Lecture #16

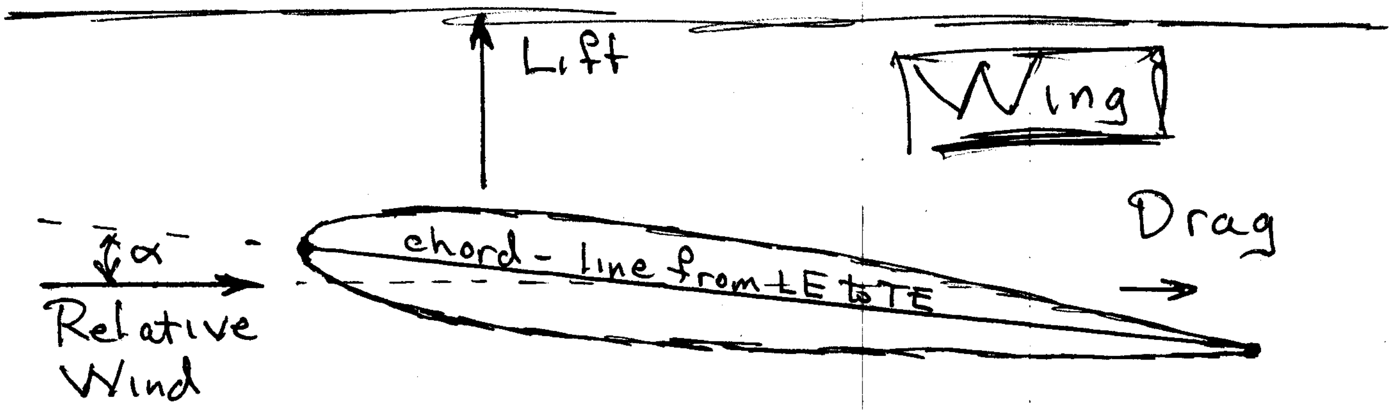
Aerodynamics of Wind Turbines

The blade of a wind turbine is a LIFTING body.

There are many types of lifting bodies:

Wings
Propellers
Fans
Wind Turbines
Sails
Balls propelled with spin
Ski Jumpers

All lifting bodies have in common a Lift Force normal to the Relative Wind of the body. In the case of an airplane wing, we want the lift force to counteract the downward force of gravity. In the case of a wind turbine, we want the lift force to pull the turbine in a circular motion about its axis of rotation



Above is a sketch for a wing -- or airfoil. Note:

- Chord line -- a straight line from the Leading Edge (LE) to Trailing Edge (TE) of the airfoil.
- Relative wind. The velocity vector of the <u>undisturbed</u> wind <u>relative</u> to the airfoil. In this case, the relative wind is horizontal, meaning the aircraft is in level flight
- Angle of attack, α, the angle between the chord line and the relative wind.

