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Wind Energy: Blade Aerodynamics

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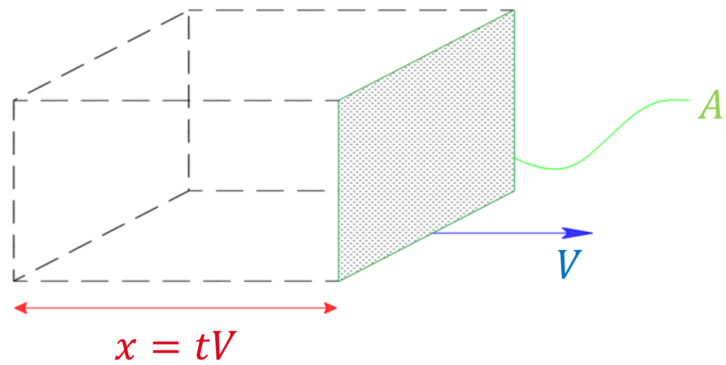
Power Available from a Wind Turbine

If we decelerated the air to standstill we could extract a power equal to the kinetic energy in the volume of air being processed per unit time. We can express this is a rate-of-change of kinetic energy in the wind

$$P_W = \frac{d}{dt} E_W$$

$$= \frac{1}{2}\rho V^2 \frac{d}{dt}\left(\frac{1}{2}\rho A V t V^2\right)$$

$$= \frac{1}{2}\rho A V^3$$



The power extracted by a turbine, P_T, is a fraction, C_P, of the wind's power and C_P, can not exceed the Betz Limit of ${}^{16}/_{27} \approx 59\%$

$$P_T = C_P P_W = C_P \frac{1}{2}\rho A V^3$$

How do turbine blades do their job?

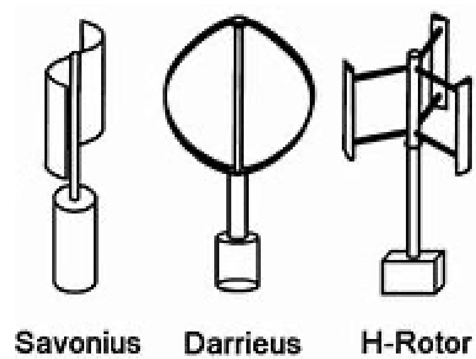
and

Why does the Betz Limit exist?

Horizontal- and Vertical-Axis Wind Turbines (HAWTs and VAWTs)

HAWTs normally use aerofoil blades and most often have three blades upwind of the tower. They need to be actively turned to face the incoming wind.

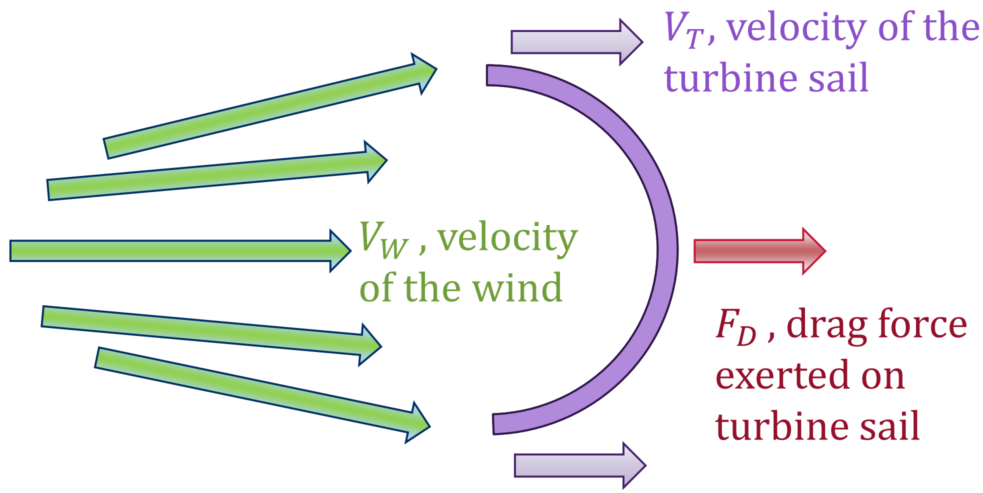
VAWT may use blades or drag cups.



This example VAWT is the bladed Darrieus form.

Generating Power from Drag

The oldest wind power machines used sails to “catch” the wind.
So, too, do Savonis style turbines.
These are drag devices with a drag force acting in direction of wind.



Drag devices are relatively inefficient and create a wide and turbulent wake.
Drag devices are not used for modern wind energy conversion.

The drag coefficient, C_D is in the region of 1.0 for most drag-type devices.
An open hemisphere has C_D = 1.42 in one direction, C_D = 0.38 in the other.
The power coefficient for a drag device reaches a maximum when $v_T = ⅓\, v_W$
and has a values of $C_P = {}^4/_{27}\, C_D \simeq 0.15$.

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Lift or drag?

Generating Power from Lift

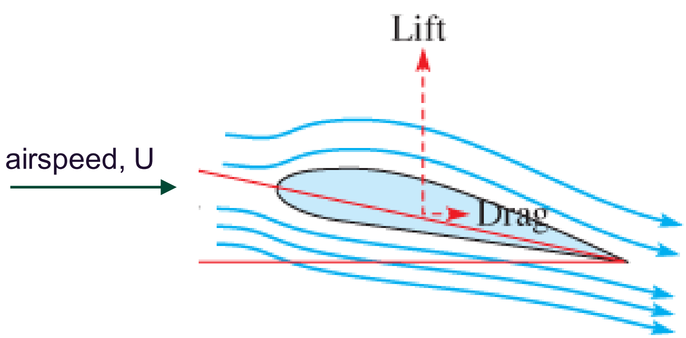
Experience has shown that an aerofoil at a small oblique angle to the relative wind is efficient at capturing wind energy.

These aerofoils utilise lift forces, rather than drag forces, to generate a useful torque (force on the blades in the direction of rotation).

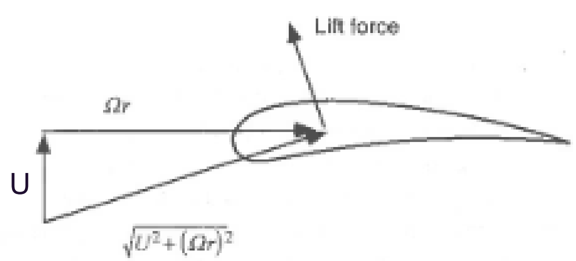
Aerofoils are designed to maximise lift force and minimize the drag force.

They have a rounded leading edge and a thin, sharp trailing edge.

On aircraft / wind tunnels:



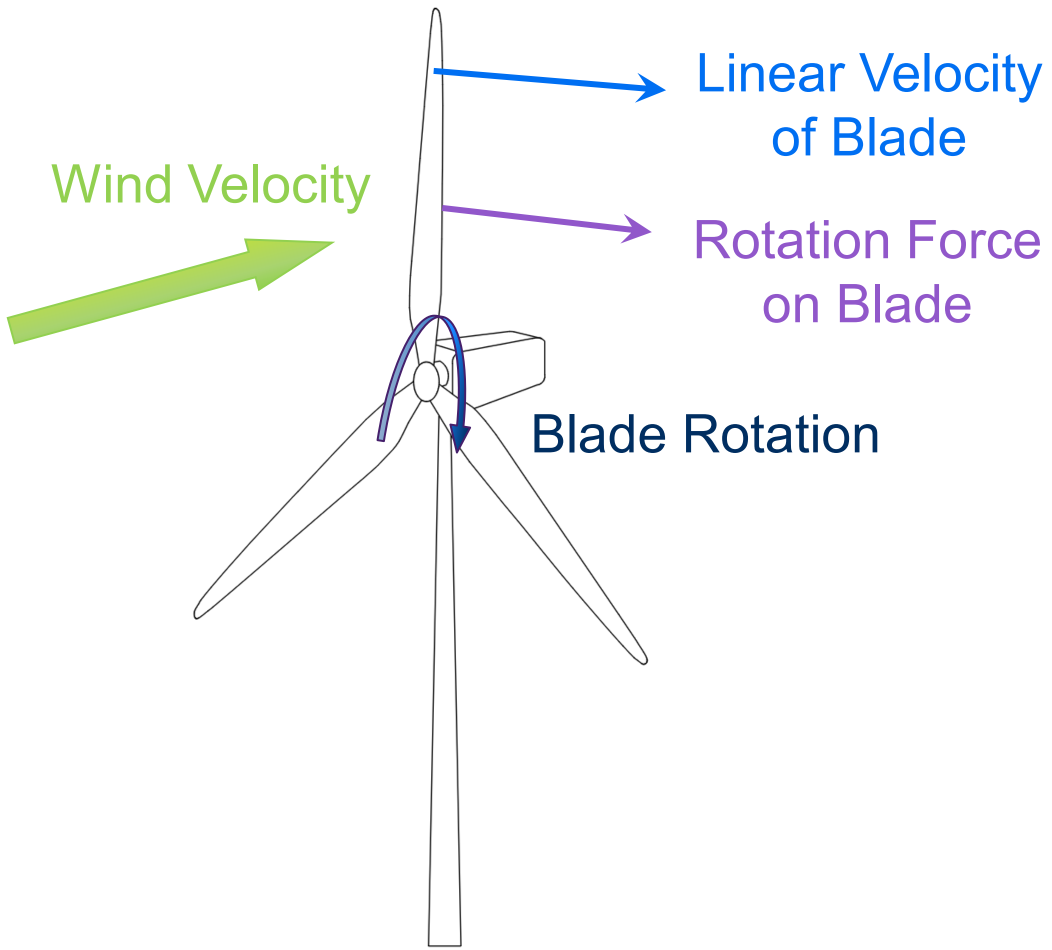
On wind turbines



Orientation

When air flows over the blades of a turbine, forces are created that turn the blades and the generator.

