Exercise Problem

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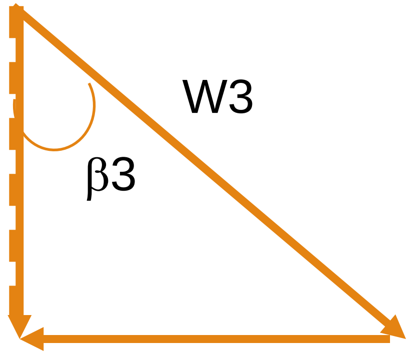
The flow at exit from a turbine stator row has a velocity of 100 m/s at an angle (α_2) of 70° to the axial direction. Calculate the tangential and axial velocity components. The rotor row is moving with a velocity of 50 m/s. Calculate the velocity magnitude relative to the rotor blades at inlet and the relative inlet flow angle (β_2). At exit from the rotor row the relative flow angle (β_3) is $-60°$. Assuming that the axial velocity is constant across the row, what is the absolute exit velocity magnitude and direction? *Answer:* 94.0 m/s, 34.2 m/s; 55.7 m/s, 52.1°; 35.4 m/s, $-15.1°$

For the turbine above, assuming that the relative flow at exit from the rotor row is unchanged, calculate the blade speed that would give absolute axial flow at exit (i.e. no swirl) *Answer:* 59.2 m/s



Lecture 4

Basic velocity triangle relationships revisited

Exercise problem

Velocity Triangle for Wind Turbines

Airfoil operation and testing

Problem

Basic Velocity Triangle Relationships

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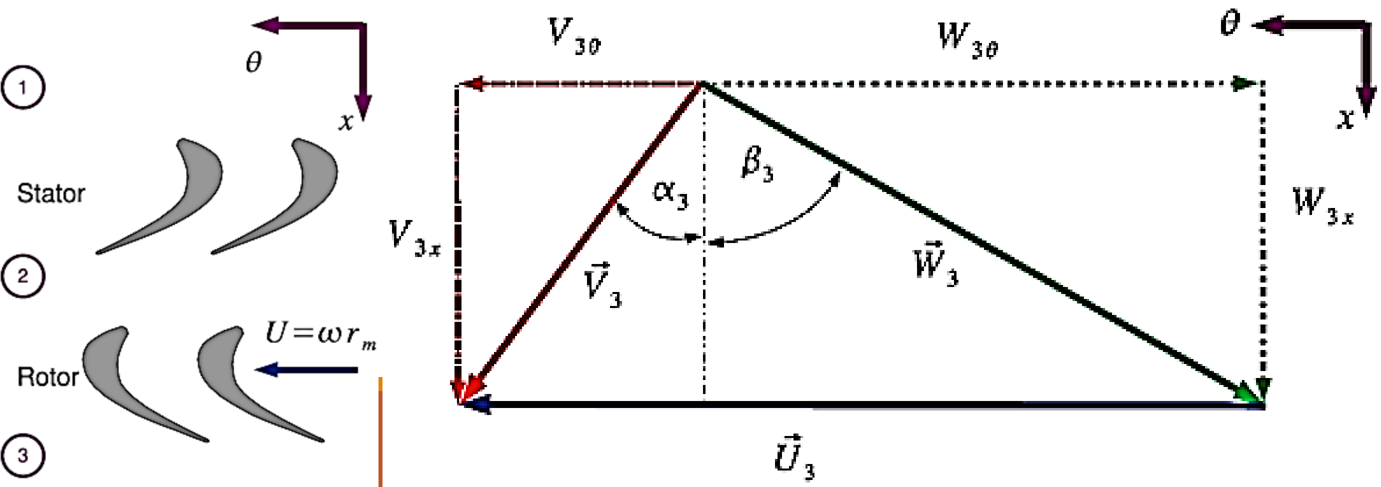
Note that velocity triangles are drawn for 2D cascade arrangement. Hence

- *Tangential and axial direction* would be considered for *axial flow machines* and
- *Tangential and radial direction* would be considered for *radial flow machines*.

$$V_x = V\cos\alpha = W\cos\beta = Wx$$

$$V_\theta = V\sin\alpha = U + W\sin\beta = U + W_\theta$$

For axial flow machine



Basic Velocity Triangle Relationships

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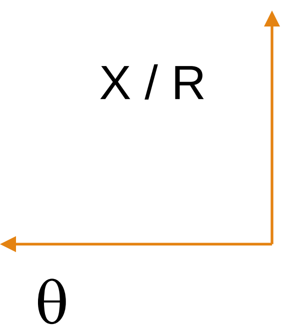
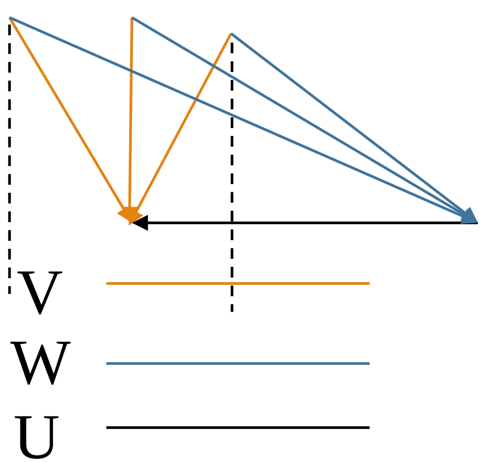
$$V_x = V\cos\alpha = W\cos\beta = Wx$$

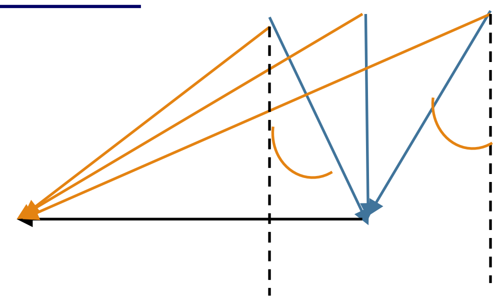
$$V_\theta = V\sin\alpha = U + W\sin\beta = U + W_\theta$$

Lets test above relations for +ve, zero and –ve value for α & β

- *Use board to explain individual cases*







Wind Turbines

Introduction

Airfoil

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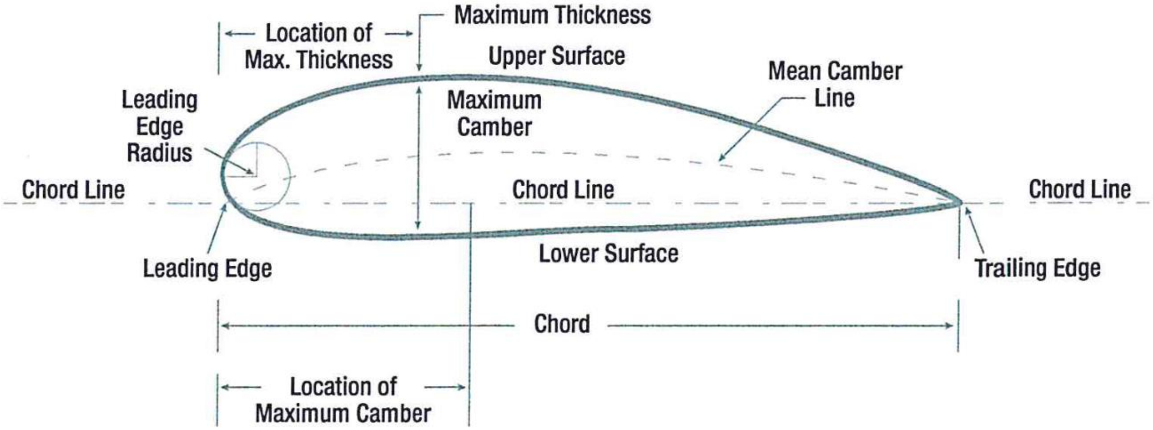


Figure 2-9. Chord and camber of a wing.