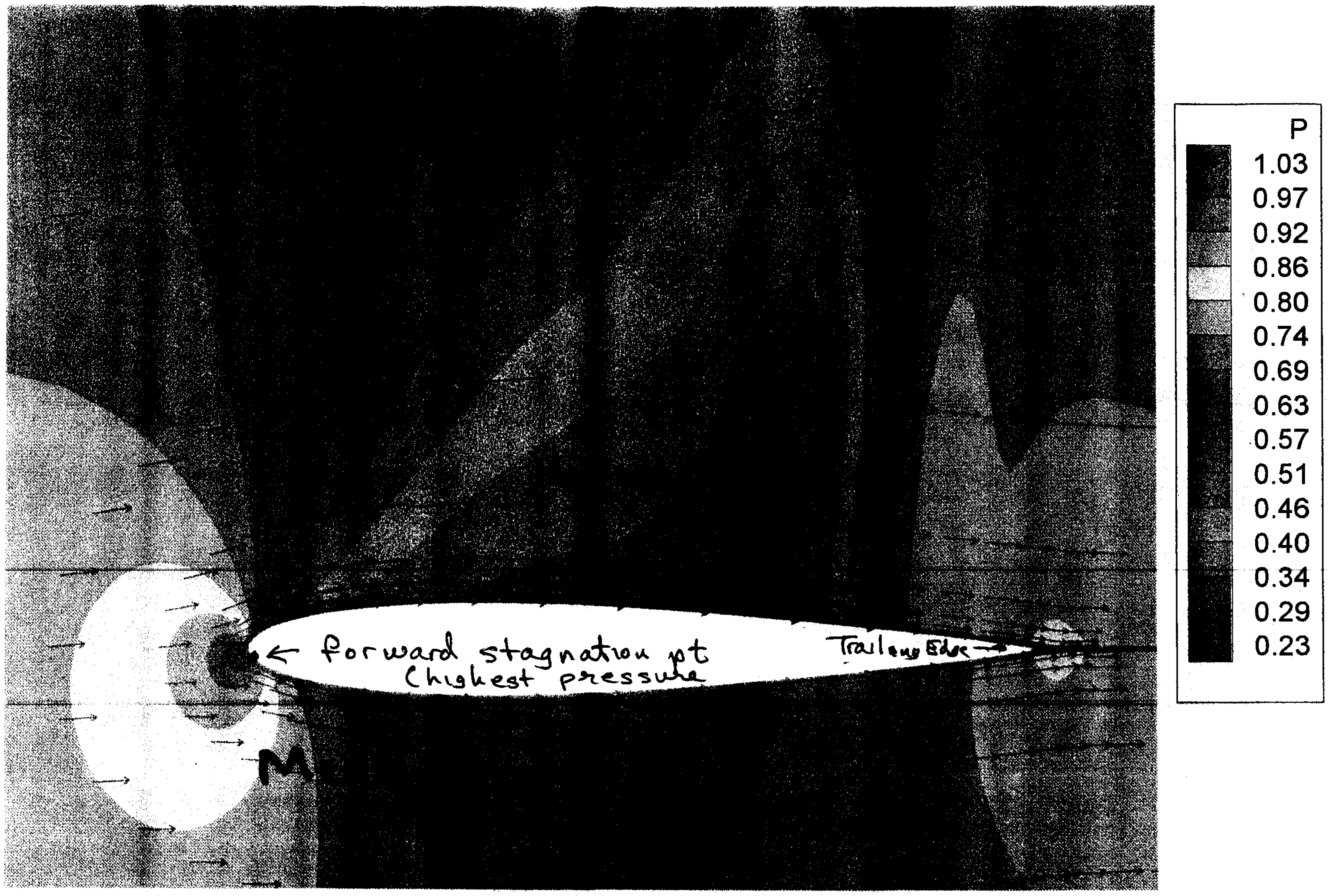
- Lift force, the force on the airfoil normal to the relative wind
- Drag force, the force on the airfoil parallel to the relative wind.

The lift and drag forces are net result of the pressure field created around the wind.

An example of a pressure field around a wing is shown on the next page.

What is seen is the following:

- Highest pressure at the forward stagnation point of the wing. This point is little bit below the LE
- Low pressure on the top of the wing, caused by acceleration of the air around the upper surface of the wing.
- Intermediate pressure on the bottom of the wing, caused by the flow of air around the lower surface of the wing.


P
1.03
0.97
0.92
0.86
0.80
0.74
0.69
0.63
0.57
0.51
0.46
0.40
0.34
0.29
0.23
forward stagnation pt
(highest pressure
Trailing Edge
M

4

- High pressure at trailing edge of the wing.

The low pressure on the upper surface, relative to the medium pressure on the lower surface, creates the upward lift force.

The drag force is created by two effects:

1) An imbalance in the pressure field in the direction parallel to the relative wind
2) Friction between the flowing air and the wing surfaces.

The difference in pressure between the upper and lower surfaces is explained by two things:

1) Bernoulli's equation
2) The distances from the forward stagnation point to the TE -- the distance on the top is longer than on the bottom.

Bernoulli's equation is

$$P + \frac{1}{2}\rho U^2 = P_0$$

where:

P = local pressure

ρ = density of air

U = local velocity magnitude of the air

P_0 = stagnation pressure

Bernoulli's equation holds if the density is constant, i.e., the air is incompressible. This condition holds if the air velocity magnitude remains below about 100 m/s, that is, if the Mach number is less than about 0.3. The Mach number is:

$$M = U/a$$

where a = speed of sound of air.

The speed of sound of air varies as $a \sim \sqrt{T}$ and for

$15\,^\circ C = 288K$, $a = 340$ m/s.

For Mach number above about 0.3, Bernoulli's equation must be corrected for aerodynamic compressibility, that is, the velocity magnitude affects the density.

