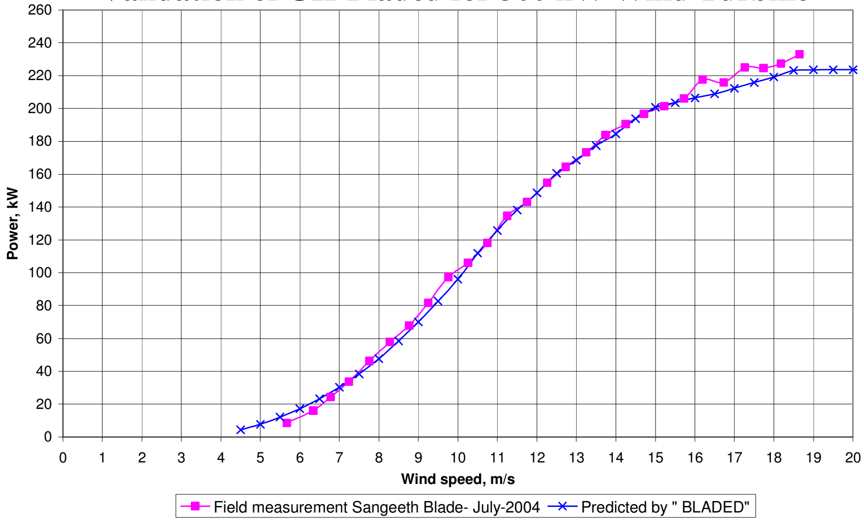
Analysis by GH-Bladed



Propulsion Division

Analysis by GH-Bladed

Validation of GH-Bladed for 300 kW Wind Turbine



Ref: Kishor Kumar and Krishna Murthy S.J., " *Aerodynamic Design and Analysis of a 500 kW Horizontal Axis Wind Turbine Rotor Blades"*, PD-PR-0514, NAL Bangalore, October 2005

Propulsion Division

Input for the Analysis

Sizing of the turbine

1. Number of blades : 2
2. Diameter of rotor : 2 m
3. Diameter of hub : 0.1446 m (taken in proportion to the 500 kW prototype)
4. Density : 1.14 kg/m^3 (Local density at Kethanure)
5. Shaft Tilt angle : 2° (taken as of 500 kW prototype)
6. Blade Cone angle : 6° (taken as of 500 kW prototype)
7. Solidity : 0.042 ($\frac{BladeArea}{SweptArea}$ found by modeling in SolidWorks)
8. Cp : 0.45 *
9. λ (tip speed ratio) : 8 (for 3 bladed stall regulated Wind Turbine) *

$$\lambda_{2b} = \lambda_{3b} \times \sqrt{1.5}$$
$$= 8 \times \sqrt{1.5}$$
$$= \mathbf{9.8}$$ (Same as 500 kW machine)

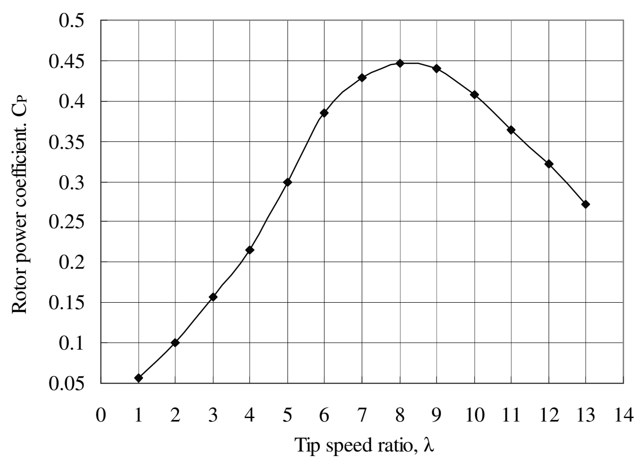
10. Wind speed :

- Cut-in speed : 4.5 m/sec
- Cut-out speed : 34 m/sec
- Average speed : 6.5 to 7 m/sec (As per Indian site conditions)
- Speed at Rated output : 14 m/sec ($V_{des} \approx V_{av} X 2$ for stall regulated HAWT)