The *mean camber line* is the locus of points halfway between the upper and lower surfaces as measured perpendicular to the mean camber line itself.

Camber: distance between chord line and mean camber line
Thickness: distance between upper and lower surface

Nomenclature of airfoil

Four-digit series: NACA

Example: NACA0012, NACA2412

First digit: maximum camber in hundredths of chord (__*cord length/100)

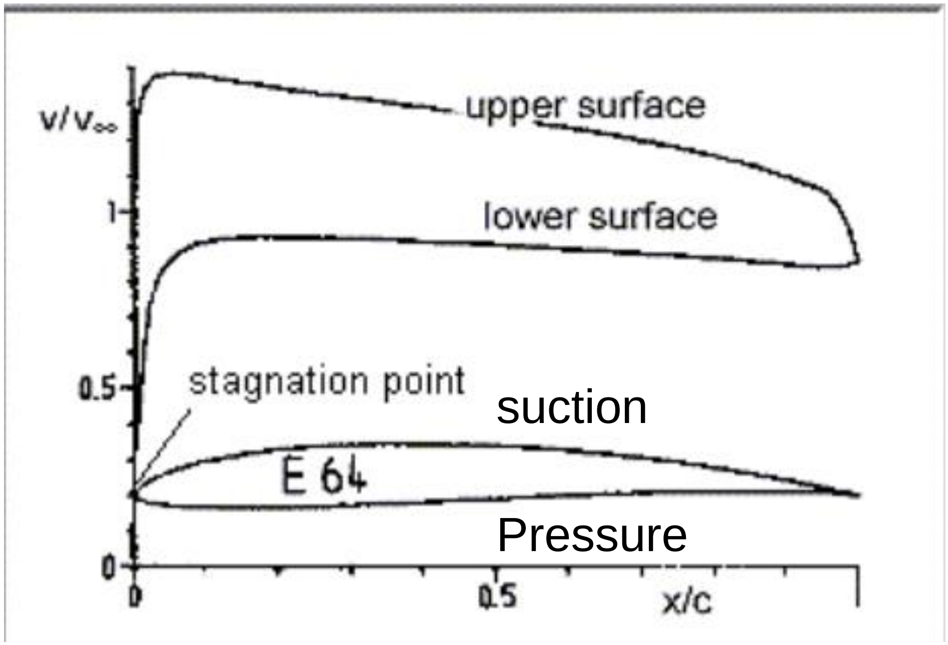
Second digit is the location of maximum camber along the chord from the leading edge in tenths of chord (__*cord length/10)

last two digits give the maximum thickness in hundredths of chord (__*cord length/100)

For the NACA 2412 airfoil, the maximum camber is 0.02c located at 0.4c from the leading edge, and the maximum thickness is 0.12c (c : chord length).

NACA00xy: symmetric airfoils

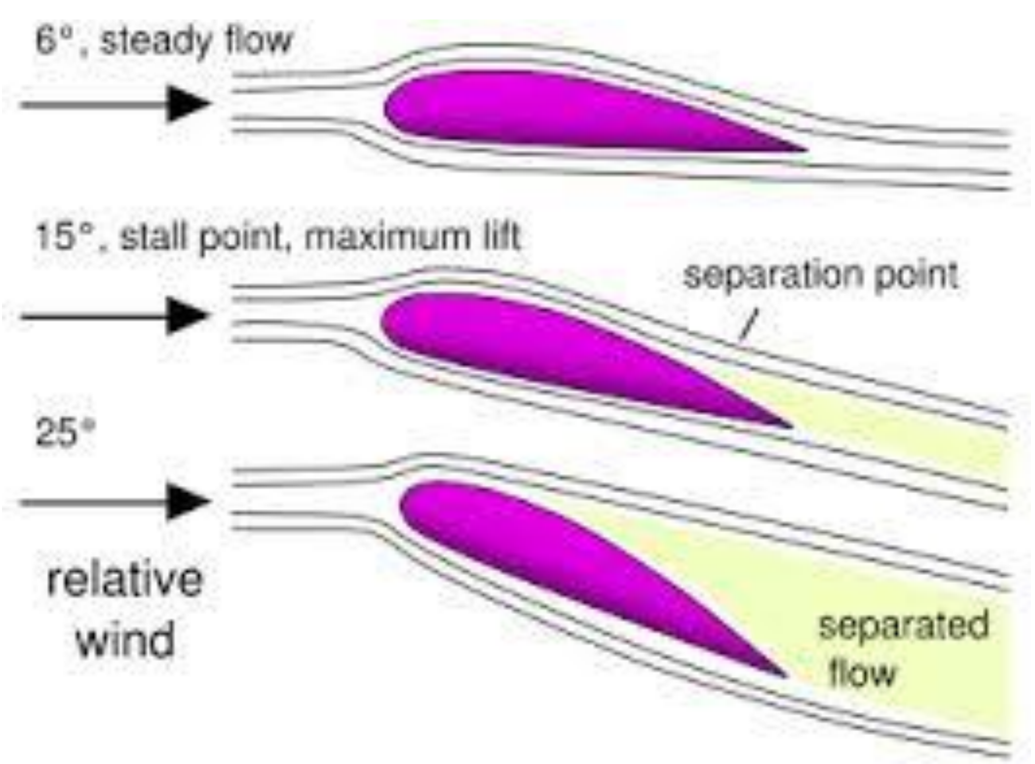
Aerodynamic forces on airfoil



Aerodynamic forces are generated due to variation in static pressure distribution on two sides of airfoil surface.

- *Bernoulli's equation would relate variations in static pressure & velocity.*
- *Coanda effect makes the fluid flow adhere to the solid surface which changes the stream tube cross sections to change velocity.*
  - Exception is flow separation where flow turning is excessive

Flow Separation at Higher Incidence Angle.



Incidence angle is angle made by incoming flow direction with chord of airfoil at leading edge.

Lift & Drag Coefficient

Lift and drag are usually expressed in terms of non-dimensional coefficient to allow scaling for size, fluid density and fluid velocity.

- *Lift coefficient*

$$C_L = \frac{L}{\frac{1}{2}\rho W^2 c}$$

- *Drag Coefficient*

$$C_D = \frac{D}{\frac{1}{2}\rho W^2 c}$$

Note that 'L' & 'D' are lift and drag force per unit length of airfoil and 'W' is relative velocity.

Flow over airfoil

- As angle of attack increases, Lift and drag increases
- Lift increases almost linearly with angle of attack but drag increases non-linearly
- At a certain angle of attack, the flow over airfoil separates which leads to sudden decrease in lift. This is called stall
- At a certain angle of attack, Lift/Drag ratio is maximum
- A good airfoil should have higher Lift/Drag ratio