The set of blades are positioned to face the wind, that is, the wind approaches the turbine perpendicular (normal) to the plane of rotation of the blades.



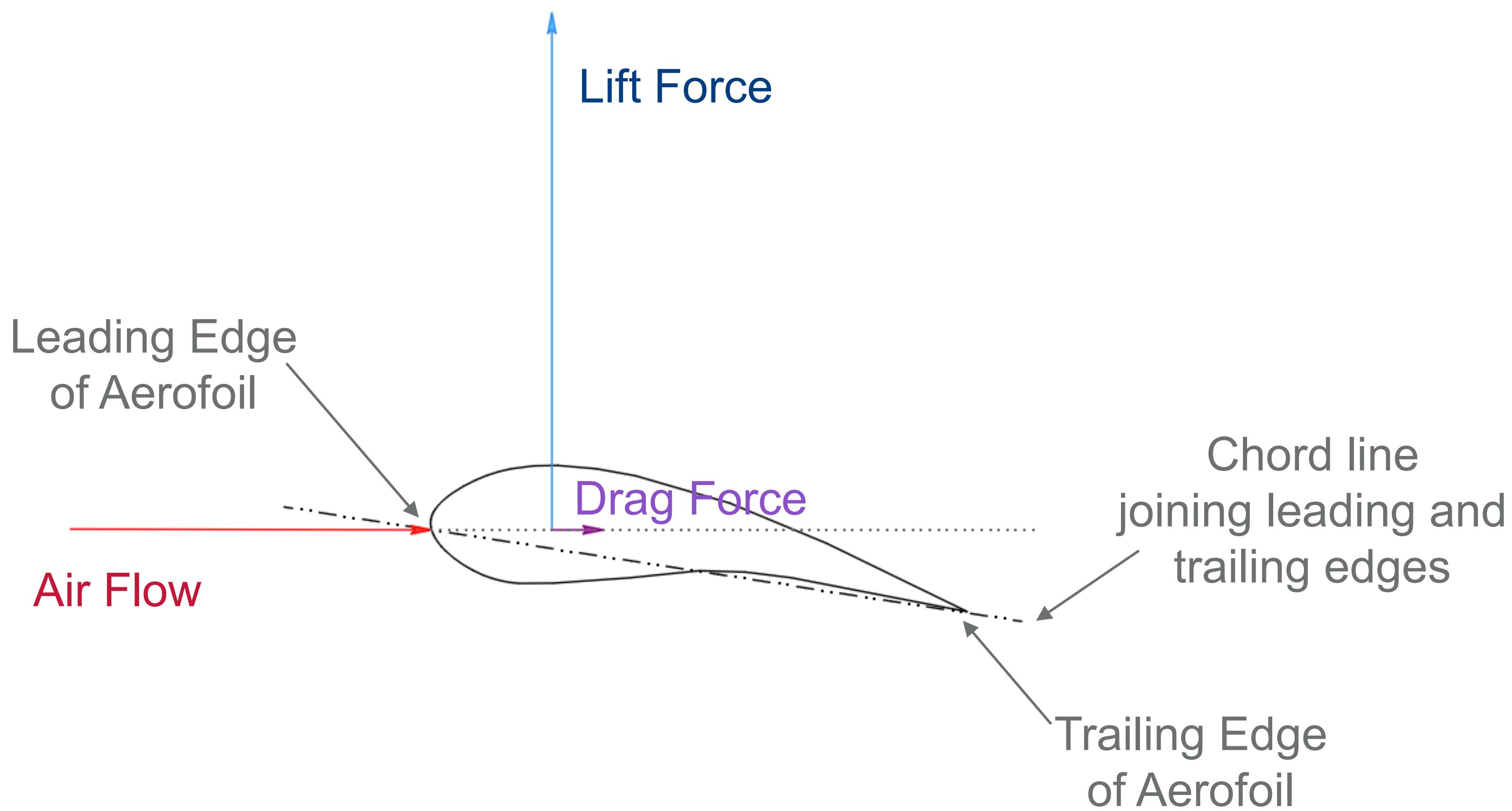
AEROFOIL AERODYNAMICS

Lift and Drag

Airflow over an aerofoil creates two forces

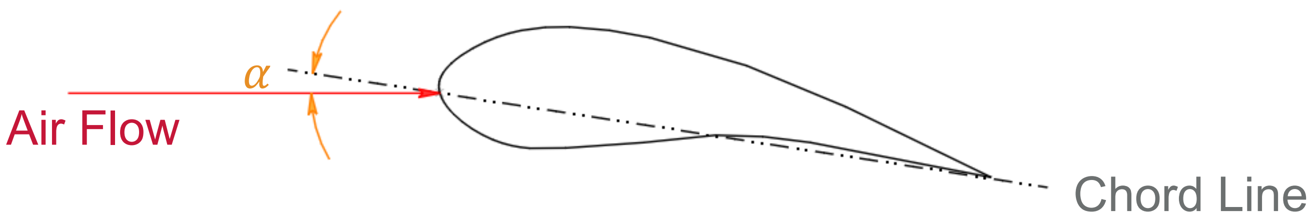
Lift is the force normal to the direction of the air flow.

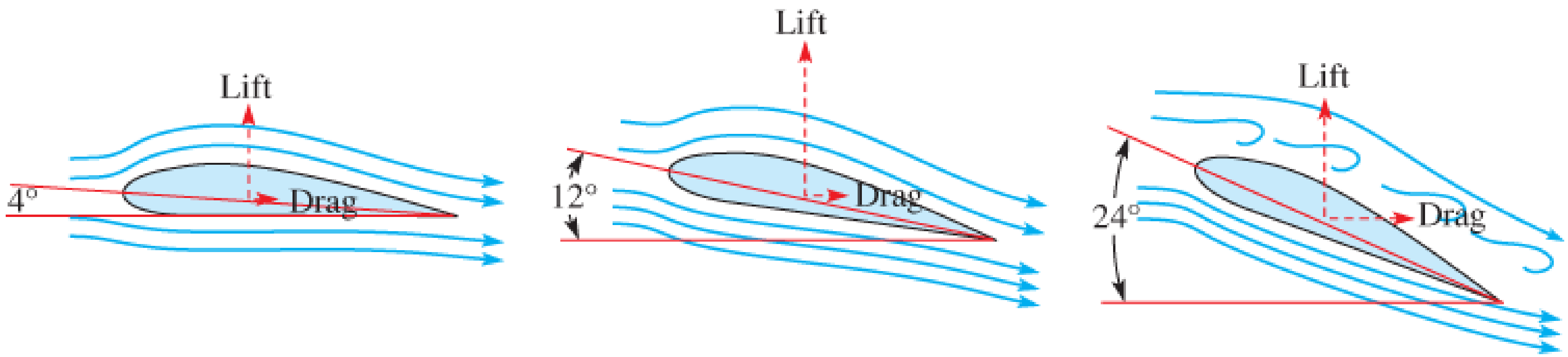
Drag is the force parallel to the direction of the air flow.



Angle of Attack

The lift and drag forces depend on the air flow over the top and bottom surfaces and therefore on the “angle of attack”, α, between the chord line of the blade and the air flow.

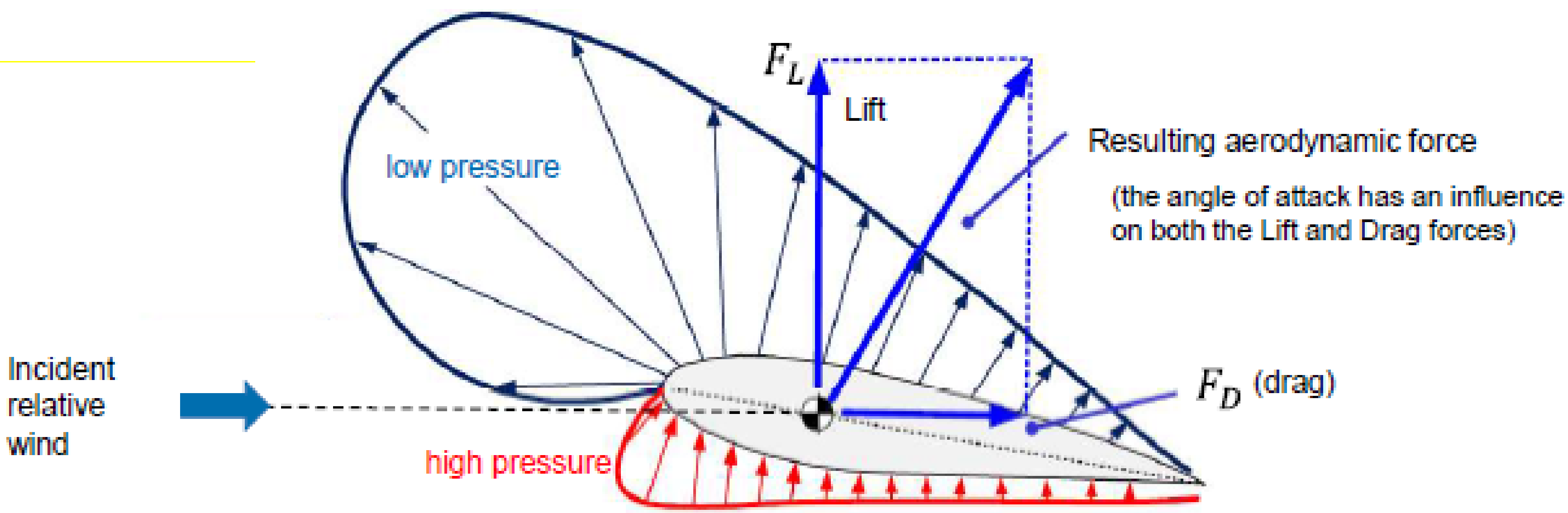




(a) Angle = 4° (b) Angle = 12° (c) Angle = 24° (stall begins)

Air is forced downward by the bottom surface creating a reaction force acting to lift the blade. Similarly, air is pulled downward at the top surface creating a reaction force to also lift the blade. Increasing α increases the momentum change in the air flow and increases the lift forces. When the flow separates and becomes turbulent at high α, lift decreases and drag increases abruptly and stall occurs.

