Renewable Energy
Lecture 18: Wind Energy

Grade: 4th Class

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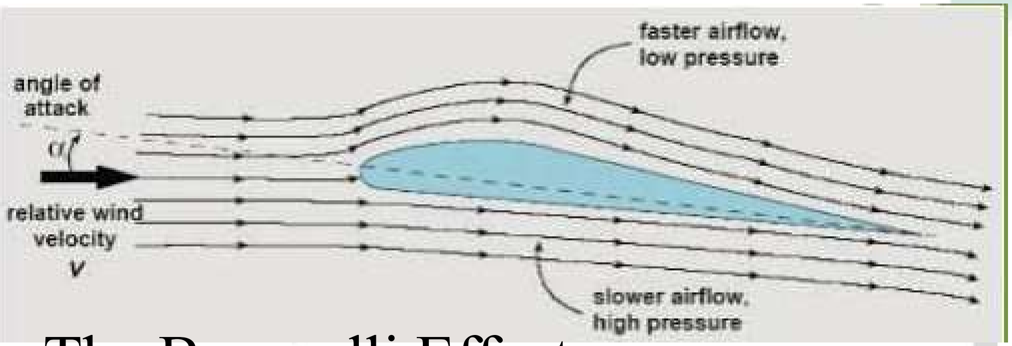
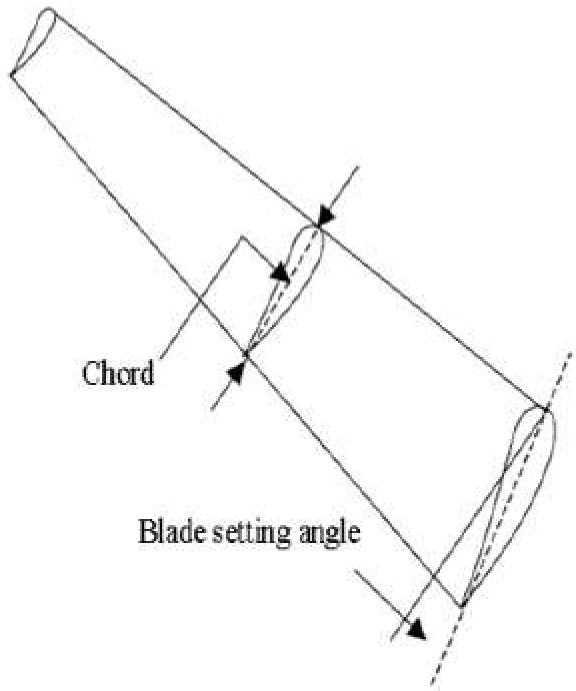
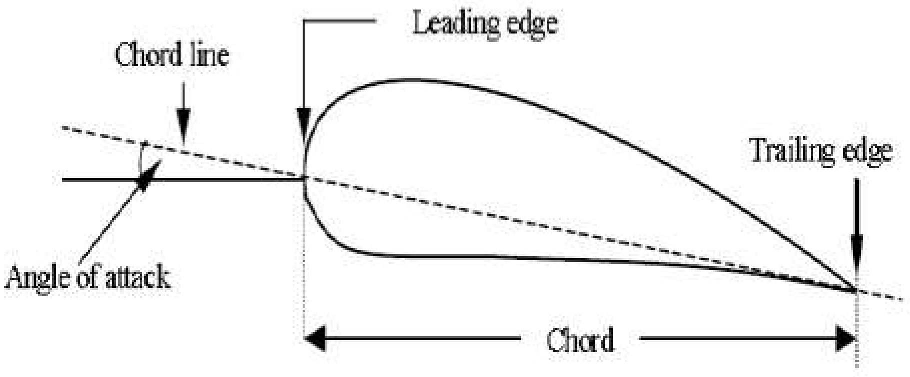
Aerodynamic of Wind Turbines

17-1: Airfoil:



The Bernoulli Effect

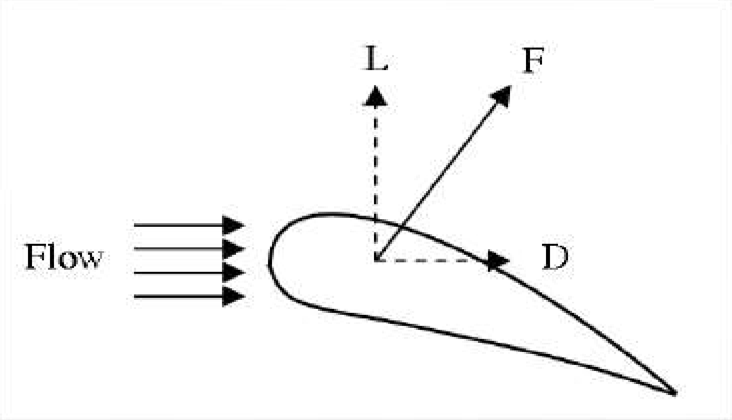




Important parameters of an airfoil

Aerodynamic of Wind Turbines

This pressure difference between the upper and lower surfaces of the airfoil will result in a force **F**. The component of this force perpendicular to the direction of the undisturbed flow is called the lift force **L** (Figure below). The force in the direction of the undisturbed flow is called the drag force **D**



Airfoil lift and drag

The lift force (L) is given by: $L = C_L \frac{1}{2} \rho_a A V^2$

drag force (D) by: $D = C_D \frac{1}{2} \rho_a A V^2$

Lift & Drag Forces

- **The *Lift Force* is perpendicular to the direction of motion. We want to make this force BIG.**

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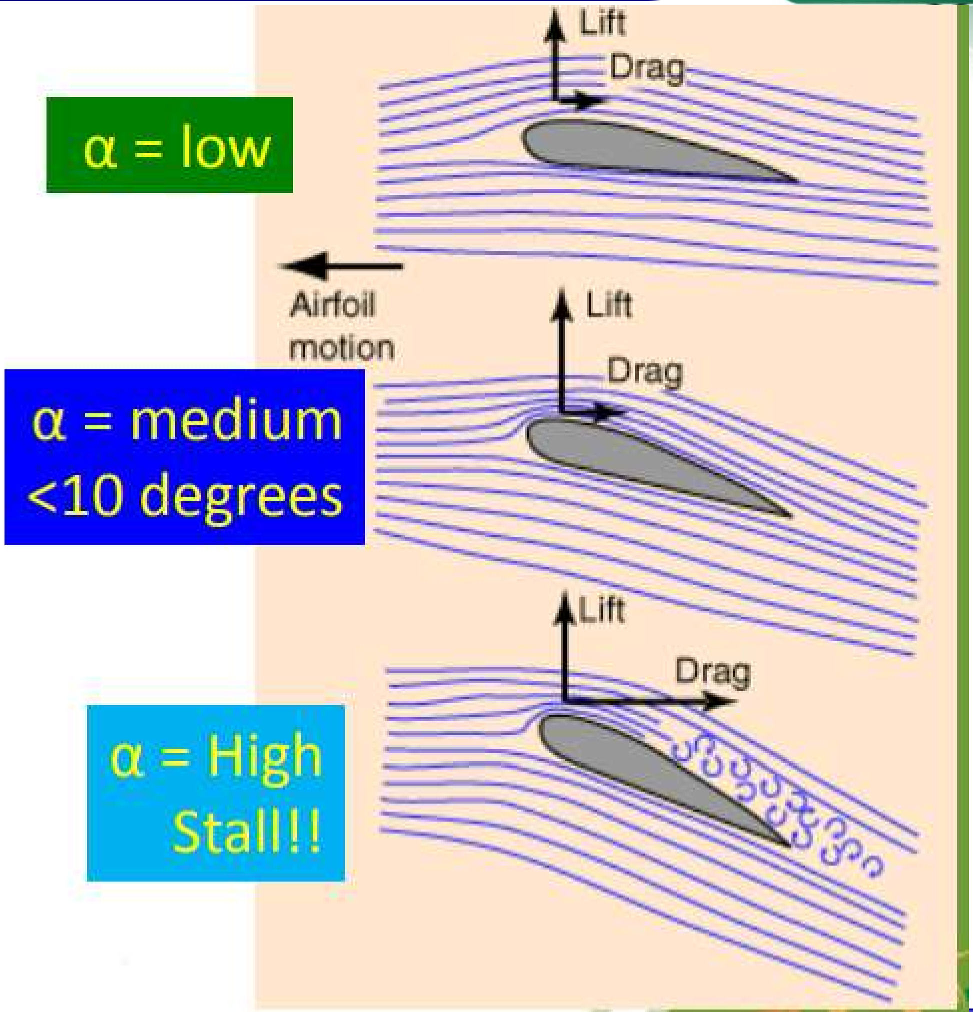


α = low

α = medium <10 degrees

α = High Stall!!

- **The *Drag Force* is parallel to the direction of motion. We want to make this force small.**

NACA 4 digit airfoil specification

This NACA airfoil series is controlled by 4 digits e.g. NACA 2412, which designate the camber, position of the maximum camber and thickness. If an airfoil number is

NACA MPXX

e.g.