Propulsion Division

Input for the Analysis

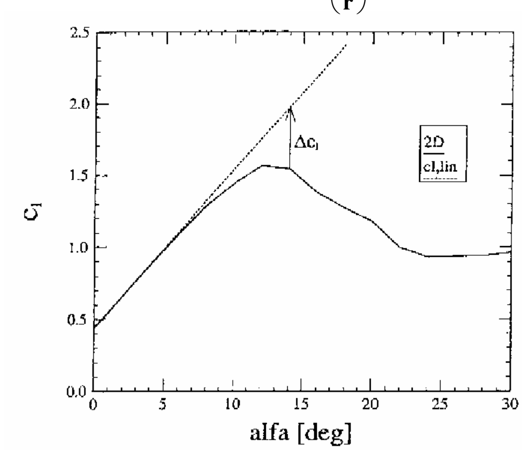
Sizing of the turbine



Ref:- Kishor Kumar and Krishna Murthy S.J., " *Aerodynamic Design and Analysis of a 500 kW Horizontal Axis Wind Turbine Rotor Blades",* PD-PR-0514, NAL Bangalore, October 2005

Various Empirical relations for Aerofoil characteristics

$$Cl_{3-D} = Cl_{2D} + 3\left(\frac{c}{r}\right)^2 \Delta Cl$$



Snel, H., Houwink, R., and Piers, W. J., *''Sectional Prediction of 3-D Effects for Separated Flow on Rotating Blades,''* Eighteenth European Rotorcraft Forum, Avignon, France, 1992.

Various Empirical relations for Aerofoil characteristics

Viterna-Corrigan Post-stall correction

At angle of attack $\alpha > \alpha_s$, we have value of C_l and C_d as below:

$$\mu > 50 \Rightarrow C_{d,\max} = 2.01$$

$$\mu \le 50 \Rightarrow C_{d,\max} = 1.11 + 0.018\mu$$

$$K_L = \frac{(C_{l,s} - C_{d,\max} \sin\alpha_s \cos\alpha_s)\sin\alpha_s}{\cos^2\alpha_s}$$

$$K_D = \frac{C_{d,s} - C_{d,\max} \sin^2\alpha_s}{\cos^2\alpha_s}$$

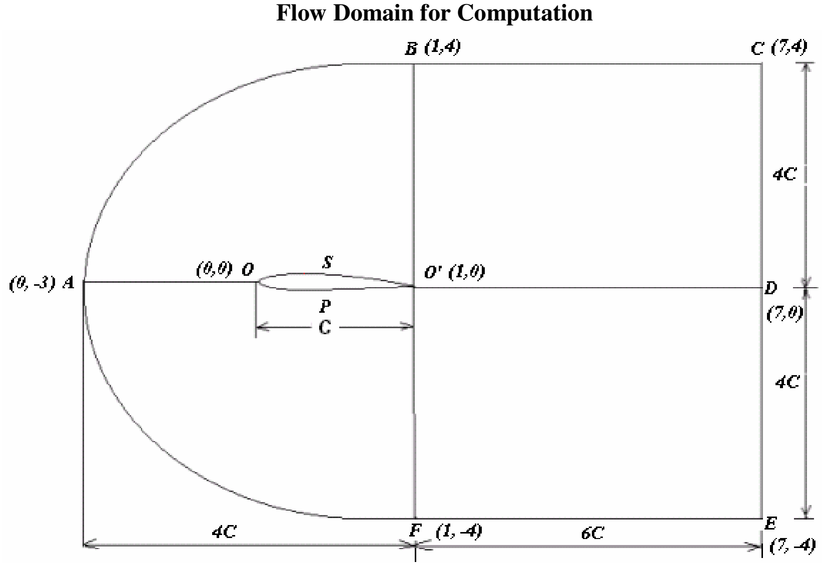
$$C_l = \left(\frac{C_{d,\max}}{2}\right)\sin 2\alpha + K_L\left(\frac{\cos^2\alpha}{\sin\alpha}\right)$$

$$C_d = C_{D,\max}\sin^2\alpha + K_D\cos\alpha$$

Viterna, L. A., and Corrigan, R. D., *"Fixed Pitch Rotor Performance of Large Horizontal Axis Wind Turbines"*, NASA Lewis Research Center, NASA Conf. Pub. 2230/DOE pub. CONF 810732, Cleveland, Ohio, July 1981

