Jet Aircraft Propulsion

Prof. Bhaskar Roy, Prof. A M Pradeep
Department of Aerospace Engineering,
IIT Bombay

Lect-14

In this lecture...

- Axial flow compressors
  - Basic operation of axial compressors
  - Velocity triangles
  - Work and compression
  - Design parameters
    - Flow coefficient
    - Loading coefficient
    - Degree of reaction
    - Diffusion factor

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Basic operation of axial compressors

- Axial flow compressors usually consists of a series of stages.
- Each stage comprises of a row of rotor blades followed by a row of stator blades.
- The working fluid is initially accelerated by the rotor blades and then decelerated in the stator passages.
- In the stator, the kinetic energy transferred in the rotor is converted to static pressure.
- This process is repeated in several stages to yield the necessary overall pressure ratio.

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Basic operation of axial compressors

- The compression process consists of a series of diffusions.
- This occurs both in the rotor as well as the stator.
- Due to motion of the rotor blades→ two distinct velocity components: absolute and relative velocities in the rotor.
- The absolute velocity of the fluid is increased in the rotor, whereas the relative velocity is decreased, leading to diffusion.
- Per stage pressure ratio is limited because a compressor operates in an adverse pressure gradient environment.

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Basic operation of axial compressors

- Turbines on the other hand operate under favourable pressure gradients.
- Several stages of an axial compressor can be driven by a single turbine stage.
- Careful design of the compressor blading is essential to minimize losses as well as to ensure stable operation.
- Some compressors also have inlet Guide Vanes (IGV) that permit the flow entering the first stage to vary under off-design conditions.

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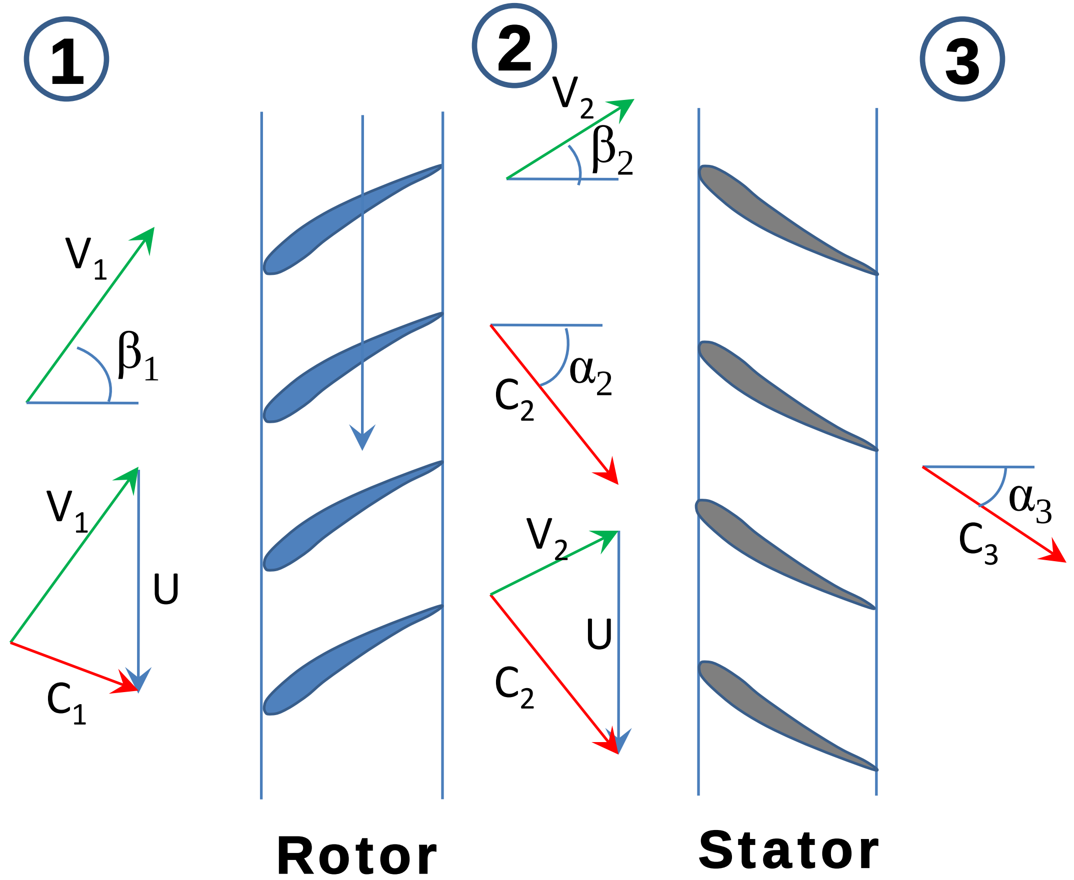
Velocity triangles