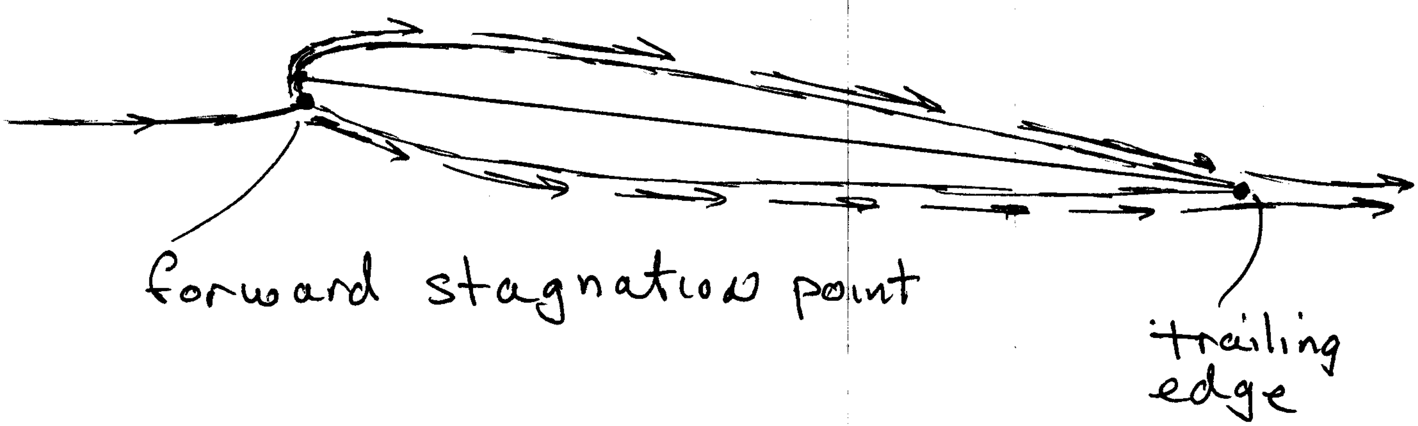
The stagnation pressure is constant as the air flows around the wing. Po is evaluated at condition far in front of the wing -- at undisturbed conditions:

$$P_o = P_{ambient} + \frac{1}{2} \rho U^2_{\substack{\text{speed} \\ \text{of aircraft} \\ \pm \text{ ambient} \\ \text{wind speed}}}$$

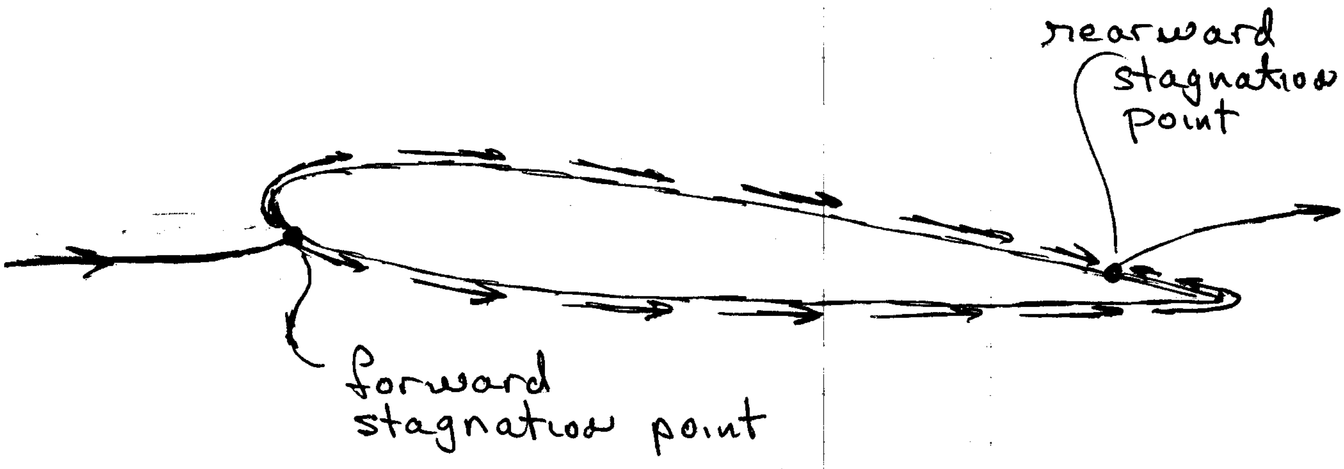
(undisturbed relative wind)

The distance from the forward stagnation point to the TE is greater for the air moving around the top of the wing than for the air flow around the bottom of the wing.

Thus, "in order to keep up and meet at the TE", the air on top has to move faster than the air on the bottom. Thus, by Bernoulli's equation, the pressure on the top of the wing is less than the pressure on the bottom of the wing. Lift is created!