Numerical Investigation of Aerofoil Characteristics

Flow Domain for Computation



Numerical Investigation of Aerofoil Characteristics

Usage of *IMPRANS* code developed by
Computational & Theoretical Fluid Dynamics Division
for obtaining 2-D aerofoil characteristics

SALIENT FEATURES OF *IMPRANS*

- *IMP*licit finite volume nodal point scheme for *RANS* equations
- Numerical Scheme evolved by combining basic ideas of
  - *Implicit finite difference technique of Beam and Warming*
  - *Nodal point schemes due to Ni and Hall*
  - *Cell-centered finite volume schemes due to Deiwert, Hollanders and Lerat*
- Dual time stepping approach *(due to Jameson)*
  - *Implicit Second order backward differencing in real time*
  - *Euler implicit time differencing in pseudo time*
- Finite volume nodal point spatial discretization - Control volume formed by joining the centroids of the neighbouring cells
- Second and fourth order artificial dissipation terms
- Algebraic eddy viscosity model due to Baldwin and Lomax
- Computation carried out in the inertial frame of reference
- Grid fixed to the moving body
- Body motion and transition location prescribed

CTFD Division

Numerical Investigation of Aerofoil Characteristics

Sample Input parameters for the calculation :

(1) Profile Name	:	NASA LS(1) – 04XX
(2) Co-ordinates	:	Design Co-ordinates
(3) Reynolds Number	:	$4 \text{ X } 10^6$
(4) Mach Number	:	0.15
(5) Angle of Attack	:	$- 10^o$ to 30^o
(6) Artificial Viscosity Co-efficient	:	0.01 to 0.03
(7) Number of iterations	:	3000
(8) Grid	:	247 X 65

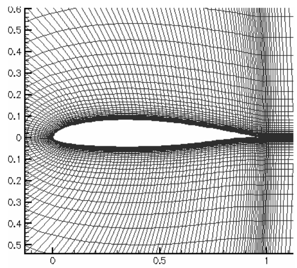
CPU Usage (obtained after computation is carried out by code)

Approximately 35 min. for 3000 iterations

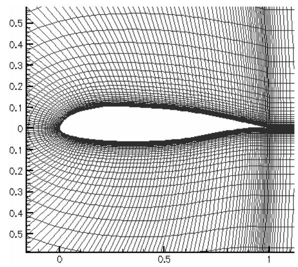
Propulsion Division

Numerical Investigation of Aerofoil Characteristics

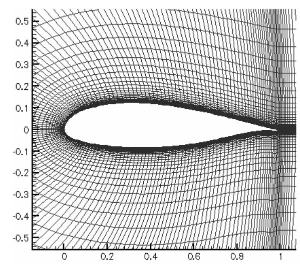
C type grid used for analysis



NASA LS(1) 0413 MOD



NASA LS(1) 0417 MOD



NASA LS(1) 0421 MOD

Numerical Investigation of Aerofoil Characteristics

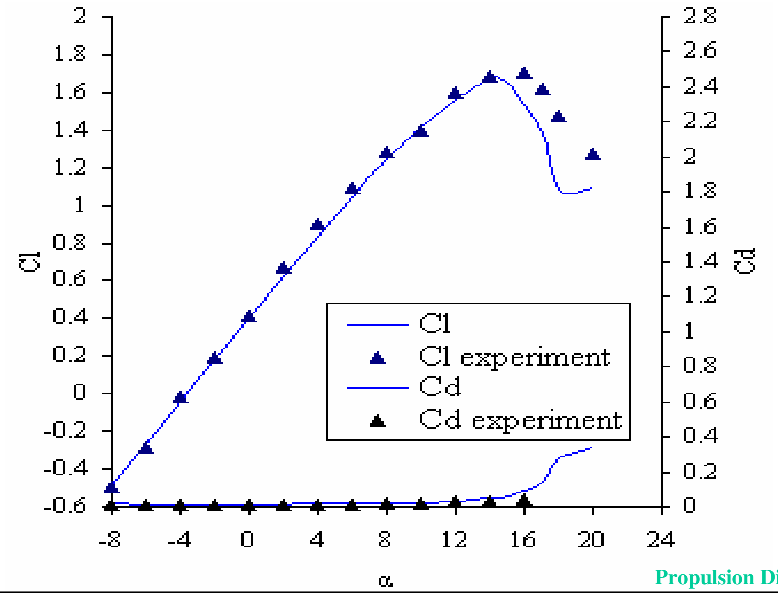
Usage of CFD-ACE+ available at
Centre for Mathematical Modelling And Computer Simulation
for obtaining 2-D aerofoil characteristics