Aerofoil Pressure Distribution



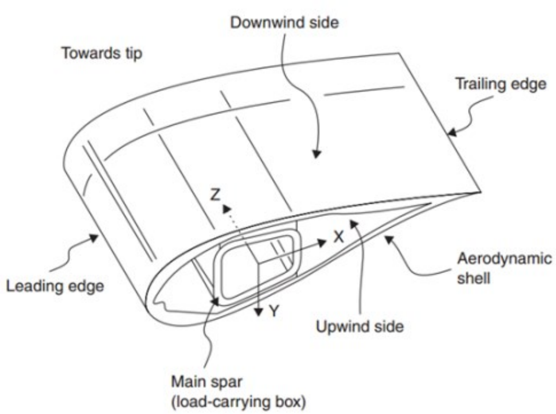
Lift and Drag Coefficients

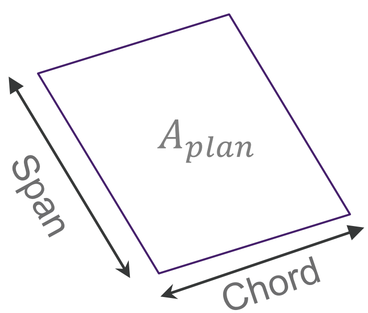
The lift and drag lift forces, F_L and F_D, on a body in a flow of velocity, V relative to the body are found to be proportional to

the fluid density ρ, (air density in our case)
the planform area A_{plan} of the body and
the ***square*** of the *incident* velocity V^2.

We can define dimensionless drag coefficients for drag and lift, C_L and C_D, that are specific to a particular blade and turbine and from which we can find F_L and F_D.

$$F_L = C_L \tfrac{1}{2}\rho A_{plan} V^2 \qquad F_D = C_D \tfrac{1}{2}\rho A_{plan} V^2$$





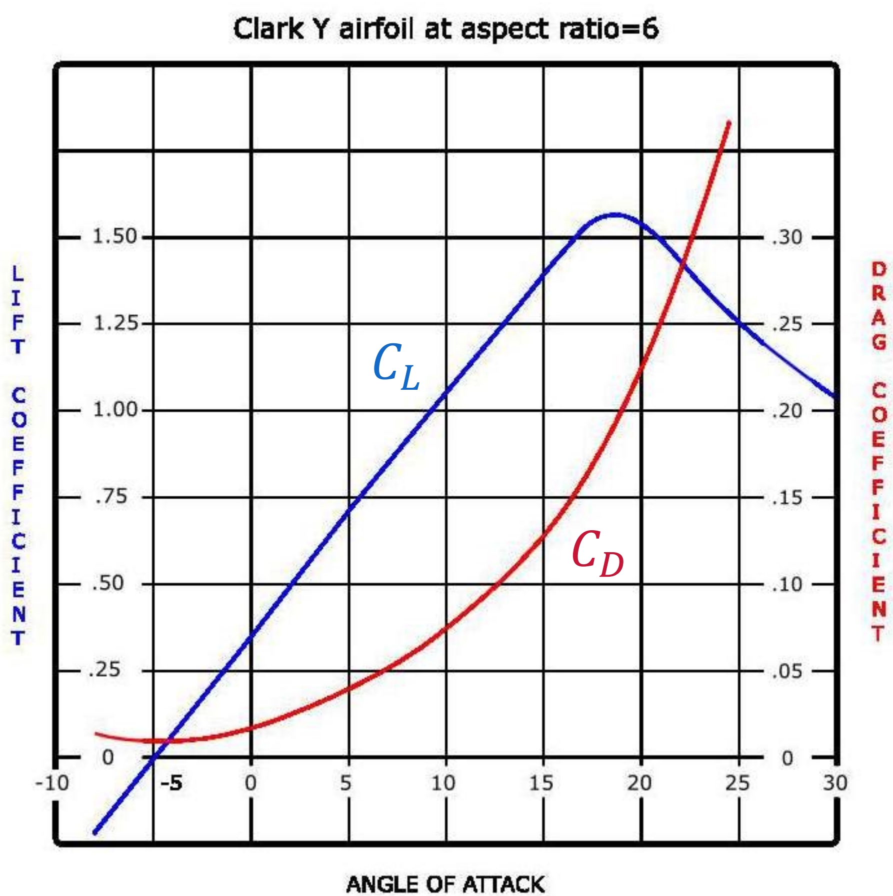
Note: forces are proportional to V^2 whereas power is the product of force and velocity so is proportional to V^3

Note: the area, A_{plan} is the area over which the flow occurs defined by the chord of the blade and the span in radial direction. This is different to the swept area of a turbine blade.

Example Lift and Drag Coefficients

For a typical aerofoil, the lift force is greater than the drag force for small angles of attack.

Note the difference in vertical scales for C_L and C_D. At $\alpha = 10°$, C_L =1.05 and C_D=0.075 giving ${}^{C_L}/_{C_D} = 14$. Wind turbine aerofoils achieve even higher ratios than this.



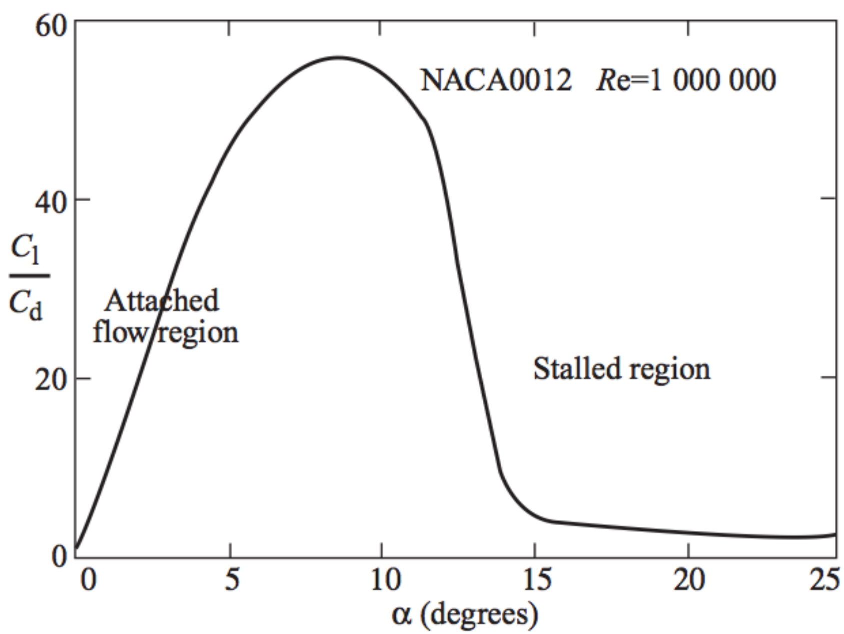
https://en.wikipedia.org/wiki/Airfoil

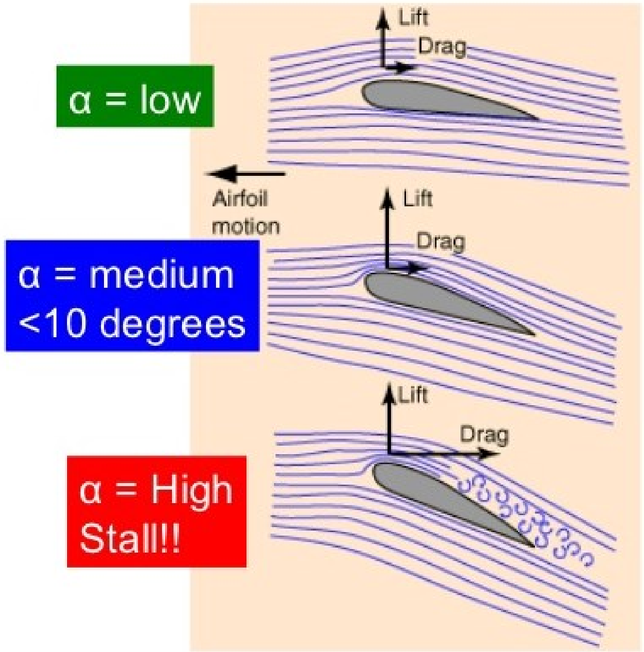
Lift-to-Drag Ratio as a Function of Angle-of-Attack

The lift-to-drag ratio of an aerofoil, ${}^{C_L}/_{C_D}$ is often take as a figure of merit.

In this graph, the optimum angle of attack, that which gives the highest lift to drag ratio, is about 9°.

Smaller angles gradually reduce the lift forces and this can be used for control purposes.