- Elementary analysis of axial compressors begins with velocity triangles.
- The analysis will be carried out at the mean height of the blade, where the peripheral velocity or the blade speed is, *U.*
- The absolute component of velocity will be denoted by, *C* and the relative component by, *V.*
- The axial velocity (absolute) will be denoted by C_a and the tangential components will be denoted by subscript *w* (for eg, C_w or V_w)
- α denotes the angle between the absolute velocity with the axial direction and β the corresponding angle for the relative velocity.

Velocity triangles



$$\vec{C} = \vec{U} + \vec{V}$$

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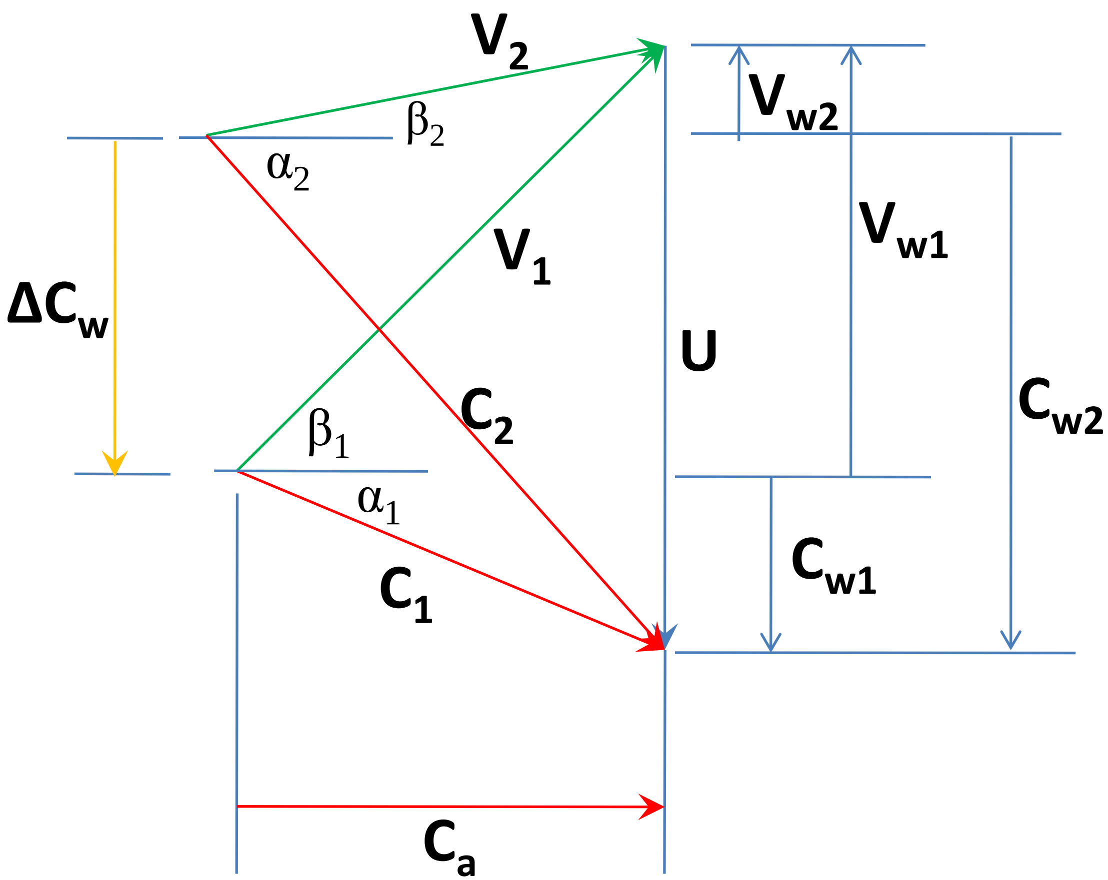