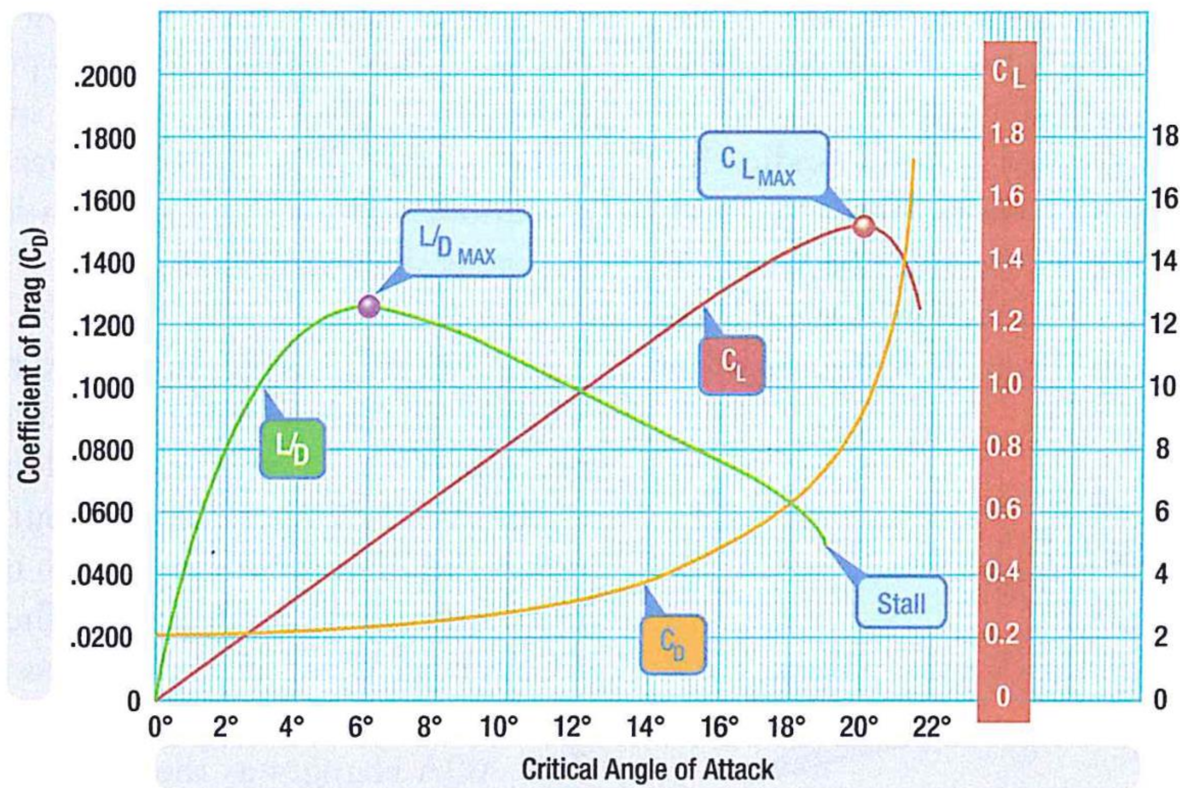


Figure 2-15. Lift Coefficients at various angles of attack.

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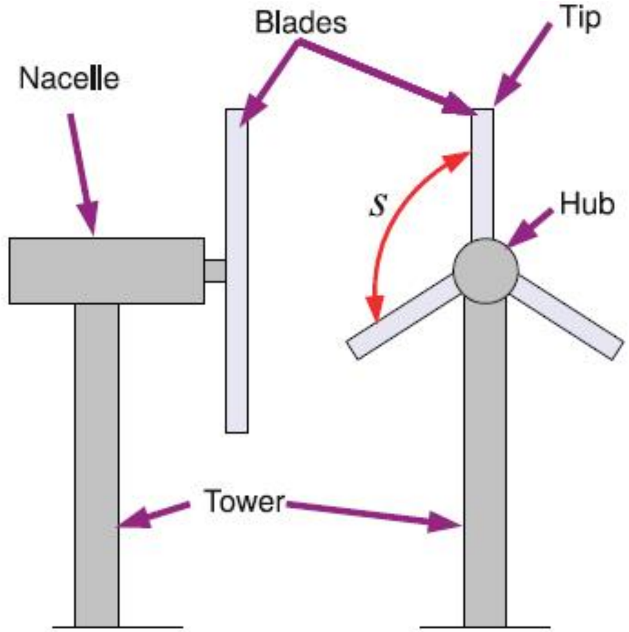
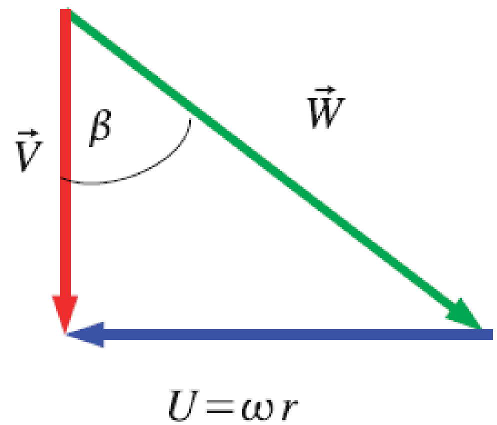
Velocity Triangle for Wind Turbine

Real Wind Turbine

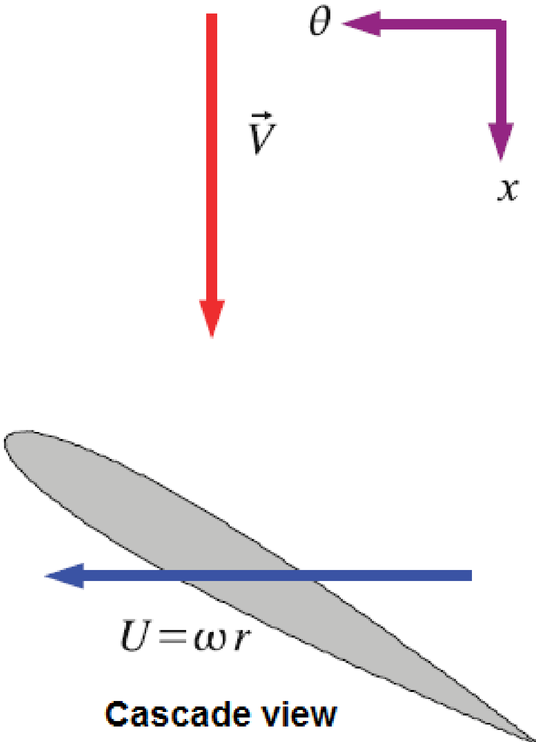


Side View

Front View



Velocity Triangle



Cascade view

Forces on Wind Turbine Blade

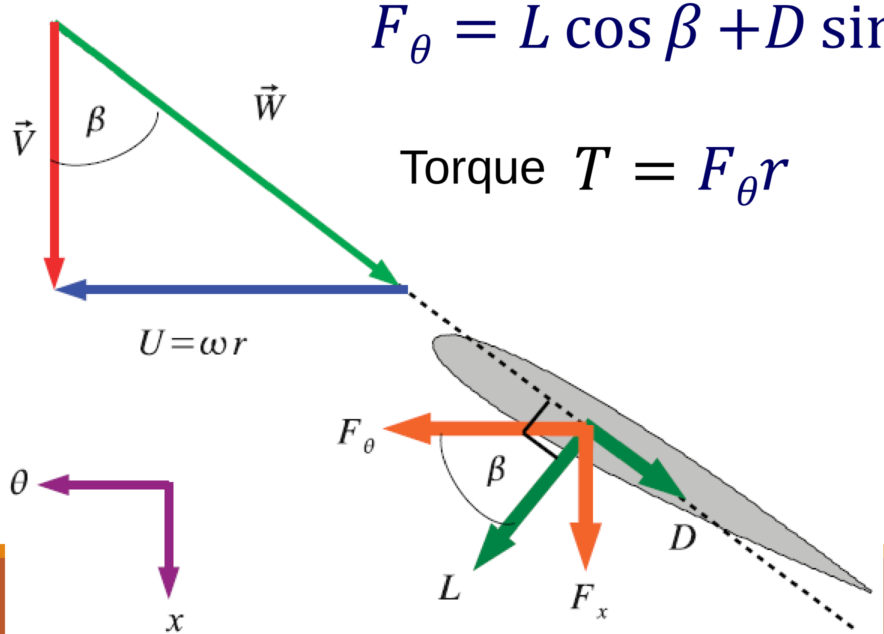
Aerodynamic forces (lift and drag) result into tangential and axial forces on turbine blade.