SALIENT FEATURES OF *CFD-ACE+*

- Unstructured, poly-hedral flow solver.
- Cell-centered control volume solution approach.
- Solves the Favre-averaged Navier-Stokes equations using finite-volume approach.
- FVM applied to structured, multi-domain, non-overlapping, non-orthogonal, body-fitted grid.
- Algorithm is pressure based.
- Code able to solve laminar and turbulent, incompressible and compressible, 2-D and 3-D, steady as well as unsteady flow.
- Several turbulent models available in the code such as Baldwin-Lomax, Launder and Spalding k-ε, RNG k-ε and k-ω.
- CFD-ACE is able to handle domain interfaces where the number of cells in adjacent domains are not equal, although each cell in the coarser-grid domain must exactly interface with an integer number of cells in the finer-grid domain.

Numerical Investigation of Aerofoil Characteristics

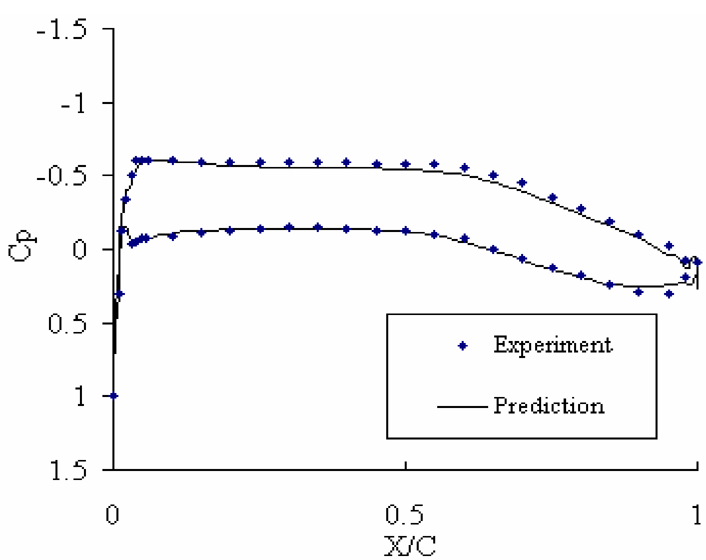
Characteristics of NASA LS(1) 0413 MOD



Propulsion Division

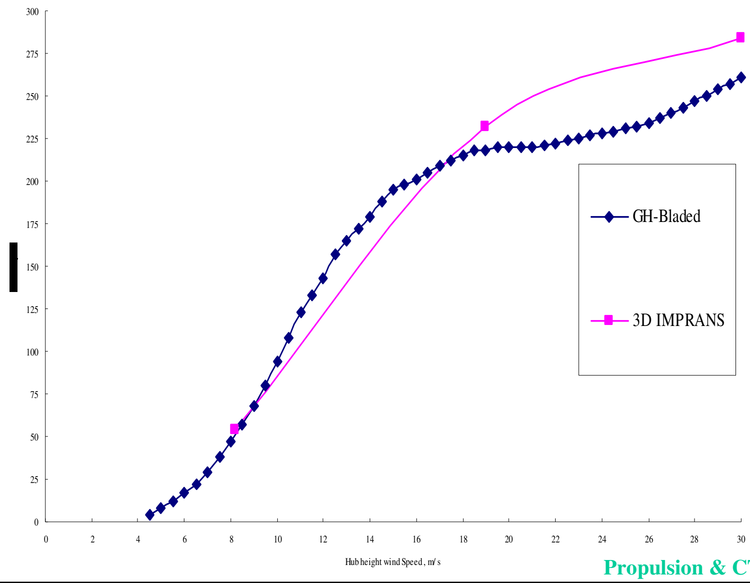
Numerical Investigation of Aerofoil Characteristics