NACA 2412

- then:M is the maximum camber divided by 100. In the example M=2 so the camber is 0.02 or 2% of the chord is the position of the maximum camber divided by 10. In the example P=4 so the maximum camber is at 0.4 or 40% of the chord.
- XX is the thickness divided by 100. In the example XX=12 so the thiickness is 0.12 or 12% of the chord.

http://airfoiltools.com/airfoil/naca4digit

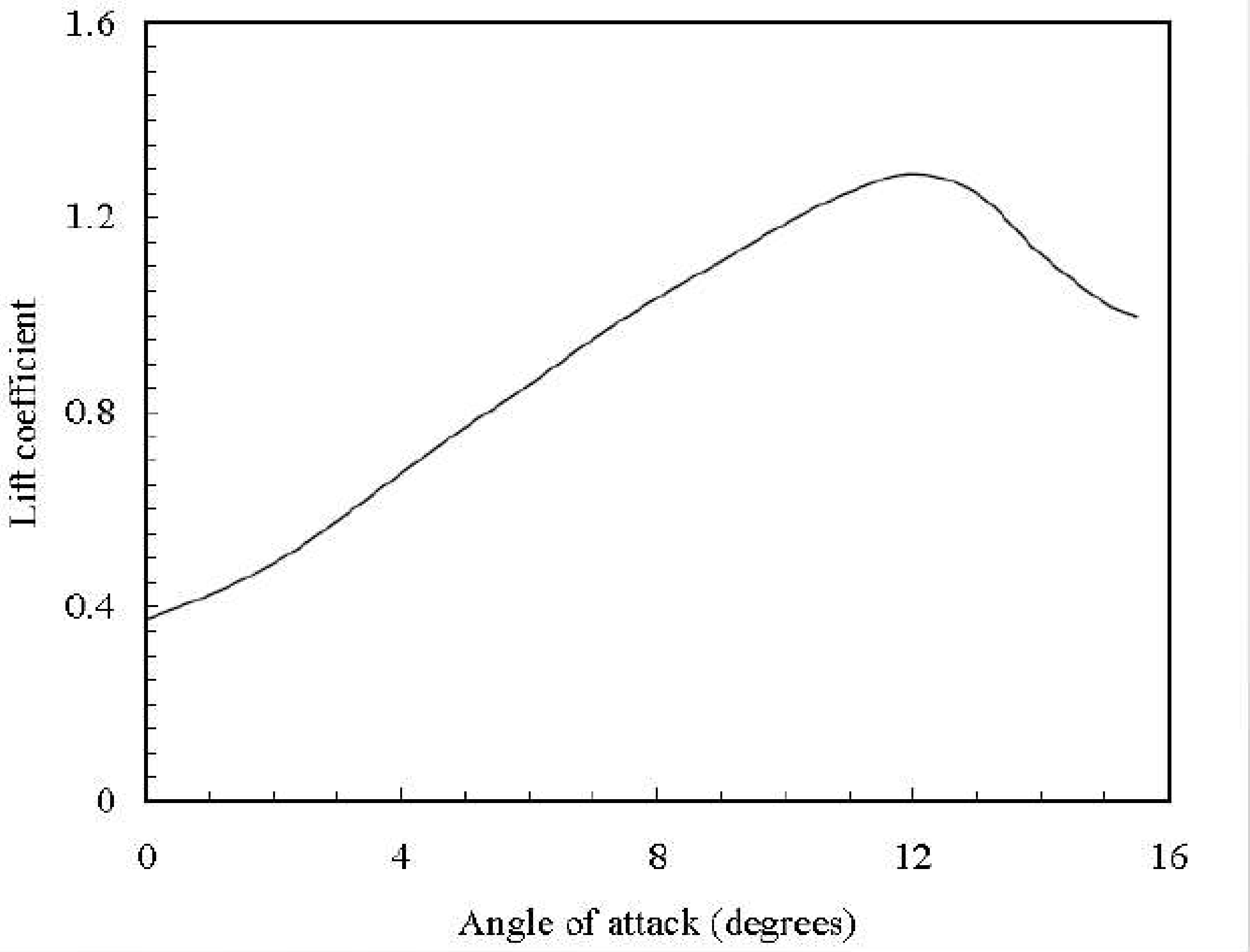
NACA 4 digit airfoil specification

The NACA 5 digit airfoils use the same thickness envelope as the 4 series but with a different camber line and numbering system.