- *Tangential force produces torque (ultimately power)*
- *Axial force gives load on wind turbine tower.*

$$F_\theta = L\cos\beta + D\sin\beta \qquad F_x = L\sin\beta + D\cos\beta$$

Torque $T = F_\theta r$

Power $P = \int_{r_h}^{r_t} F_\theta r\omega dr$ (r_t: Tip radius, r_h: Hub radius)



Generation of aerodynamic forces needs to be understood

Example A wind turbine is designed to work at a condition with a wind speed of 10 m/s and an air density of 1.22 kg/m^3. The turbine has blades with a NACA 0012 profile and is rotating at one revolution per second. The blade chord length is 0.5 m. Taking the design point at 85% maximum lift condition and ignoring the drag on the aerofoil estimate the power output per unit blade span at a radius of 6 m for each blade.

For NACA 0012 profile 85% maximum lift condition

- $C_L = 1.1$
- *Ignoring drag forces*

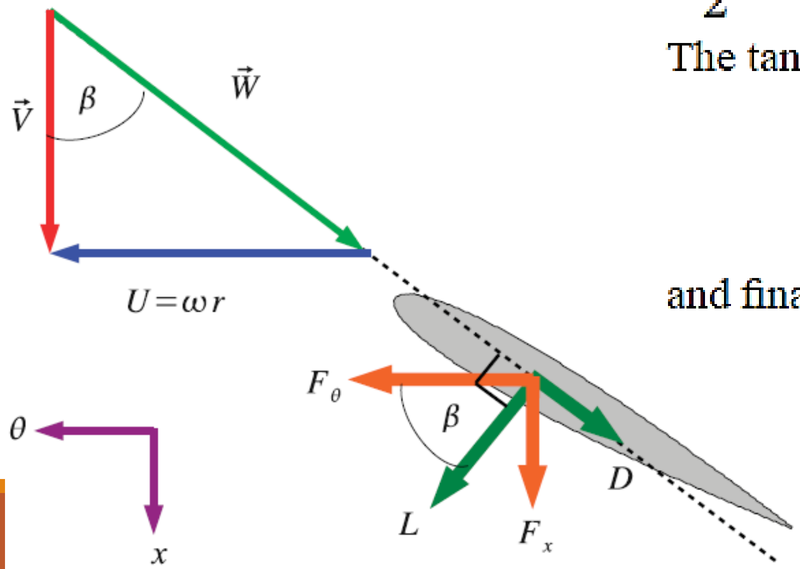
$$U = \omega r = 1 \times 2\pi \times 6 = 37.7\ m/s$$

$$W = \sqrt{U^2 + V^2} = \sqrt{37.7^2 + 10^2} = 39\ m/s$$

$$L = C_L \frac{1}{2} \rho W^2 c = 1.1 \times \frac{1}{2} \times 1.22 \times 39^2 \times 0.5 = 510\ N/m$$

The tangential force per unit span can be calculated:

$$F_\theta = L \cos\beta = 510 \times \cos 75.1^\circ = 131\ N/m$$



and finally the power output per unit span can be calculated

$$P = F_\theta \times \omega r = 131 \times 37.7 = 4939\ W/m$$

Example A wind turbine is designed to work at a condition with a wind speed of 10 m/s and an air density of 1.22 kg/m^3. The turbine has blades with a NACA 0012 profile and is rotating at one revolution per second. The blade chord length is 0.5 m. Taking the design point at 85% maximum lift condition and ignoring the drag on the aerofoil estimate the power output per unit blade span at a radius of 6 m for each blade.