Cp variation of NASA LS(1) 0413 MOD at 0 deg angle of attack



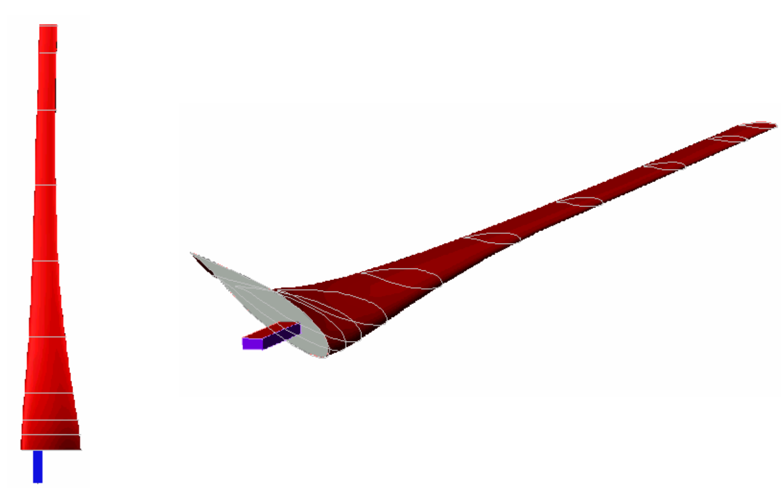
Propulsion Division

Numerical Investigation of Wind Turbine POWER CURVE



Propulsion & CTFD Division

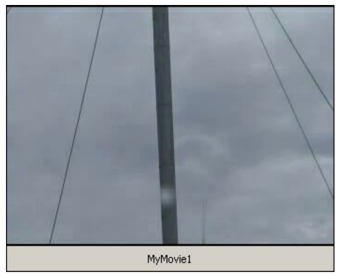
WIND TURBINE BLADE



Propulsion Division

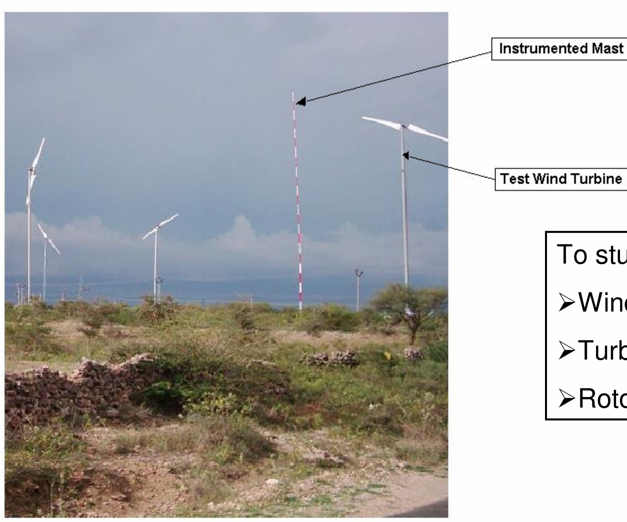
Wind Energy Division

Fibre Reinforced Plastics
Division



Click here for the movie

Field studies at Sangeeth wind farm, Kethanur



50m instrumented mast and test wind turbine-Sangeeth Wind Farm, Kethanur, Coimbatore District.