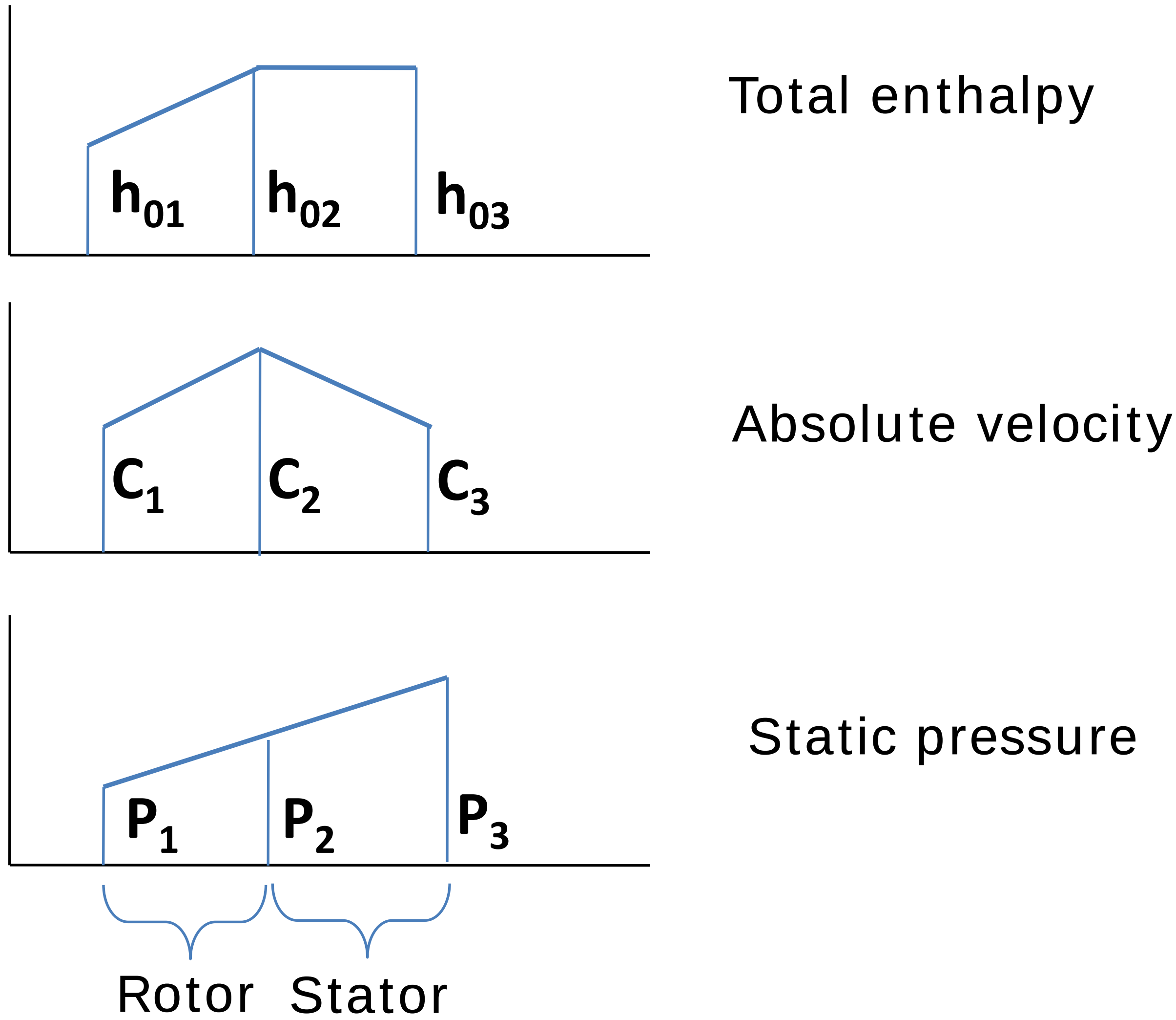
Velocity triangles



Property changes across a stage



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Work and compression

- Assuming $C_a = C_{a1} = C_{a2}$, from the velocity triangles, we can see that

$$\frac{U}{C_a} = \tan\alpha_1 + \tan\beta_1 \quad \text{and} \quad \frac{U}{C_a} = \tan\alpha_2 + \tan\beta_2$$

- By considering the change in angular momentum of the air passing through the rotor, work done per unit mass flow is

$w = U\left(C_{w2} - C_{w1}\right)$, where C_{w1} and C_{w2} are the tangential components of the fluid velocity before and after the rotor, respectively.