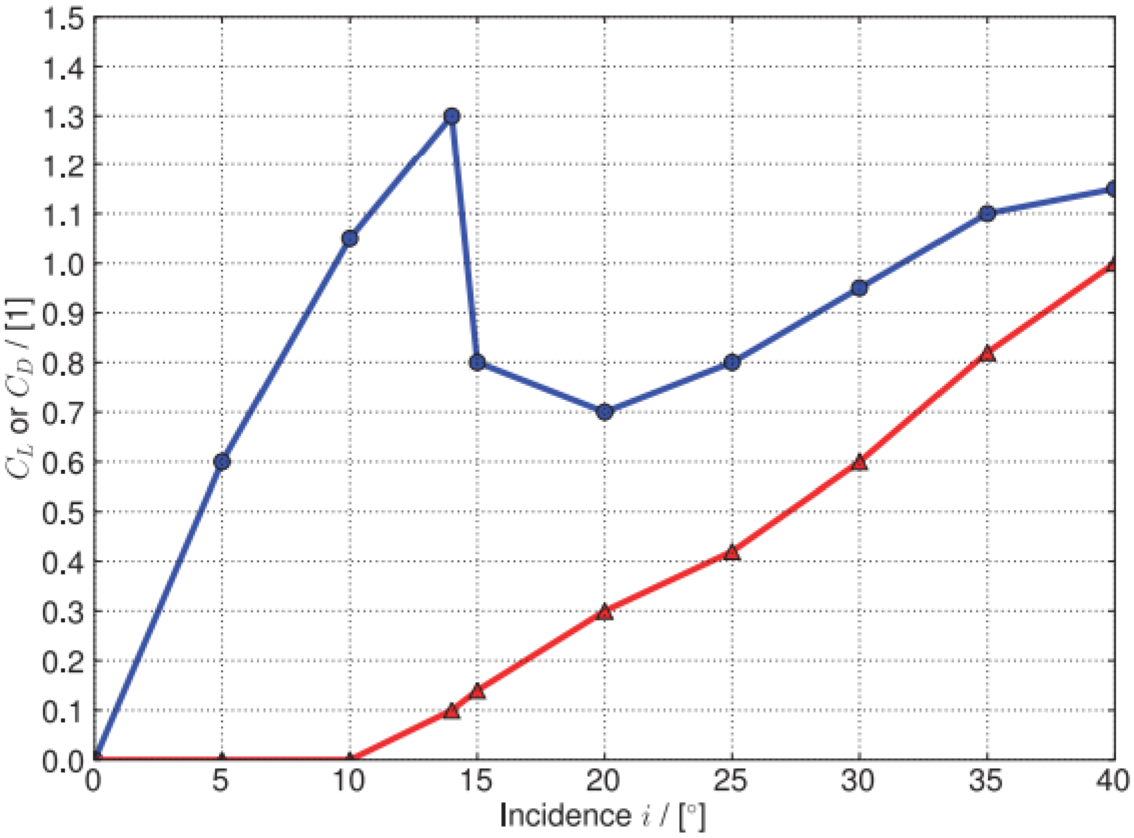


Figure 3.5: C_L and C_D for a NACA 0012 Aerofoil

Lecture 5

Airfoil Nomenclature

Wind Turbine Design

Turbine Power Control

Exercise Problem

Aero-foil Nomenclature

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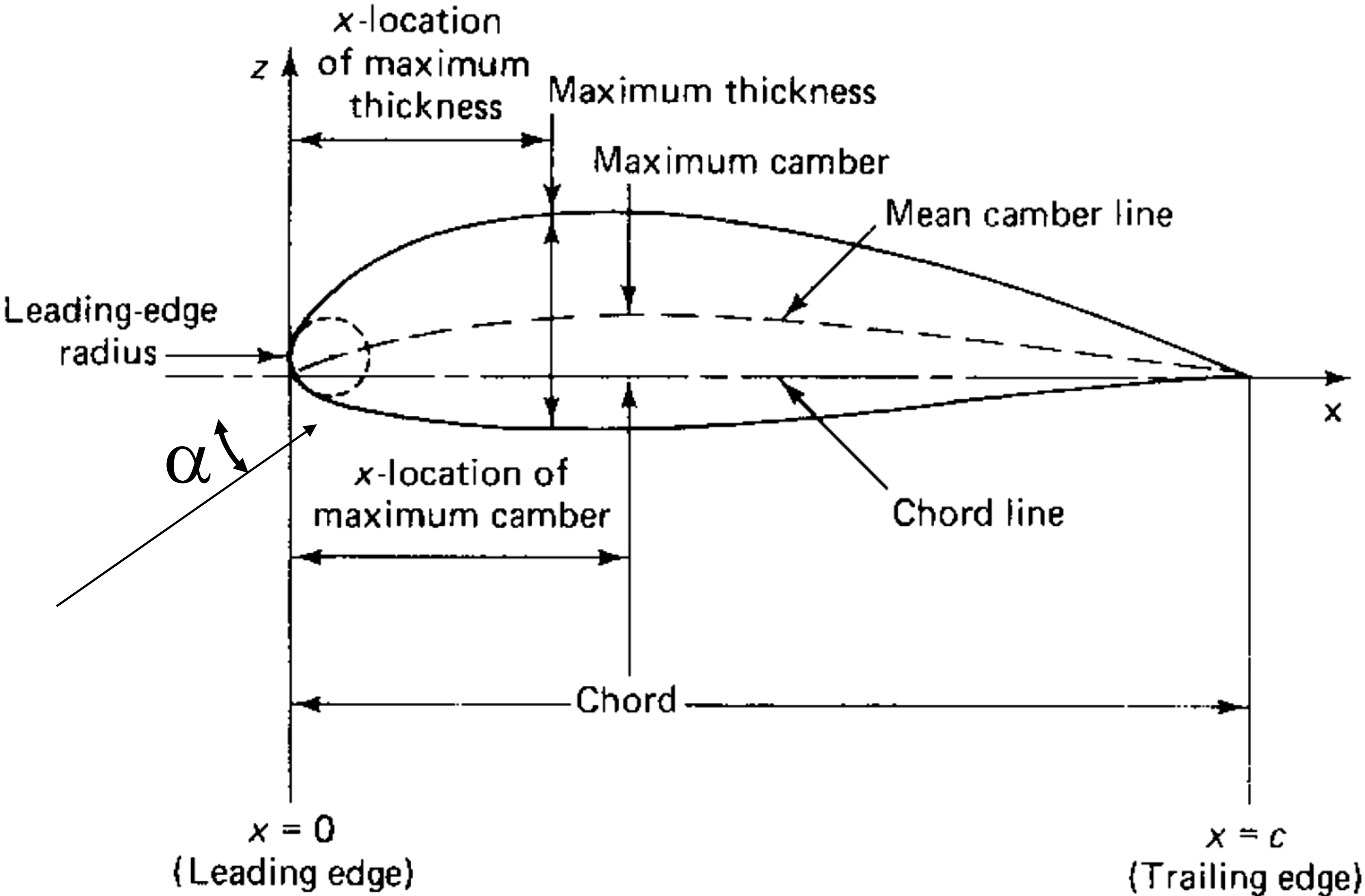


Wind Turbine Design

Wind Turbine Design

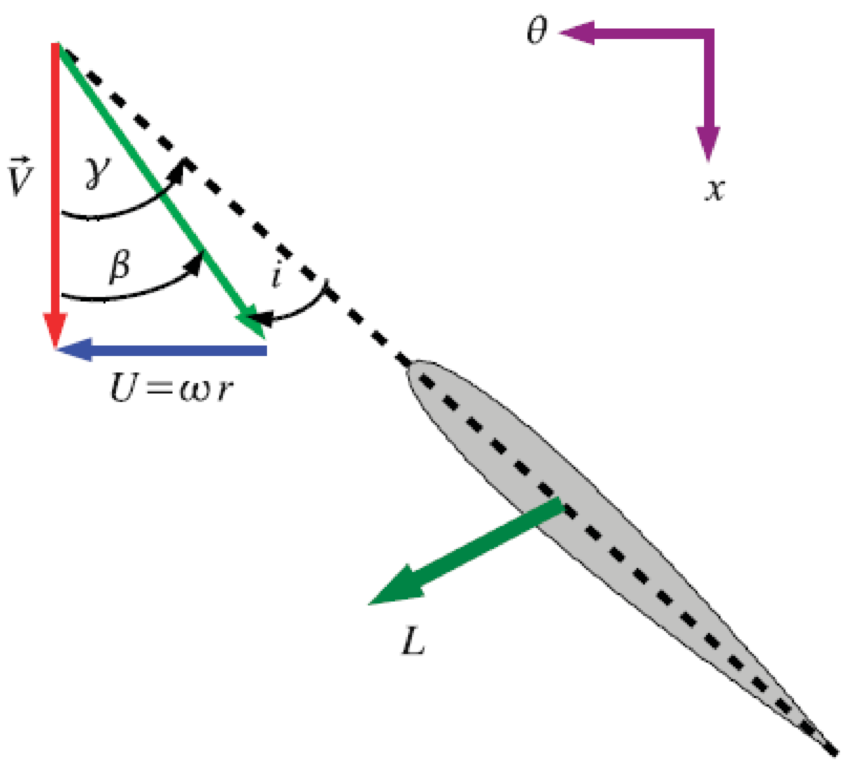
Wind turbine design is the process of defining the form and specifications of a wind turbine to extract energy from the wind.

The shape and dimensions of the blades of the wind turbine are determined by the aerodynamic performance required to efficiently extract energy from the wind, and by the strength required to resist the forces on the blade.

So a aerodynamicist can change:

- *Airfoil shape*
- *Airfoil chord length*
- *Airfoil of blade setting angle.*

Note that i =β - γ or |i| = |β| - |γ|



γ Blade angle
i incidence
β Flow angle

Example For a wind turbine with the same parameters as the previous example. That is: NACA 0012 aerofoil, air density of 1.22 kg/m^3, chord length of 0.5 m, rotational speed of one revolution per second. Calculate the wind speed at which the blade will stall at a 6m radius if the blade angle (γ) remains constant.

γ=? U=37.7, β=-75.1 CL=1.1 corresponding to i=10

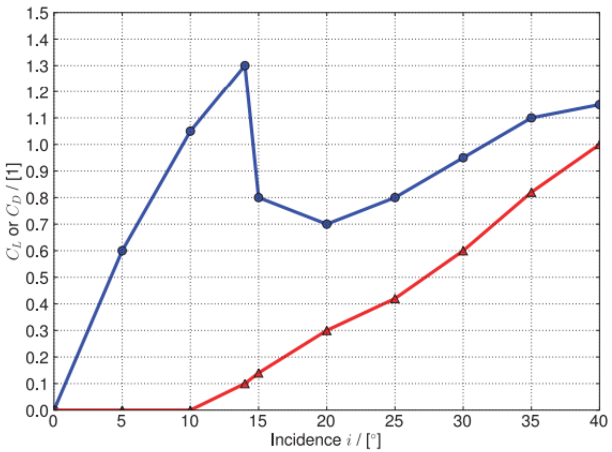


Figure 3.5: C_L and C_D for a NACA 0012 Aerofoil

|γ| = |i|+ |β|= 85.1

In case of stall angle of incidence will become 14

|β|= 85.1-14

tan β =(-U/V)

Calculate V=12.9 m/s

Example If the blade hub section in the example above at a radius of 1.5m is designed to stall at the same wind condition, what would be the local blade angle?