To study:

- Wind pattern
- Turbine performance
- Rotor characteristics

NAL

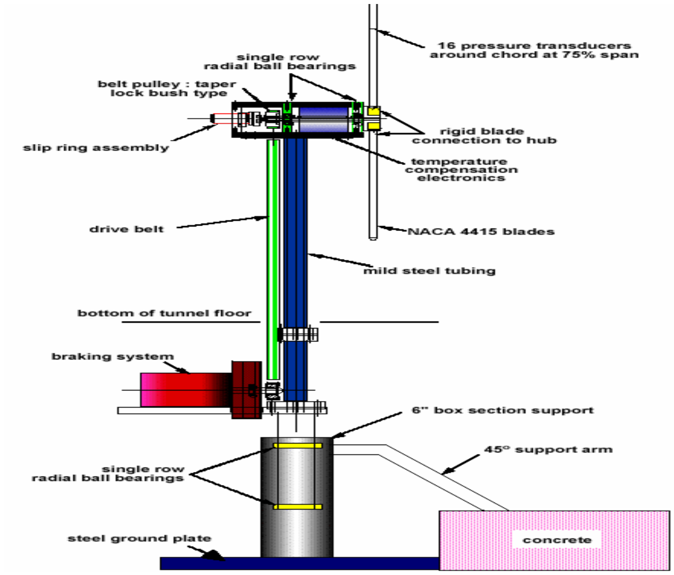
Conclusion
&
Future Scope

Conclusion

- Comparative study of analysis of wind turbine by BEMT, WTPE and GH-Bladed is carried out.
  - BEMT with Prandtl Hub-Tip loss and transition factor gives good match with the analysis from GH-Bladed.
  - Power prediction from BEMT and WTPE are on higher side at higher wind velocity. This is because no post-stall correlations have been included in them.
- A preliminary study of available CFD tools have been done while investigating the aerofoil characteristics. For thin aerofoil profile and in the attached flow regime, IMPRANS code gave good prediction for Cl.
- Parametric Study of the wind turbine under consideration is carried out using GH – Bladed software so as to analytically get an understanding of change in various parameters of the rotor on the turbines output and characteristics.

Future Works

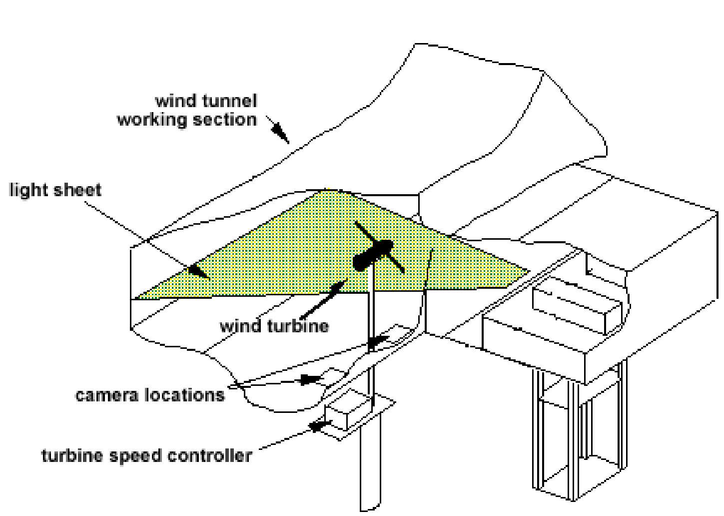
Experimental 2 meter diameter Stall Regulated Wind Turbine



Propulsion Division

Future Works

Experimentation of 2 m diameter Stall Regulated Wind Turbine



Joint project between the Department of Aerospace Engineering, University of Glasgow and the Fluid Loading and Instrumentation Centre of the Department of Civil and Offshore Engineering at Heriot-Watt University

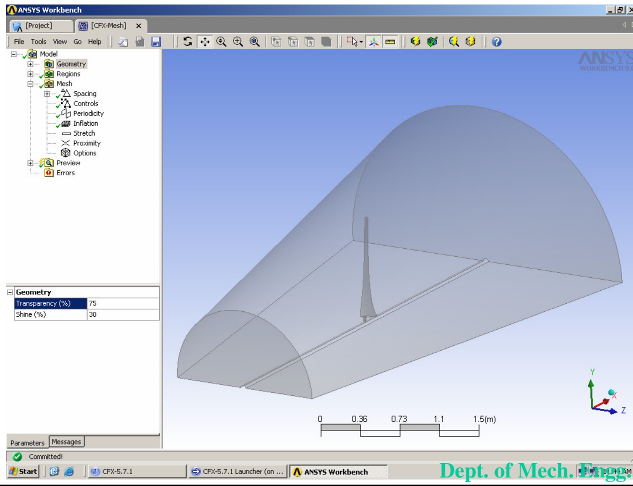
Propulsion Division

Future Works

An attempt to do 3D analysis of Wind turbine with CFD software

Usage of commercial CFD software package *CFX* for obtaining 3-D analysis of Wind Turbine