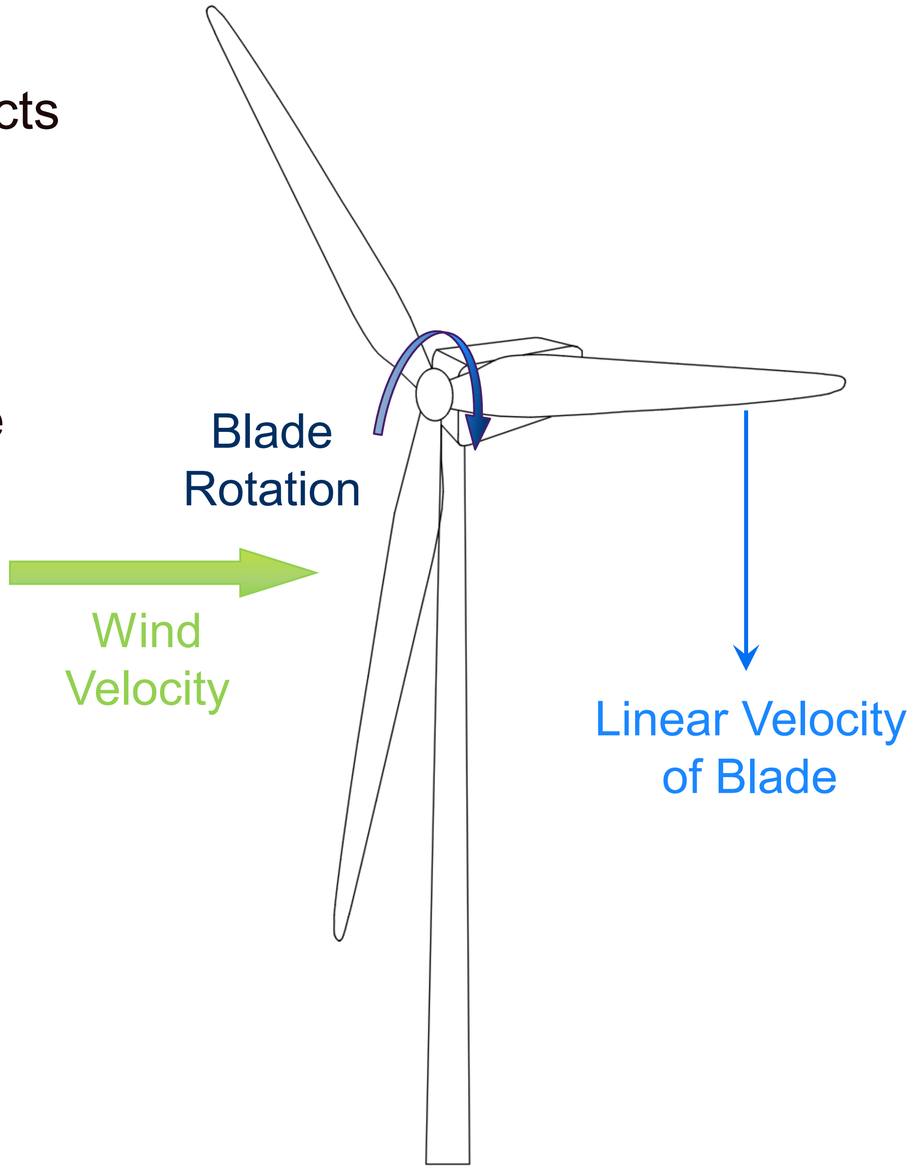
At some value $\alpha = \alpha_{stall}$, the flow separates from the aerofoil.
The lift stops increasing and may fall, and the drag increases rapidly.
This is termed stall and usually occurs for α between 10° and 15°.

BLADE AERODYNAMICS

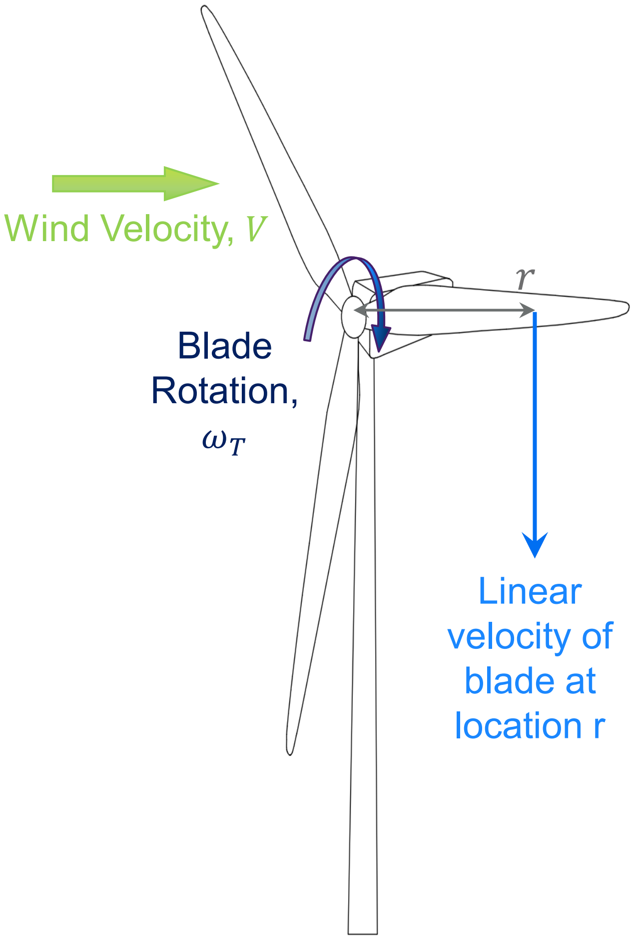
Two Components of Airflow

For a wind turbine, there are two effects causing airflow over the blade.

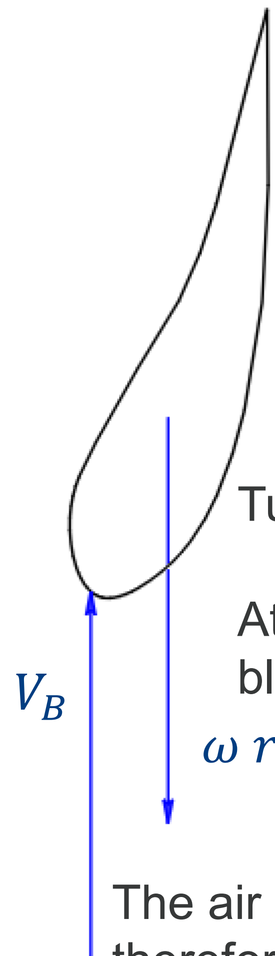
1. the wind, V is flowing past the turbine and its blades.
2. the blade is in motion through the air with linear velocity, V_B.



Airflow Over Blade Due to Rotation



End-on view of the section of a blade travelling down the page at a distance r from the hub.
(A blade spinning clockwise which is a the 3 o'clock position)



Turbine blade rotates at ω <rad/s>

At a radially distance r <m> along the blade, the linear velocity is $\omega\, r$ <m/s>

The air velocity over the blade is therefore $V_B = \omega\, r$ <m/s>

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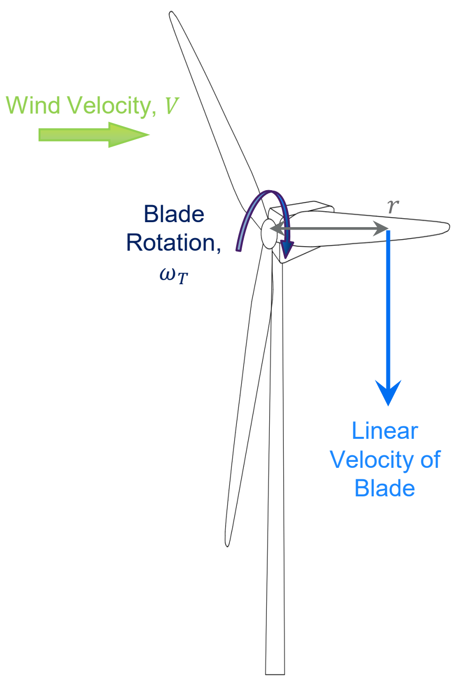
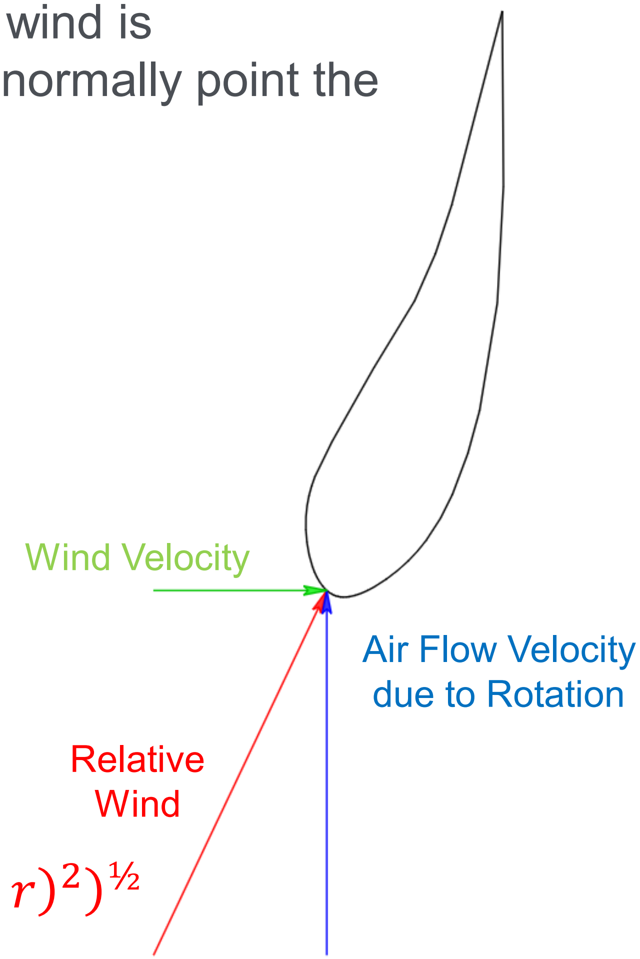
Relative Wind Velocity

Combing the airflow due to the wind and the airflow due to rotation give a resultant or relative wind.

The two flows are perpendicular because the wind is perpendicular to the plane of rotation (i.e. we normally point the turbine into the upstream wind flow).