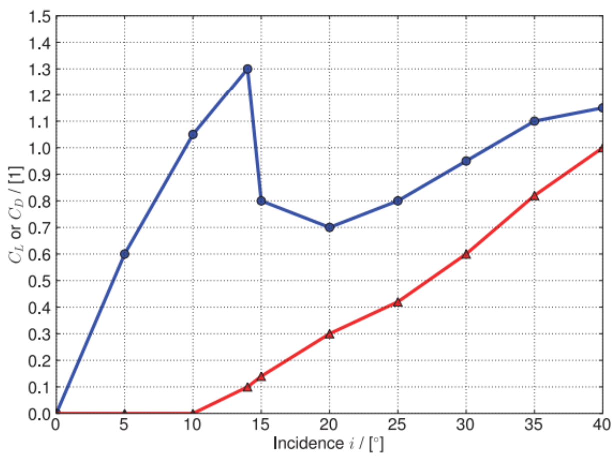
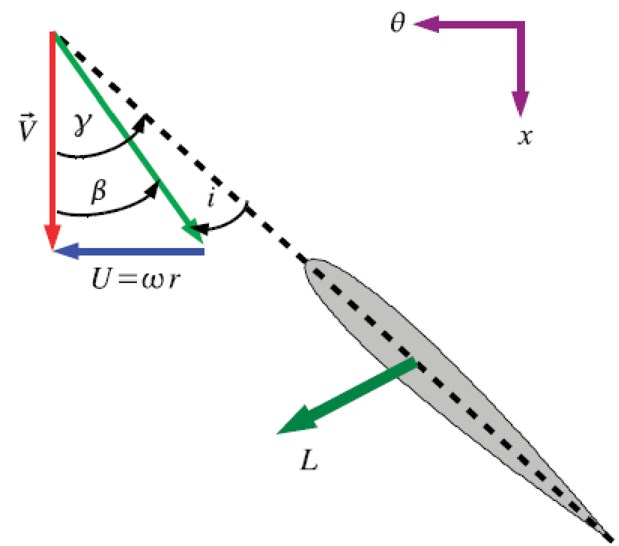


Figure 3.5: C_L and C_D for a NACA 0012 Aerofoil



V=12.9m/s

U=?

β=tan-1(-U/V)

|γ| = |i_stall|+ |β|= 50.1

Angle of incidence

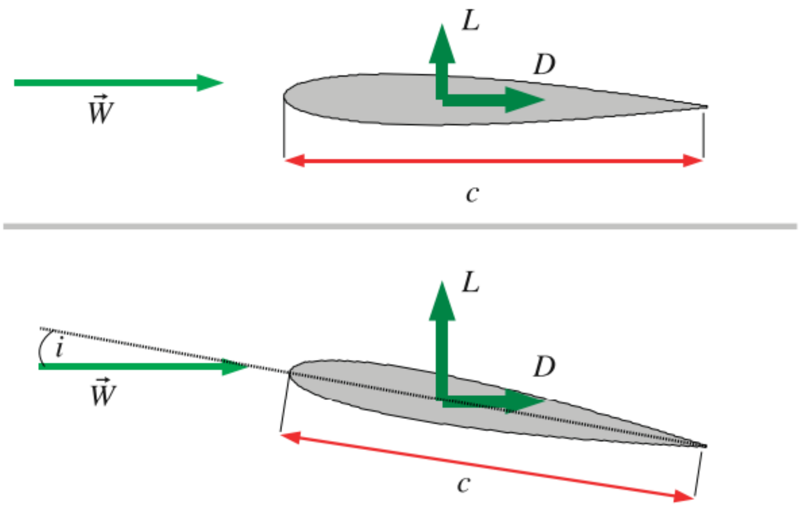
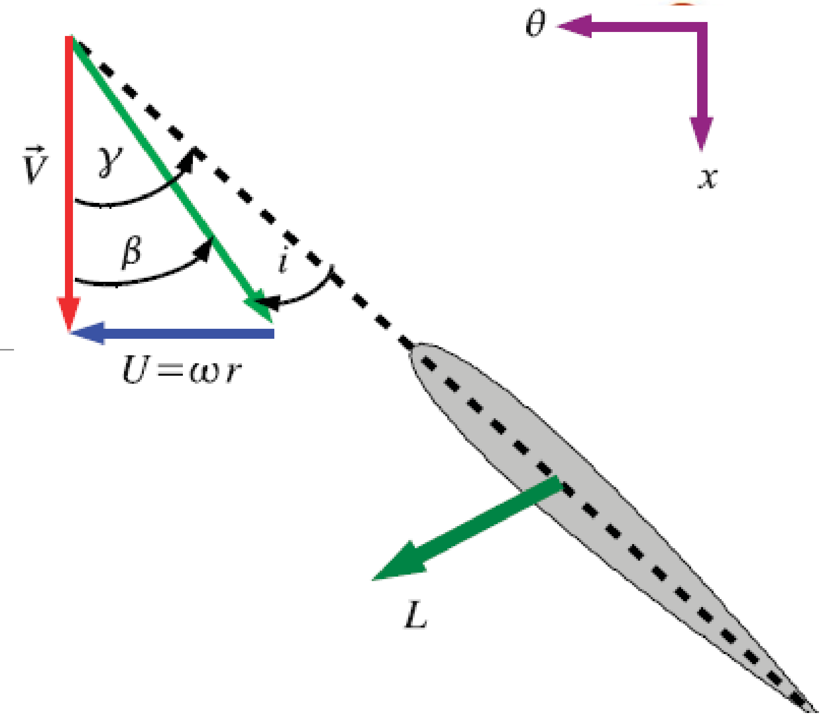
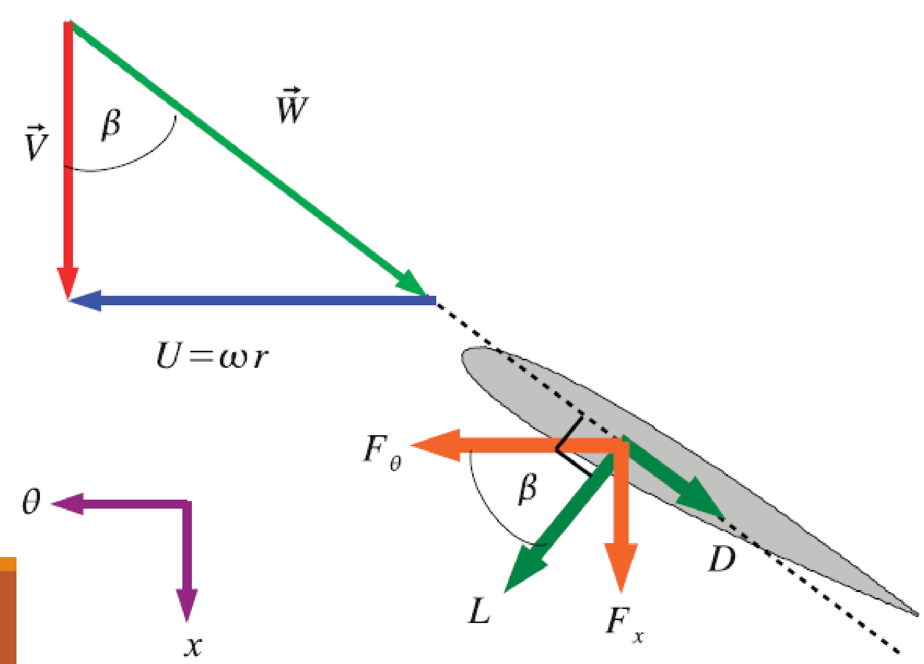


Figure 3.4: Aerofoil at Two Incidences





Turbine Power Control

The speed at which a wind turbine rotates must be controlled for efficient power generation and to keep the turbine components within designed speed and torque limits.

- *The centrifugal force on the spinning blades increases as the square of the rotation speed, which makes this structure sensitive to over-speed.*
- *The power of the wind increases as the cube of the wind speed, turbines have to be built to survive much higher wind loads (such as gusts of wind) than those from which they can practically generate power.*
- *Wind turbines have ways of reducing torque in high winds.*
  - **Yaw and pitch control** are generally used to control power of wind turbine which can be achieved through changing **yaw & blade setting angle**.