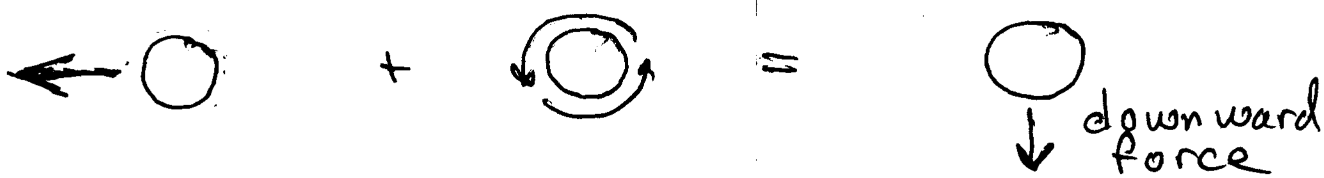
Question: could we have a situation for which the distance traveled by the air of the two sides of the wing would be equal?
This would look like the picture on the next page:



The very sharp, nearly 180° turn at the trailing edge would be very difficult (impossible) for a real fluid to make. On paper, an ideal fluid can make the turn. If one adds "circulation" to the ideal fluid solution depicted above, the real fluid result is obtained.

Ideal + Circulation = Real

Thus, for a baseball pitcher to throw a curve ball:

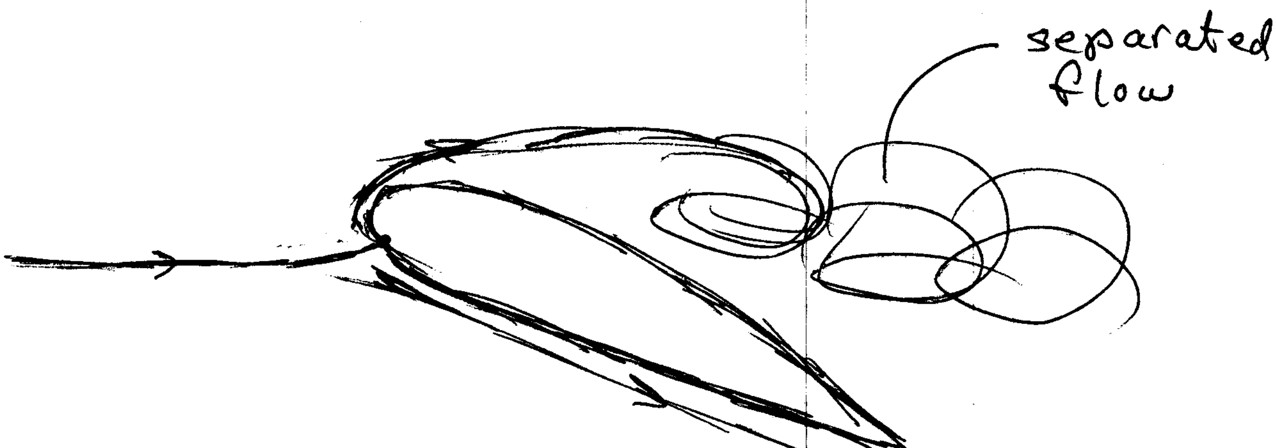


Lift and drag on a wing change as the angle of attack changes. This is illustrated by Figure 7.28, p 286, in the text.

The lift increases nearly linearly with α up to a point. Drag increases exponentially with α.

For the data in Figure 7.28, peak lift occurs at about $\alpha \cong 20°$.

Above this angle, the flow on the upper surface of the wing separates -- the wing stalls!

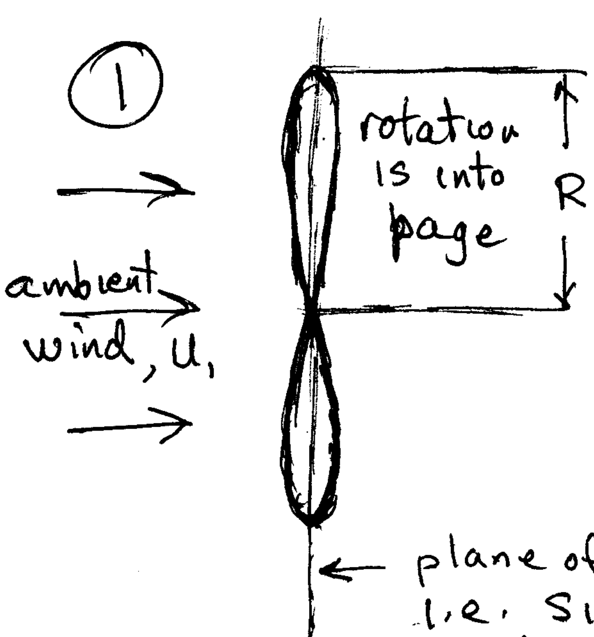


Thus, there is a practical limit to the angle of attack.