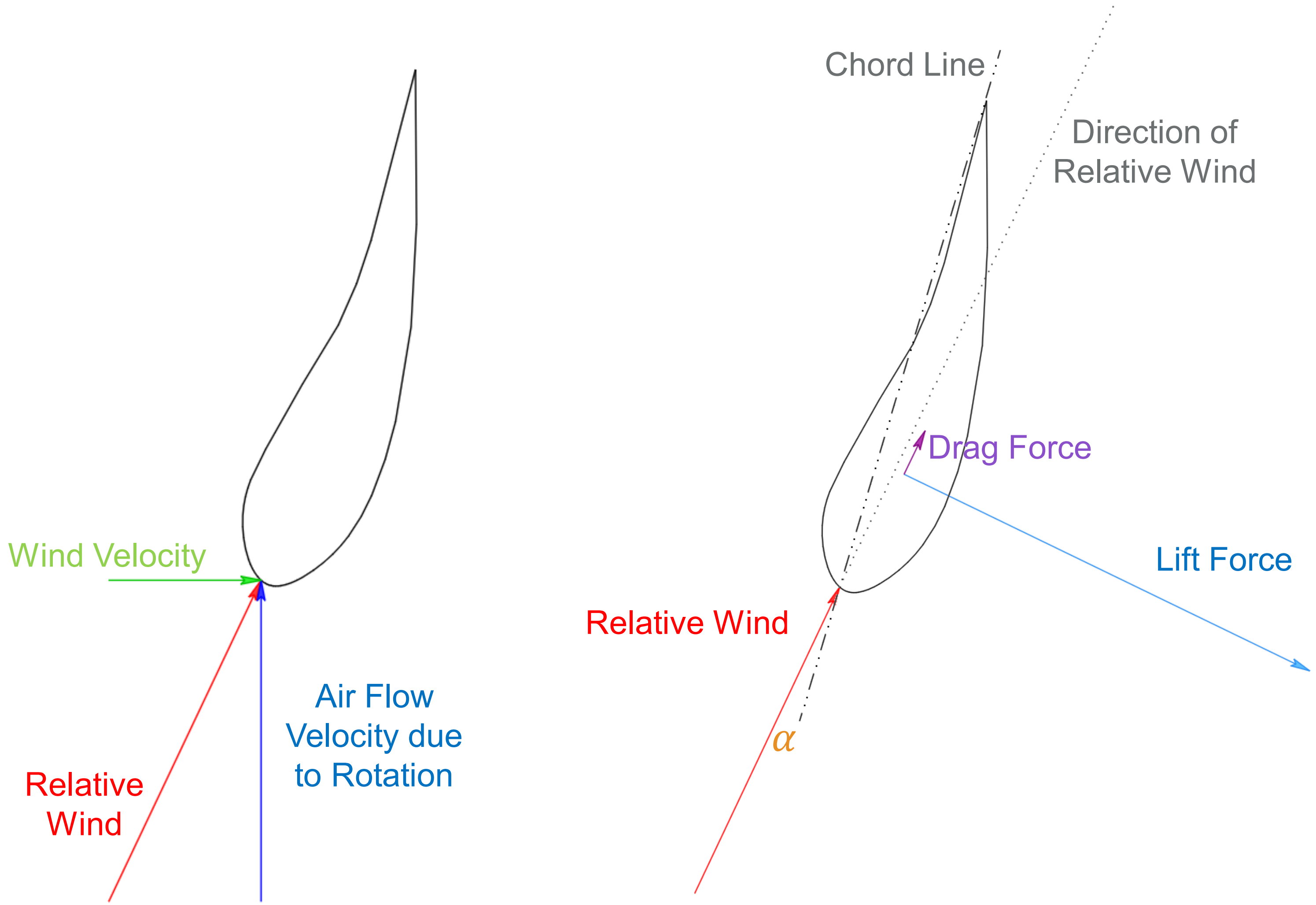




$$V_R = (V^2 + (\omega\, r)^2)^{½}$$

Lift and Drag

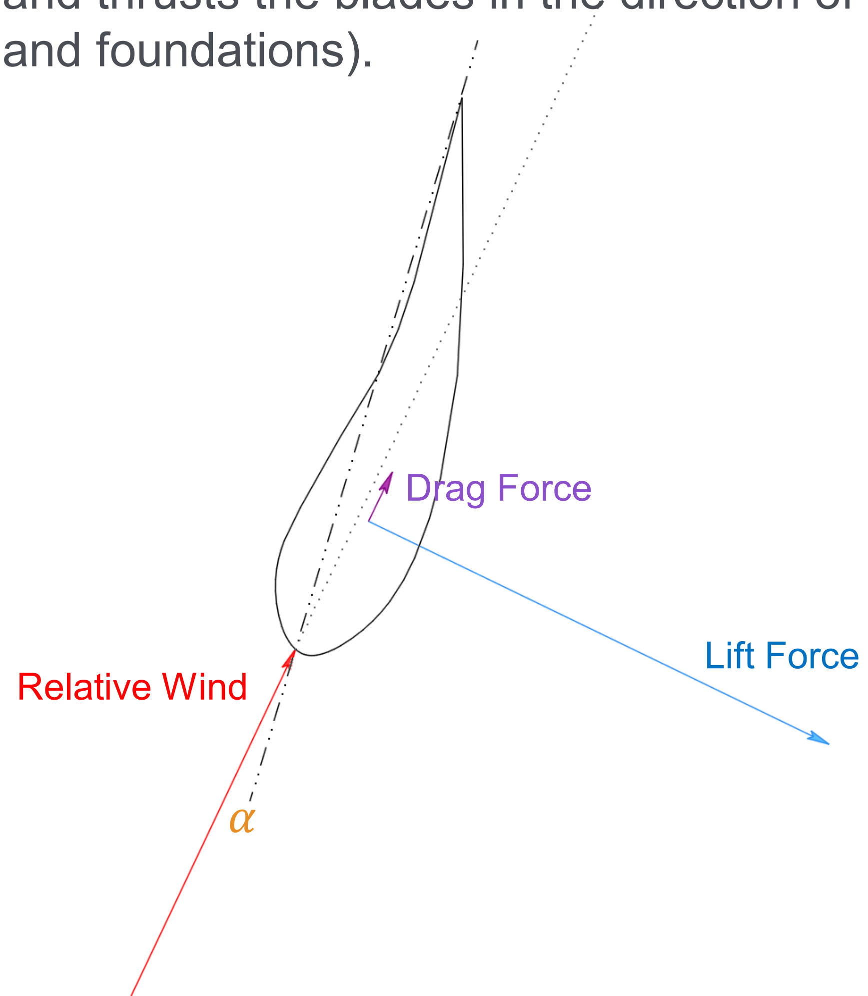
Now that the relative wind flow has been found, the lift and drag forces can be found (using the angle of attack and the lift and drag coefficients of the blade).

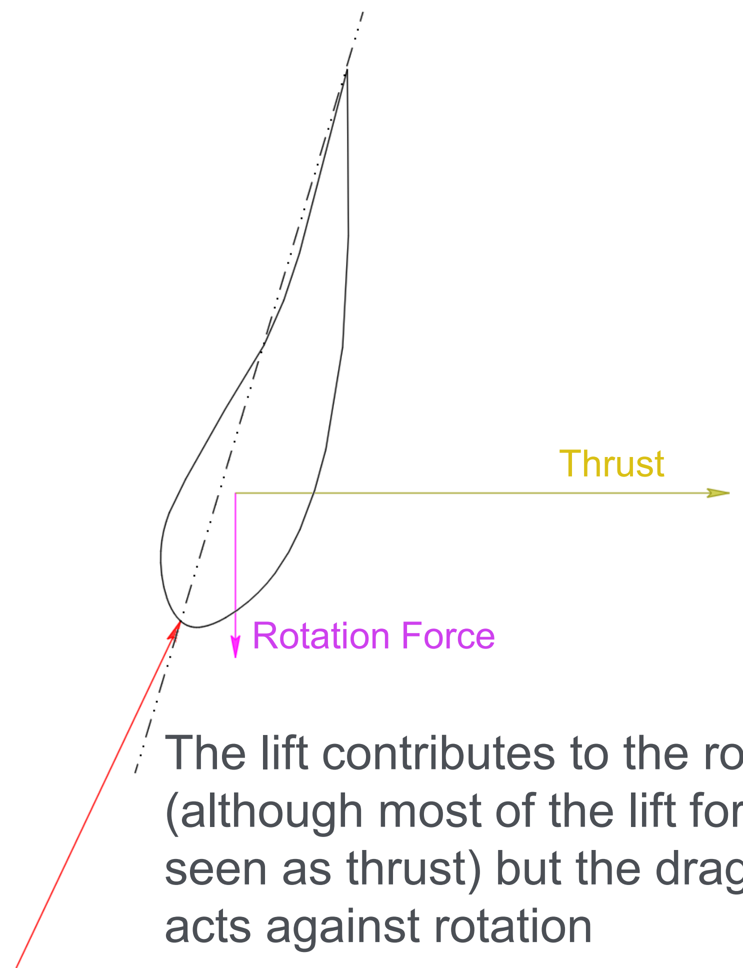


Rotation and Thrust

Lift and drag act perpendicular and parallel, respectively, to the relative wind.

We need to resolve these into components that act in the plane of rotation and normal to that plane. These are the forces that rotate the blades (and do useful work) and thrusts the blades in the direction of the wind (and must be resisted by the tower and foundations).