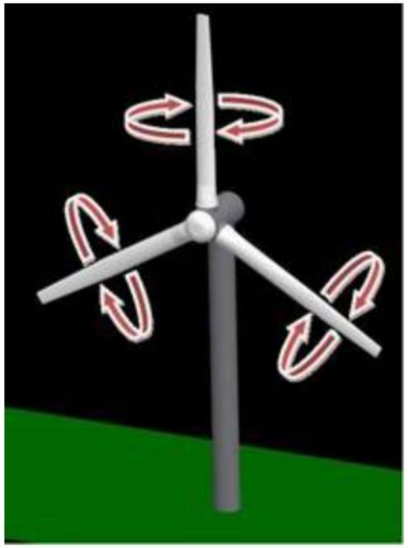


Figure 5. Pitch Adjustment

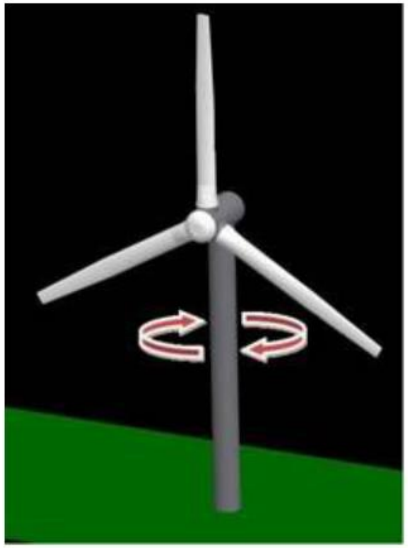


Figure 6. Yaw Adjustment

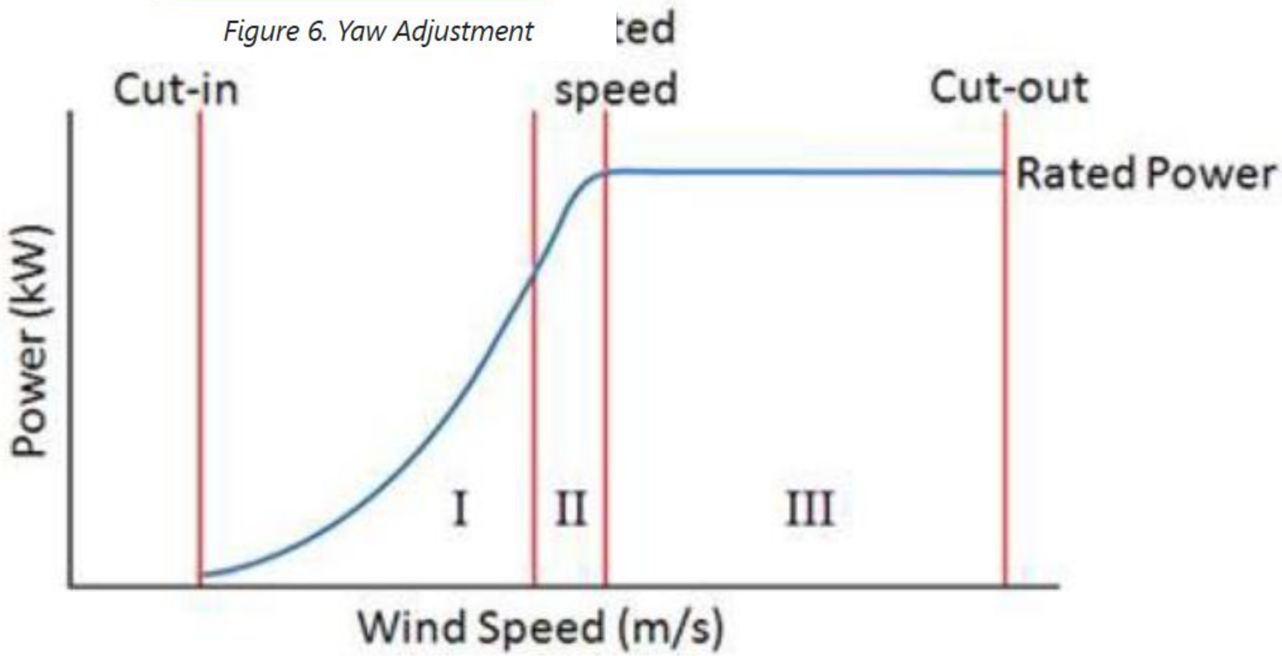


Figure 4. Ideal Wind Turbine Power Curve

Turbine Power Control

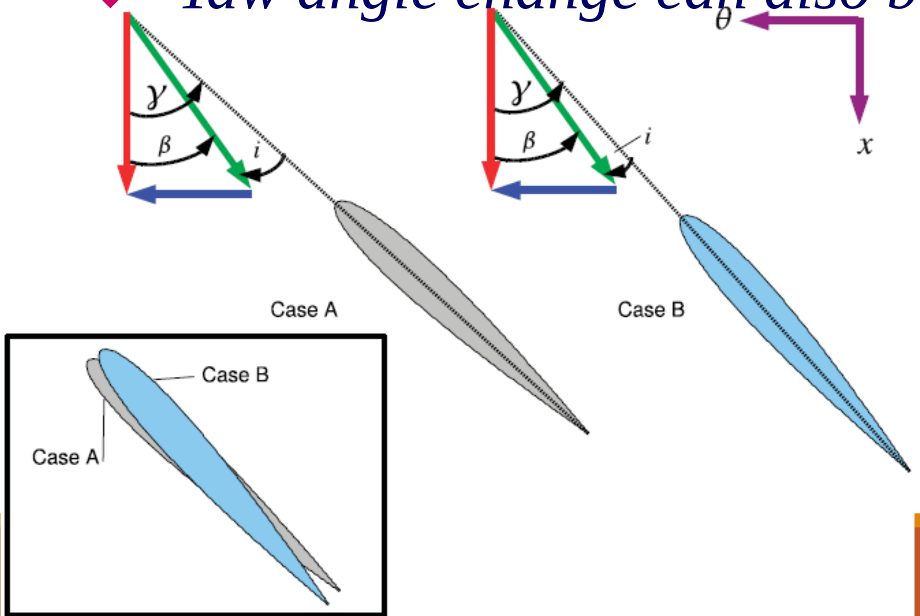
Stall & Pitch Control

1. At higher wind speed blades will stall and lift force will reduce due to which tangential force will also decrease and drag will increase so there is need to ensure the structure can endure the increased axial loading.

Turbine Power Control

Stall & Pitch Control

- *At large incidence angle flow separation leads to sudden decrease in lift generated by blade simultaneously increasing the drag.*
- *Control can be achieved by changing blade setting angle which changes the pitch.*
- *Yaw angle change can also be used to affect lift and power control.*



Turbine Power Control

Yaw & Pitch Control mechanism

[redacted]

[redacted]