For a wind turbine, we need to orient the blade so that the angle of attack is not too small (since then the lift will be small) and not too big (since then the blade will stall), and so that there is a good component of lift in the direction of rotation of the blade (pulling the blade through its rotation). The relative wind here is the sum of two velocities:

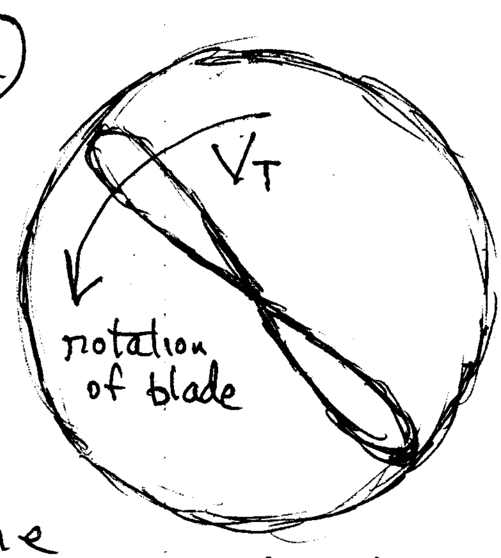
1) the ambient wind
2) the rotation of the blade

1



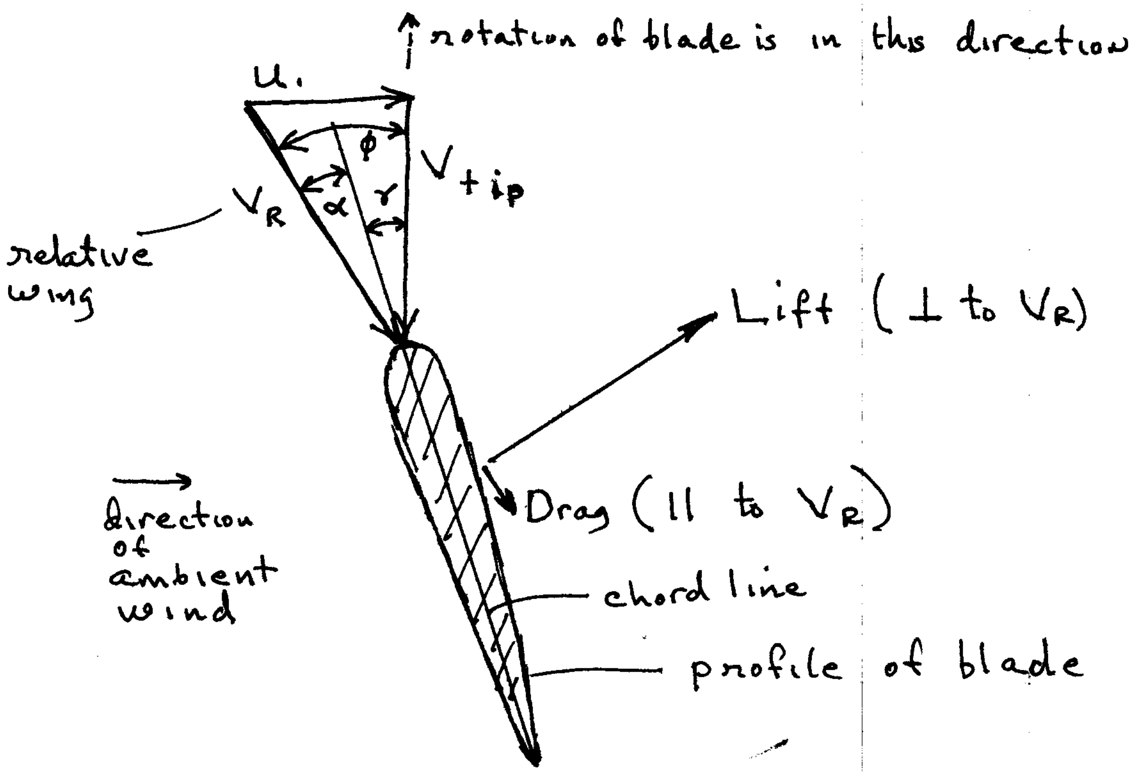
← plane of turbine
i.e. side view of turbine

2



front view of turbine

If we look down on view 1 of the turbine, we see the profile of the turbine blade (at the tip).



Note : γ = blade set angle
α = angle of attack
$\phi = \gamma + \alpha$

V_R = relative wind = $\sqrt{U_1^2 + V_{tip}}$

$V_{tip} = 2\pi RN$, where N = speed of turbine as revolutions per second and R = radius of turbine from hub (axis of rotation) to tip

$\tan\phi = U_1/V_{tip}$

The force in the direction of rotation of the turbine, pulling it, is :

$$\boxed{F_T = L\sin\phi - D\cos\phi}$$