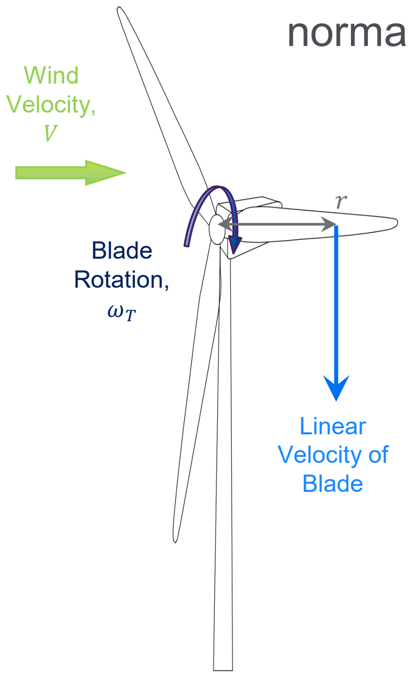




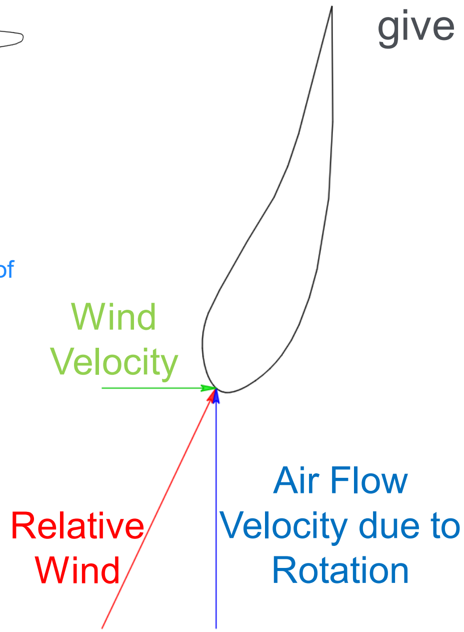
The lift contributes to the rotation (although most of the lift force is seen as thrust) but the drag force acts against rotation

Summary of Origins of Rotation Force

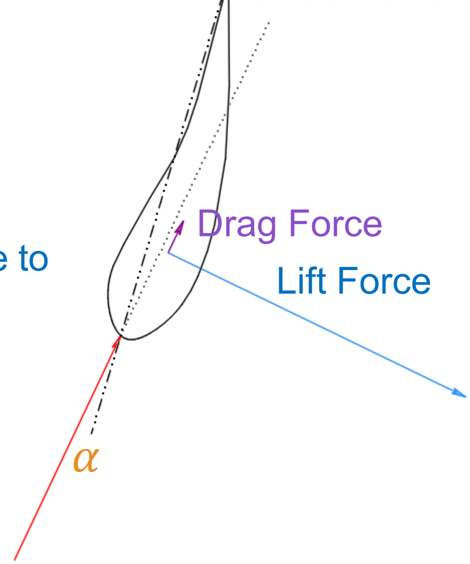
Blades rotate in plane that is normal to wind flow.



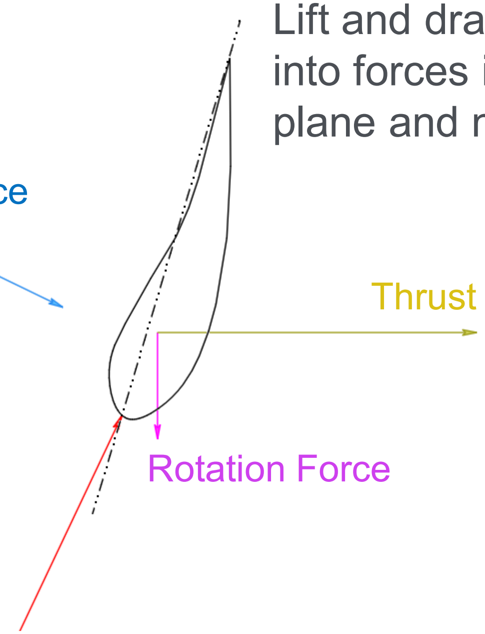
Air flow from wind and air flow from motion of blade combine to give relative wind.



Lift and drag, perpendicular and parallel and to relative wind, are found from angle of attack and coefficients of the blade aerofoil.



Lift and drag resolved into forces in rotation plane and normal to it.

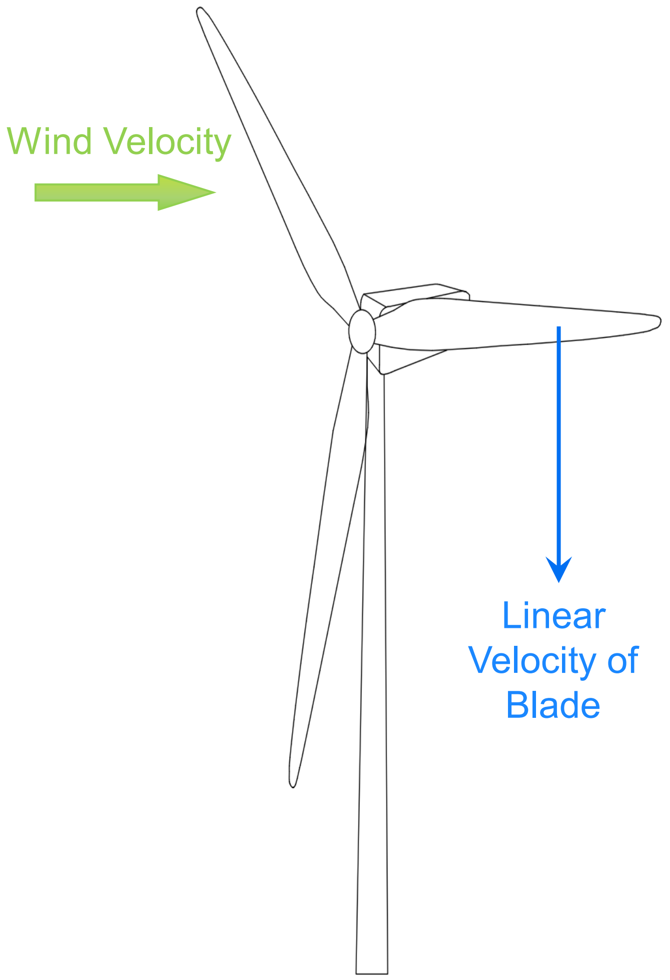


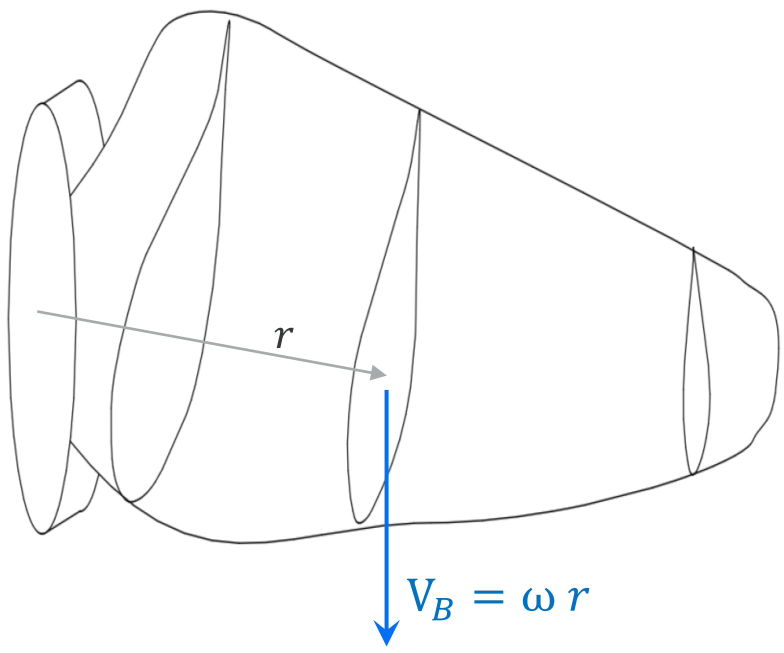
Don’t Forget Thrust Force on the Tower

Blade Profile

The profile and angle of the aerofoil of the blade changes along its length.

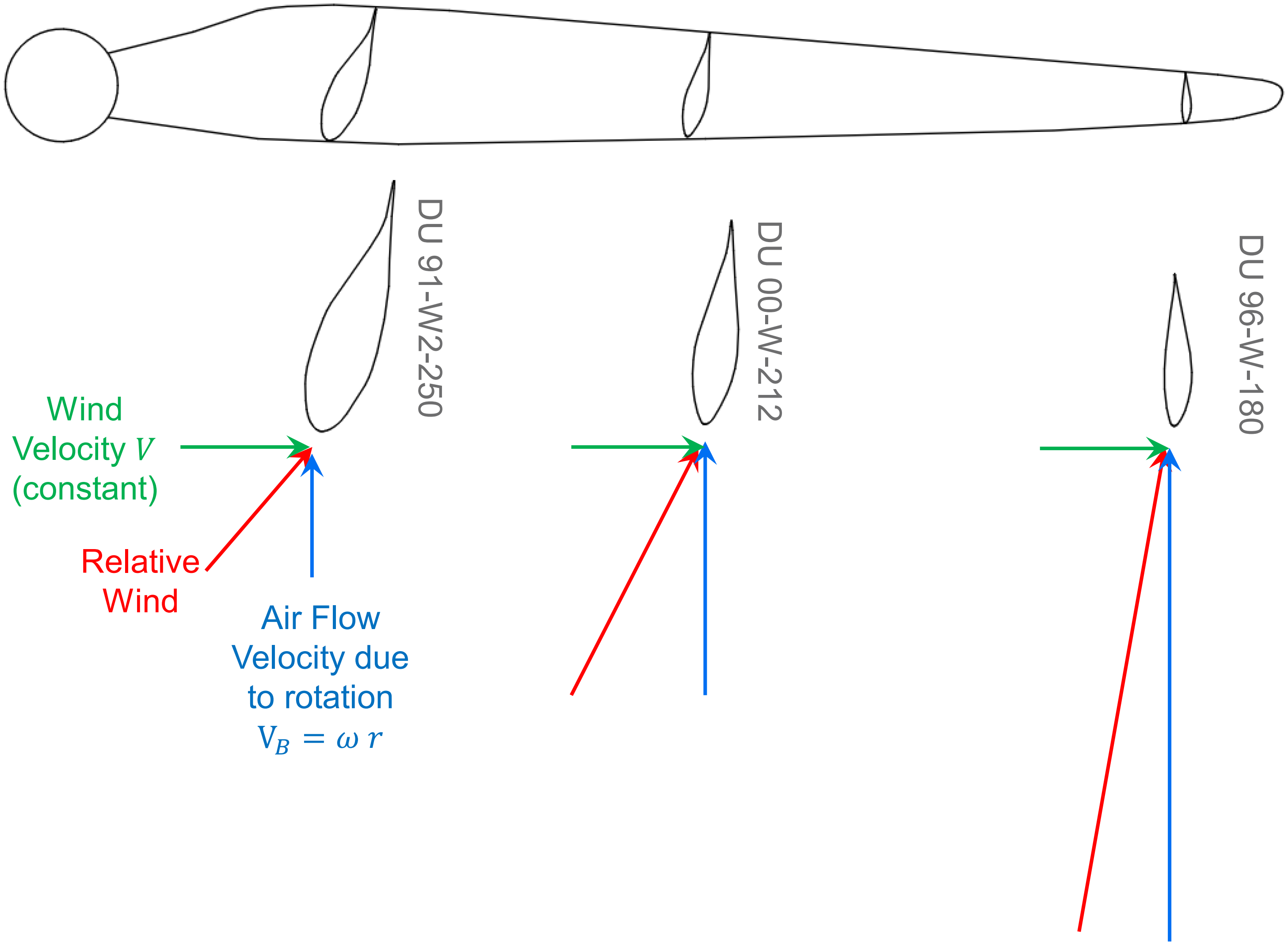
This is necessary because the airflow due to blade motion depends on the linear velocity of the blade which depends on the radially distance along the blade $V_B = \omega r$.