Turbine Power Control

Wind Turbine

Blade Pitch Control

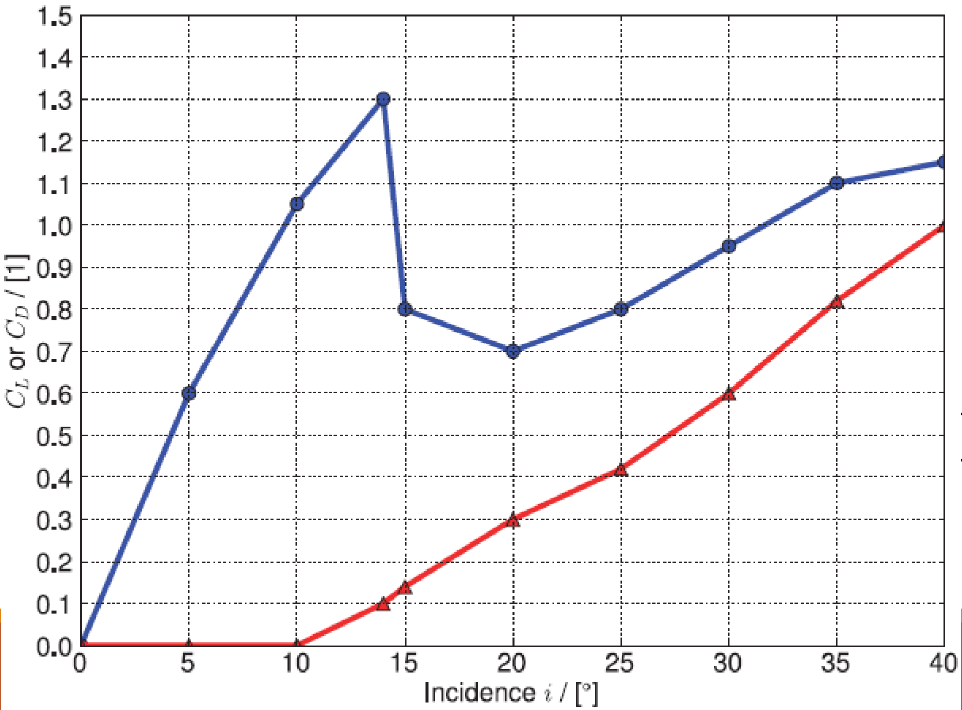
by

www.mekanizmalar.com

A two-blade wind turbine is designed to operate at an atmospheric condition (the air density can be taken as 1.22 kg/m^3) with a wind speed of 22 mph. The turbine blades of 10 m length are attached to a nacelle of a radius of 1 m. A preliminary blading design is considered by using a NACA 0012 profile with a constant chord length of 1.5 m. The rotational speed of the turbine is 30 rev/min. The blading design is taken at a condition corresponding to 80% of the maximum lift.

Calculate the blade angle and the power output per unit blade-span at 20%, 50% and 80% spanwise sections for each blade. Note that the blade starts at radius of 1 m so the tip radius is 11 m. Estimate the total power output of the wind turbine using the results from the three spanwise sections and an approximate integration.

Answers: $-53.8°$; $-72.4°$; $-80.8°$; 1.201 kW/m; 3.75 kW/m; 7.92 kW/m; 86kW



$$L = C_L \frac{1}{2} \rho W^2 c$$

$$F_\theta = L \cos\beta + D \sin\beta$$

$$P = \int_{r_h}^{r_t} F_\theta r \omega dr$$

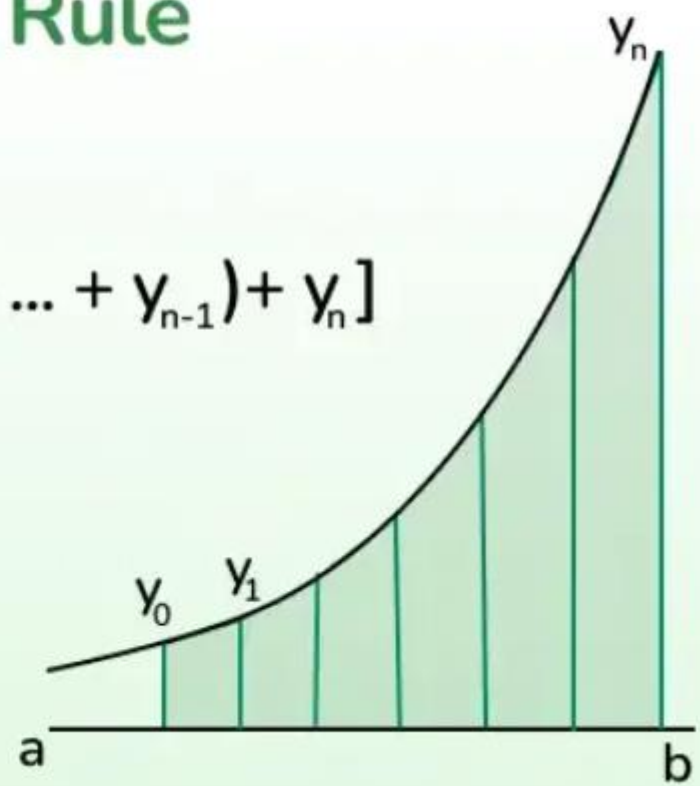
For 80% of maximum lift

- $C_L = 1.04$; $i = 10°$; *neglect drag.*
  - $|i| = |\beta| - |\gamma|$

Trapezoidal Rule

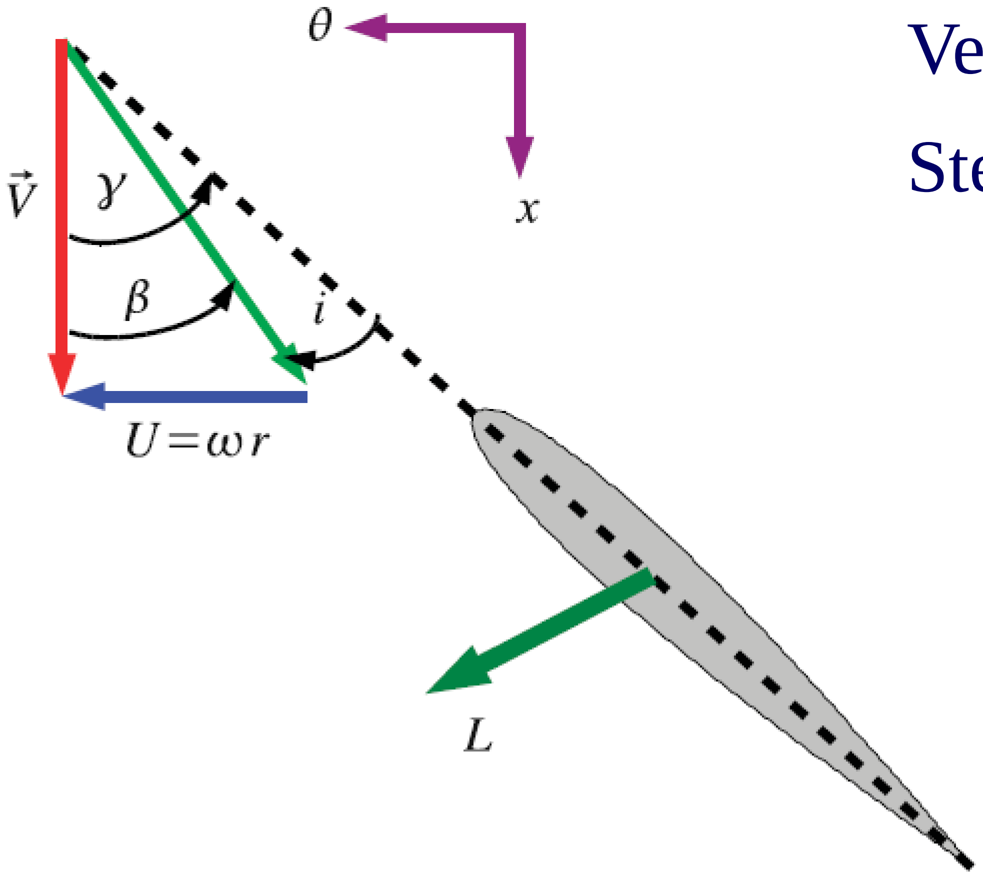
$$\text{Area} = \int_a^b y\,dx \approx \frac{1}{2}h[y_0 + 2(y_1 + y_2 + \ldots + y_{n-1}) + y_n]$$

$$\text{where } h = \frac{b - a}{n}$$



Formula For Trapezoidal Rule

Problem continued



Velocity triangle.

Steps to follow:

- *Get V, U and W magnitudes and directions.*
- *Get blade setting angle gamma at different locations*
- *Find lift force and tangential force on blade per unit span at different locations.*
- *Use the per unit span-wise power estimates to get overall power produced.*