NACA LPQXX
e.g.
NACA 23012

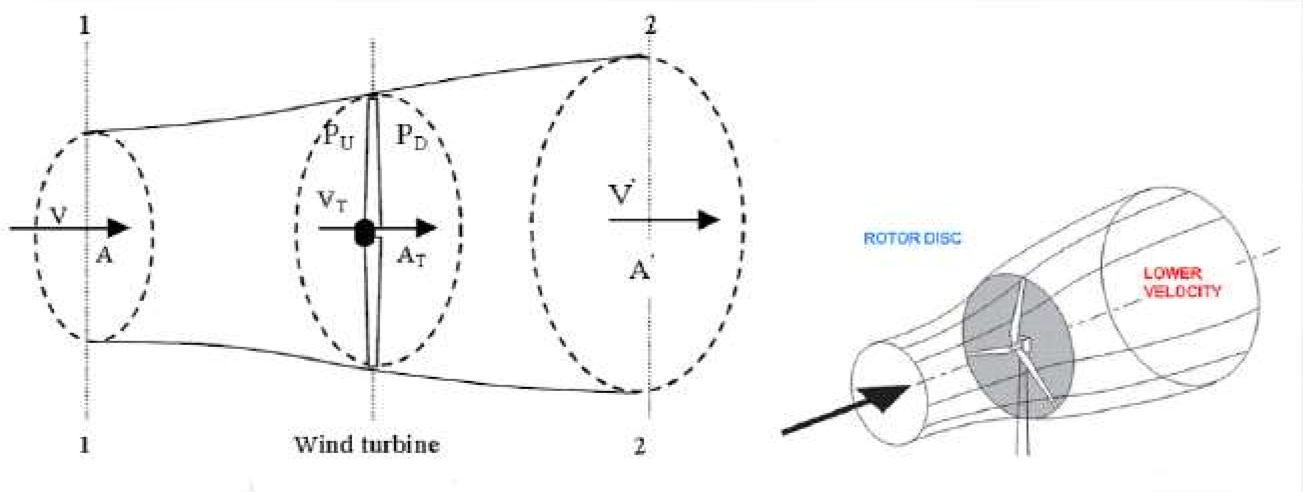
Digits	Letter	Example	Description
1	L	2	This digit controls the camber. It indicates the designed coefficient of lift (Cl) multiplied by 3/20. In the examble L=2 so Cl=0.3
2	P	3	The position of maximum camber divided by 20. In the examble P=3 so maximum camber is at 0.15 or 15% chord
3	Q	0	0 = normal camber line, 1 = reflex camber line
4 & 5	XX	12	The maximum thickness as percentage.In the examble XX=12 so the maximum thickness is 0.12 or 12% chord

Aerodynamic of Wind Turbines



Effect of angle of attack on airfoil lift

Aerodynamic Theories



The axial stream tube model

$$\rho_a A\, V = \rho_a A_T V_T = \rho_a A' V' \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17\text{-}3)$$

$$F = \rho_a\, A\, V^2 - \rho_a\, A'\, V'^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17\text{-}4)$$

Aerodynamic Theories

As $AV=A'V'=A_T\,V_T$ from Eq. (17-3), the thrust can be expressed as:

$$F = \rho_a\, A_T\, V_T\, (V - V') \qquad \text{......................... (17-5)}$$

Let p_U and p_D be the pressure at the upstream and down stream side of the rotor respectively. Hence:

$$F = (p_U - p_D)A_T \qquad \text{......................... (17-6)}$$

Applying the Bernoulli's equation at the sections and considering the assumption that the static pressures at sections 1-1 and 2-2 are equal to the atmospheric pressure p, we get:

$$p + \frac{\rho_a V^2}{2} = p_U + \frac{\rho_a V_T^2}{2} \qquad \text{......................... (17-7)}$$

and

Aerodynamic Theories

$$p_U - p_D = \frac{\rho_a(V^2 - V'^2)}{2} \qquad \text{..........................(17-9)}$$

Substituting the above expression for $(p_U - p_D)$ in Eq. (17-6):

$$F = \frac{\rho_a A_T(V^2 - V'^2)}{2} \qquad \text{..........................(17-10a)}$$