Blade Profile

To maintain an optimum angle of attack along the length of the blade, the chord line angle of aerofoil is rotated, that is, the blade profile twists.



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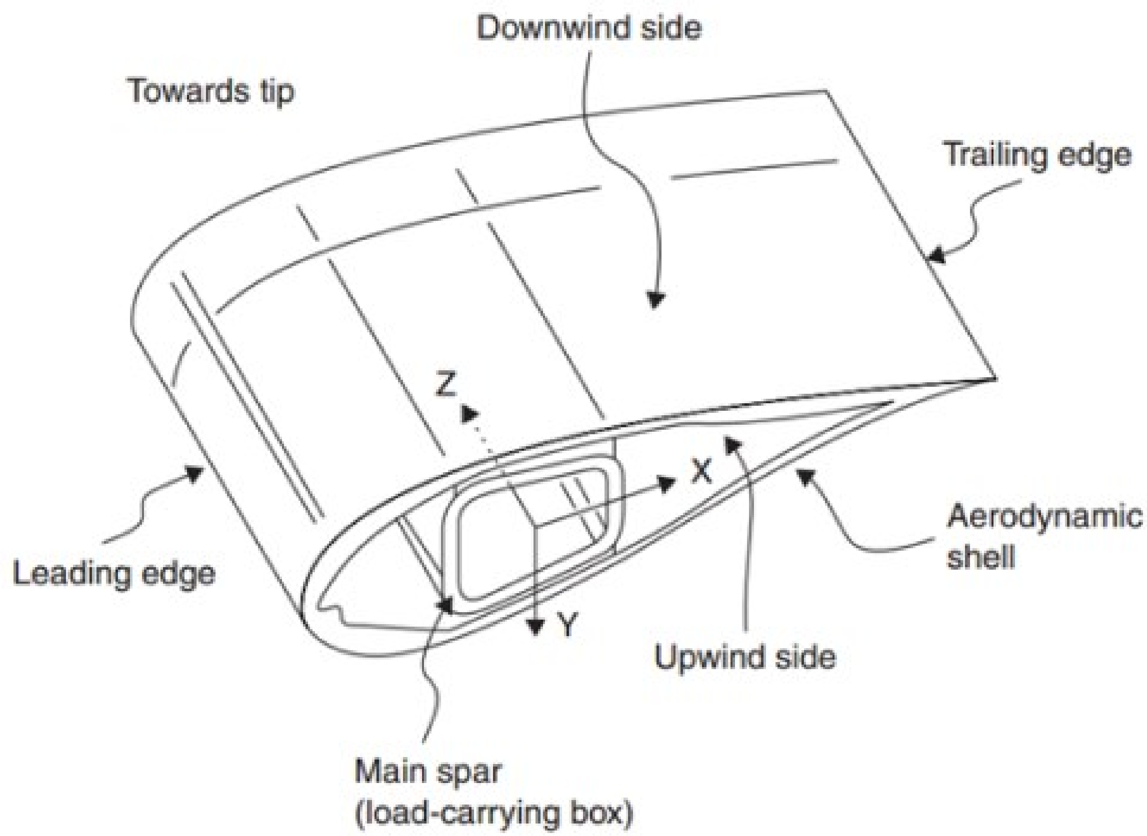
Blade Profile

The blade also needs to be strong near its root so is thicker in that region to accommodate a large “spar” so its profile changes along its length.

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Turbine Power

In general, a force vector, $\bar{F}$ extracts power from the velocity vector, $\bar{V}$ according to the scalar product $P = \bar{F} \cdot \bar{V}$

(the product of the velocity by the force acting parallel to it)

For a turbine blade we would take the force in the plane of rotation and the linear velocity of the blade at each point along the blade and integrate that over the blade length.

At each point we would need to find the lift and drag forces as calculated from the angle of attack and blade coefficients.

Such a computation is beyond the scope of this module.

We will simply consider that all those calculations are included in deriving the power coefficient of the turbine, C_P from which we get

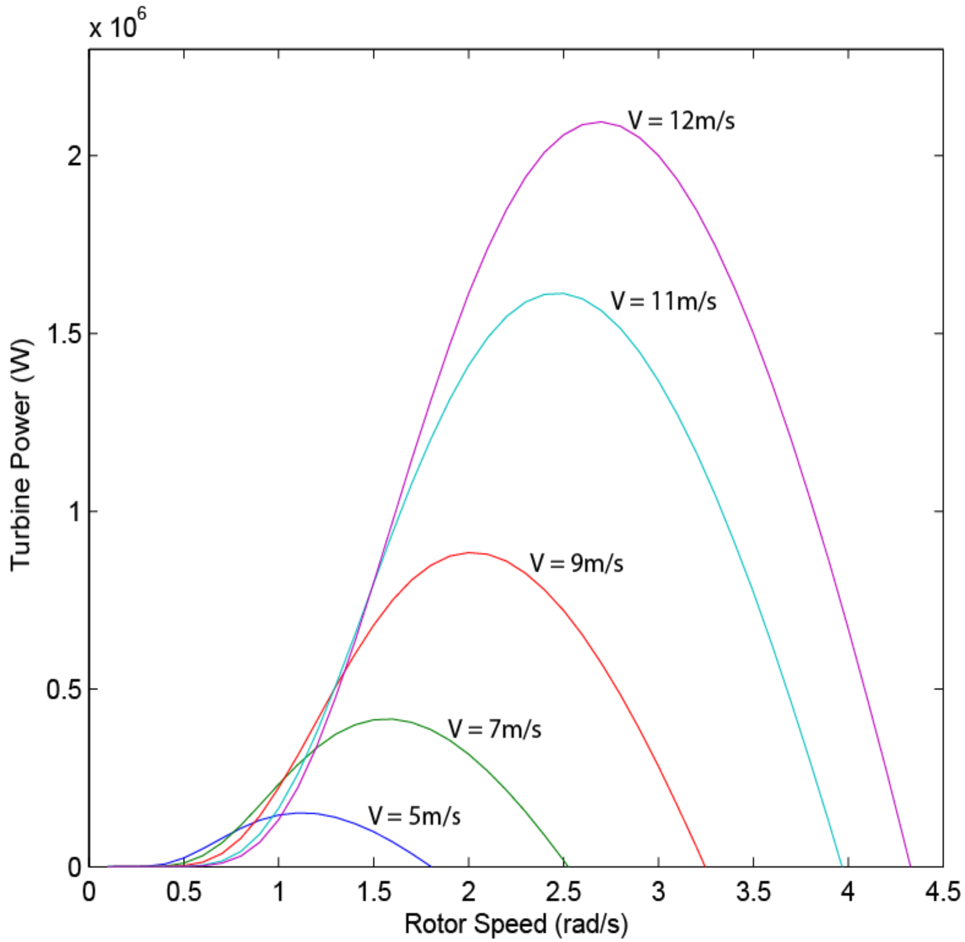
$$P_T = C_P \frac{1}{2} \rho A V^3$$

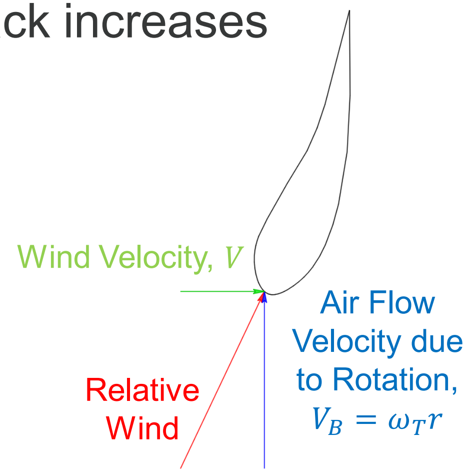
Power as a Function of Turbine Speed

The power yield of a turbine increase with the cube of wind velocity but it is also a function of speed of rotation of the blades.

There is an optimum rotor speed for each wind speed.

- If the blades rotate too **fast**, the motion-induced air flow becomes large and the angle-of-attack reduces below optimum.
- If the blades rotate too **slow**, the motion-induced air flow becomes small and the angle-of-attack increases above optimum.