IMPORTING FLOW DOMAIN IN .igs FORMAT IN ANSYS WORKBENCH



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Future Works

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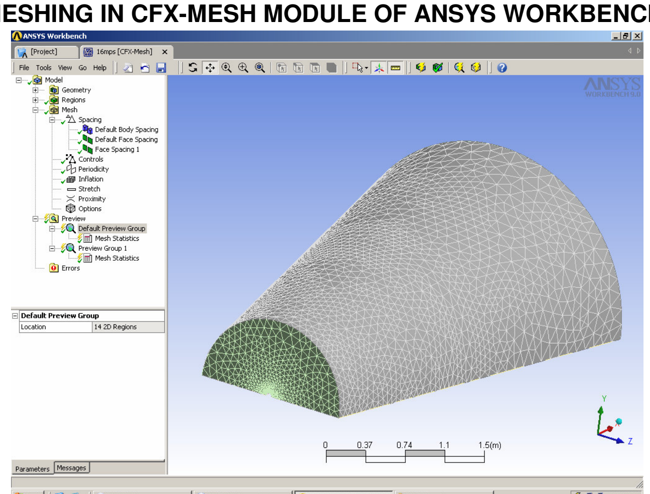
Usage of commercial CFD software package *CFX* for obtaining 3-D analysis of Wind Turbine

MESHING IN CFX-MESH MODULE OF ANSYS WORKBENCH



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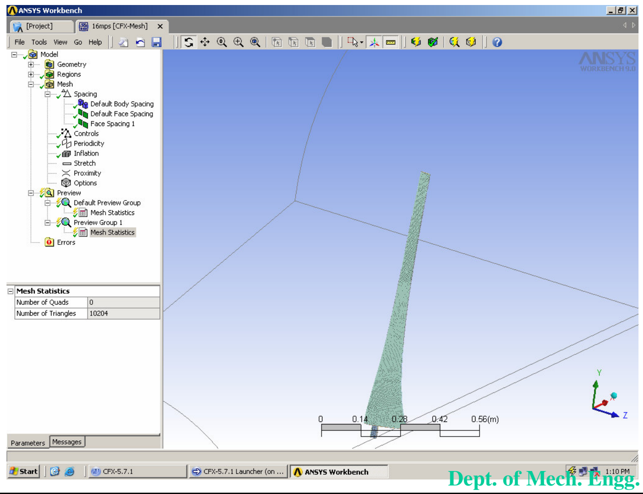

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Future Works

An attempt to do 3D analysis of Wind turbine with CFD softwares

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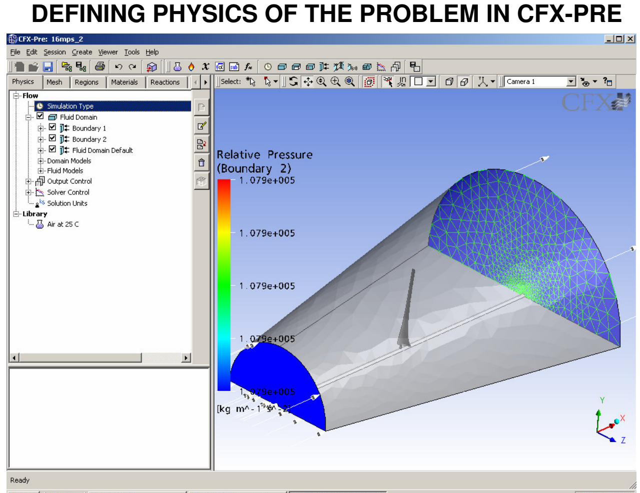
DEFINING PHYSICS OF THE PROBLEM IN CFX-PRE



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Thank you