Comparing Eqs. (17-5) and (17-10a) we get:

$$V_T = \frac{(V - V')}{2} \qquad \text{..........................(17-10)}$$

The axial induction factor (**a**) indicates the degree with which the wind velocity at the upstream of the rotor is slowed down by the turbine. Thus

$$a = \frac{(V - V_T)}{2} \qquad \text{..........................(17-11)}$$

Aerodynamic Theories

The mass flow through the rotor over a unit time is:

$$m = \rho A_T V \qquad \text{......................... (17-14)}$$

Hence the power developed by the turbine due to this transfer of kinetic energy is:

$$P_T = \frac{1}{2}\rho_a\, A_T\,(V^2 - V'^2) \qquad \text{......................... (17-15)}$$

Substituting for V_T and V′ from Eqs. (17-12) and (17-13), we get:

$$P_T = \frac{1}{2}\rho_a\, A_T\, V^3\, 4a(1-a)^2 \qquad \text{......................... (17-16)}$$

Comparing Eq. (17-16) with the expression for power coefficient in Eq. (16-8), we can see that:

$$C_P = 4a(1-a)^2 \qquad \text{......................... (17-17)}$$

Aerodynamic Theories

For $\mathbf{C_P}$ to be maximum,

$$\frac{dC_P}{da} = 0 \qquad \text{……………………. (17-18)}$$

Thus differentiating Eq. (17-17), equating it to zero and solving, we get **a=1/3**.

Substituting for **a** in Eq. (17-17), the maximum theoretical power coefficient of a horizontal axis wind turbine is **16/27** and the maximum power produced is:

$$P_{Tmax} = \frac{1}{2}\,\rho_a\,A_T\,V^3\,\frac{16}{27} \qquad \text{……………………. (17-19)}$$

Aerodynamic Theories

17-3: Rotor design:

Input parameters are to be identified for such a design:

1. Radius of the rotor (**R**)
2. Number of blades (**B**)
3. Tip speed ratio of the rotor at the design point ($\boldsymbol{\lambda_D}$)
4. Design lift coefficient of the airfoil ($\mathbf{C_{LD}}$)
5. Angle of attack of the airfoil lift ($\boldsymbol{\alpha}$)

$$P_D = \frac{1}{2} C_{PD}\, \eta_d\, \eta_g\, \rho_a\, A_T\, V_D^3$$

The radius of the rotor can be estimated as:

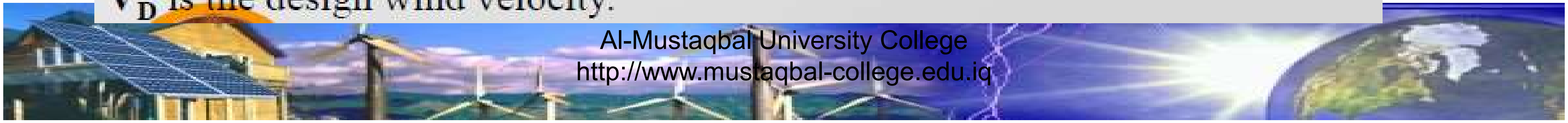
$$R = \left[\frac{2P_D}{C_{PD}\, \eta_d\, \eta_g\, \rho_a\, \pi\, V_D^3}\right]^{\frac{1}{2}}$$

$\mathbf{C_{PD}}$ is the design power coefficient of the rotor,

$\boldsymbol{\eta_d}$ is the drive train efficiency,

$\boldsymbol{\eta g}$ is the generator efficiency

$\mathbf{V_D}$ is the design wind velocity.



Aerodynamic Theories

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Aerodynamic Theories

If the design is to be based on the energy required for a specific application (EA), the rotor radius can be calculated by:

$$R = \left[\frac{2\, E_A}{\eta_S\, \rho_a\, \pi\ V_M^3\ T}\right]^{\frac{1}{2}}$$

η_S is the overall system efficiency,

V_M is the mean wind velocity over a period

T is the number of hours in that period.

17-4: Wind energy conversion systems:

17-4-1: Wind electric generators:

The major components of a commercial wind turbine are:

Tower; Rotor ; High speed and low speed shafts; Gear box ;Generator; Sensors and yaw drive ; Power regulation and controlling units ;Safety systems

Power Generated by HWind Turbine

How much power a wind turbine with 50 meters long blade can generate with a wind speed of 12 m/s? The site of the installation is about 1000 feet above sea level. Assume 40% efficiency (η).

Air density is lower at higher elevation. For 1000 feet above sea level, ρ is about 1.16 kg/m^3

$$\text{Power} = \tfrac{1}{2}(\rho)(A)(V)^3(\eta)$$

$$= 0.5(1.16)(\pi 50^2)(12)^3(0.4)$$

$$= 3.15 \times 10^6 \text{ Watt}$$

$$= 3.15 \text{ MW}$$

where we assumed the turbine efficiency is 40%.