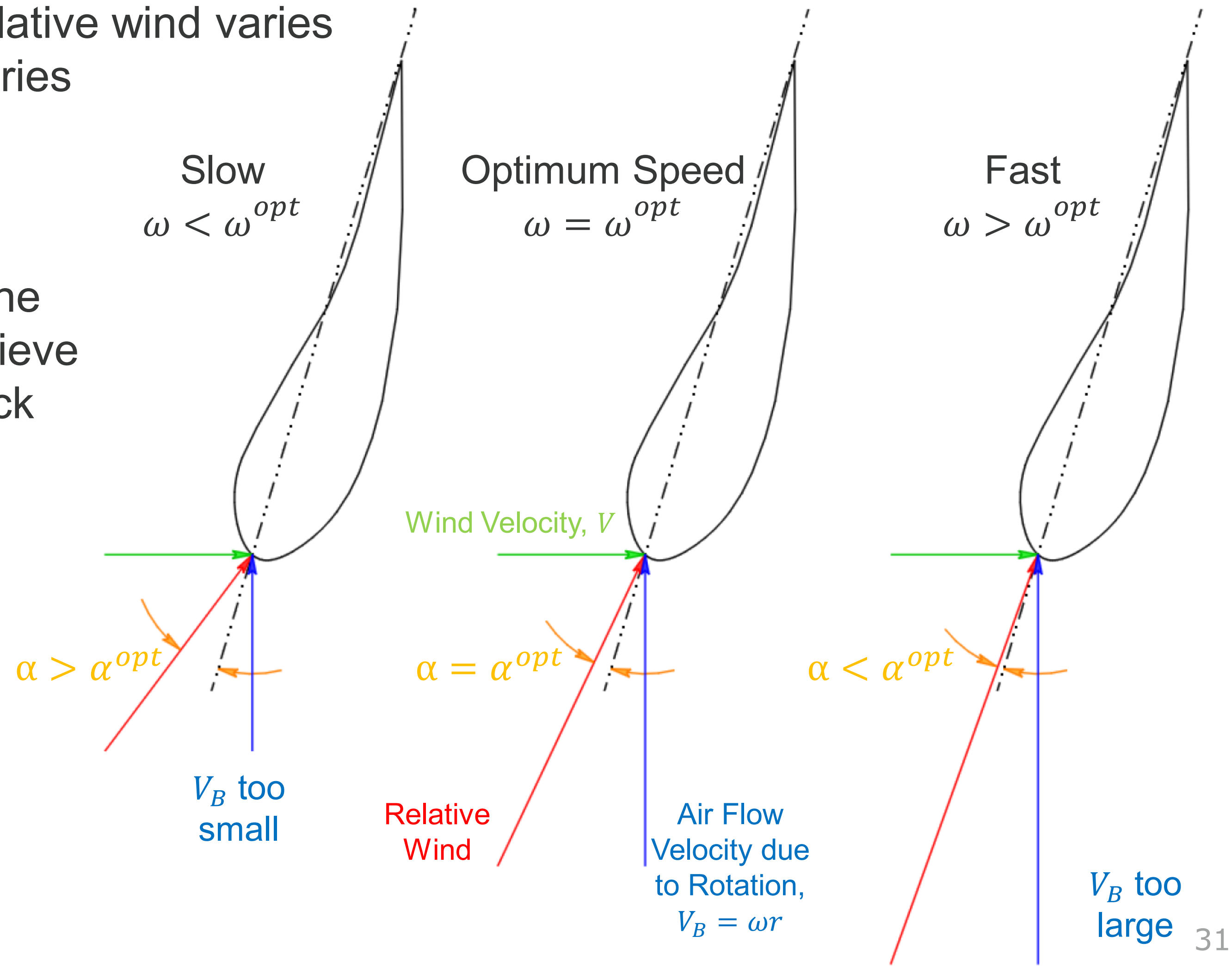


Angle of Attack as a Function of Turbine Speed

V_W is constant in these diagrams but

- ω_T varies and therefore:
- V_B varies
- the direction of the relative wind varies
- the angle of attack varies

V_B and V_W must stay in the correct proportion to achieve the optimal angle of attack



Normalised C_P Curves

To maintain an optimum angle of attack, the motion-induced flow and wind flow must stay in a fixed proportion.

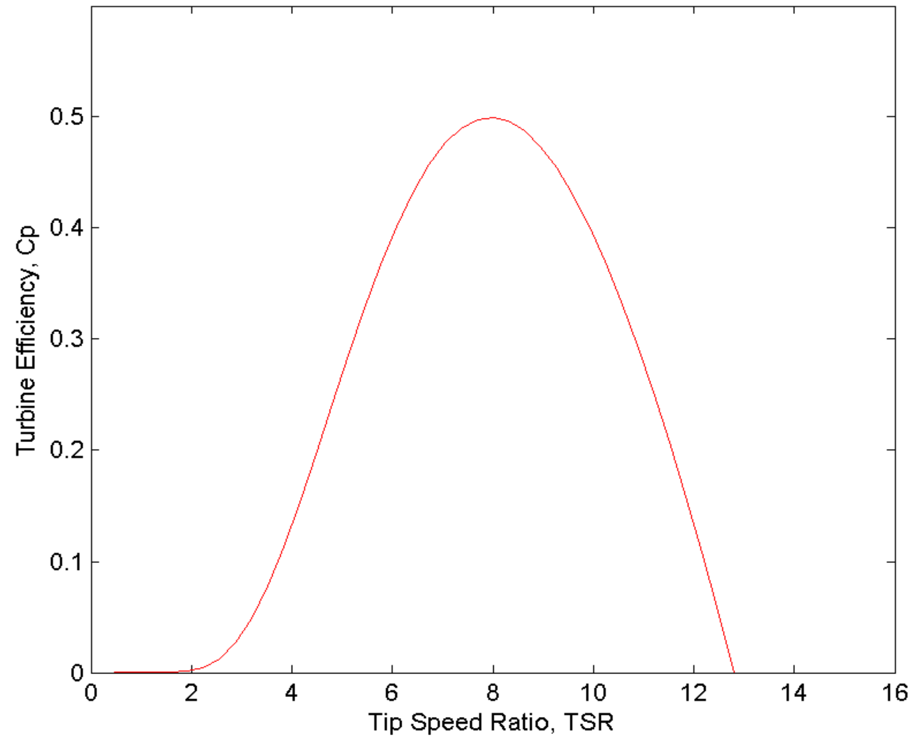
In other words, **the speed to rotation of the blades should increase in proportion to wind speed**.

We define this proportionality using the "tip speed ratio", λ (or TSR) which is the ratio of the linear velocity of the tip of the blade to the wind velocity:

$$\lambda = \frac{\omega R}{V}$$

Where R is the radial length of the blade and therefore ωR is the linear velocity of the tip of the blade.

The curve of C_P, against tip-speed ratio is convenient way of characterising a turbine and can be used to compute C_P for any combination of wind speed and rotor speed.



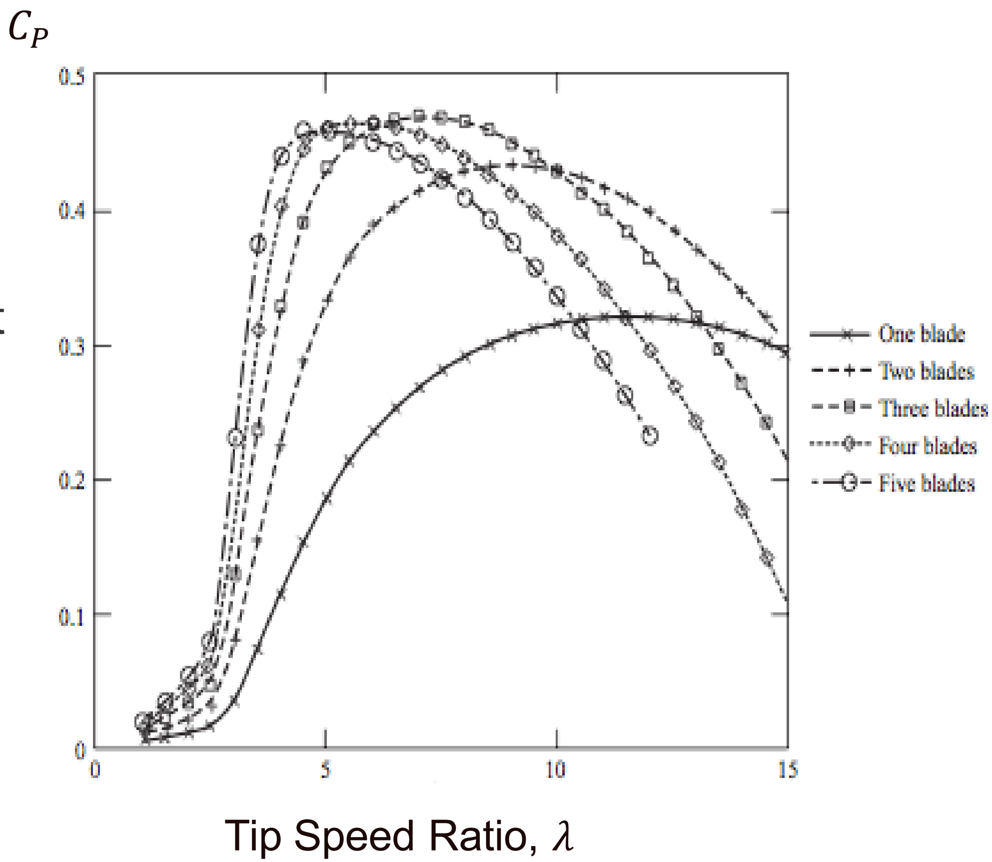
There is an optimal λ which gives the peak C_P.

In this example it is at about 8.

For a wind speed of 12.5 m/s and λ=8, the tip speed is 100 m/s, about 30% of the speed of sound.

C_p versus λ for various blade numbers

- With slow blade rotation or too few blades, some of the energy in the flow is not captured
- With fast blade rotation or too many blades, turbulent disturbances in the wake of a blade adversely affect the next blade and reduce lift forces
- A lower number of blades requires a higher tip speed ratio – good for use with low flow rates driving electrical generators
- But two-blade and one-blade turbines are difficult from a mechanical point of view.
- Three blades is the common choice.



Why 3-bladed, upwind HAWTs dominate

- Upwind rotors avoid the bad interactions between a tower wake and the blades (wake of the blade hits the tower rather than wake of the tower hits the blade).

- HAWTs are generally more efficient than VAWTs (and can be larger)
- HAWT rotors experience steadier force because of the uniform wind
- VAWT are inherently unsteady and this causes stress and mechanical failure.

- One blade is best in terms of aerodynamics but there are mechanical problems with 1 and 2 blade rotors when being moved in yaw to follow wind (their moment-of-inertia in yaw is not constant).
- Blade numbers beyond 3 reduce efficiency.
- 3 blades is a good compromise.