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Work and compression

The above equation can also be written as,

$$w = UC_a(\tan\alpha_2 - \tan\alpha_1)$$

Since, $(\tan\alpha_2 - \tan\alpha_1) = (\tan\beta_1 - \tan\beta_2)$

$$\therefore w = UC_a(\tan\beta_1 - \tan\beta_2)$$

In other words, $w = U\Delta C_w$

- The input energy will reveal itself in the form of rise in stagnation temperature of the air.
- The work done as given above will also be equal to the change in stagnation enthalpy across the stage.

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Work and compression

$$h_{02} - h_{01} = U\Delta C_w$$

$$T_{02} - T_{01} = \frac{U\Delta C_w}{c_p} \Rightarrow \frac{\Delta T_0}{T_{01}} = \frac{U\Delta C_w}{c_p T_{01}}$$

Since the flow is adiabatic and no work is done as the fluid passes through the stator, $T_{03} = T_{02}$

Let us define stage efficiency, η_{st}, as

$$\eta_{\mathrm{st}} = \frac{h_{03s} - h_{01}}{h_{03} - h_{01}}$$

This can be expressed as

$$\frac{T_{03s}}{T_{01}} = 1 + \eta_{\mathrm{st}} \frac{\Delta T_0}{T_{01}}$$

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Work and compression

In the above equation, $\Delta T_0 = T_{03} - T_{01}$

In terms of pressure ratio,

$$\frac{P_{03}}{P_{01}} = \left[1 + \eta_{st}\frac{\Delta T_0}{T_{01}}\right]^{\gamma/(\gamma-1)}$$

This can be combined with the earlier equation to give,

$$\frac{P_{03}}{P_{01}} = \left[1 + \eta_{st}\frac{U\Delta C_w}{c_p T_{01}}\right]^{\gamma/(\gamma-1)}$$

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Work and compression

- From the above equation that relates the per stage temperature rise to the pressure ratio, it can be seen that to obtain a high temperature ratio for a given overall pressure ratio (for minimizing number of stages),
  - High blade speed: limited by blades stresses
  - High axial velocity, high fluid deflection *(β_1-β_2):* Aerodynamic considerations and adverse pressure gradients limit the above.

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Design parameters

- The following design parameters are often used in the parametric study of axial compressors:
  - Flow coefficient,

    $$\phi = C_a / U$$

  - Stage loading,

    $$\psi = \Delta h_0 / U^2 = \Delta C_w / U$$

  - Degree of reaction, R_x
  - Diffusion factor, D^*

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Degree of reaction

- Diffusion takes place in both rotor and the stator.
- Static pressure rises in the rotor as well as the stator.
- Degree of reaction provides a measure of the extent to which the rotor contributes to the overall pressure rise in the stage.

Degree of reaction

$$R_x = \frac{\text{Static enthalpy rise in the rotor}}{\text{Stagnation enthalpy rise in the stage}}$$

$$= \frac{h_2 - h_1}{h_{03} - h_{01}} \approx \frac{h_2 - h_1}{h_{02} - h_{01}}$$

For a nearly incompressible flow,

$$h_2 - h_1 \cong \frac{1}{\rho}\left(P_2 - P_1\right) \text{ for the rotor}$$

and for the stage, $h_{03} - h_{01} \cong \dfrac{1}{\rho}\left(P_{03} - P_{01}\right)$

$$\therefore R_x = \frac{h_2 - h_1}{h_{02} - h_{01}} \cong \frac{P_2 - P_1}{P_{02} - P_{01}}$$

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Degree of reaction

From the steady flow energy equation,

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

$$\therefore R_x = \frac{h_2 - h_1}{h_{03} - h_{01}} = \frac{V_1^2 - V_2^2}{2U(C_{w2} - C_{w1})}$$

For constant axial velocity, $V_1^2 - V_2^2 = V_{w1}^2 - V_{w2}^2$

And, $V_{w1} - V_{w2} = C_{w1} - C_{w2}$

On simplification, $R_x = \frac{1}{2} - \frac{C_a}{2U}(\tan\alpha_1 - \tan\beta_2)$

or, $R_x = \frac{C_a}{2U}(\tan\beta_1 + \tan\beta_2)$

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Degree of reaction

- Special cases of R_x
  - $R_x=0, \beta_2 = -\beta_1$, There is no pressure rise in the rotor, the entire pressure rise is due to the stator, the rotor merely deflects the incoming flow: impulse blading
  - $R_x=0.5$, gives $\alpha_1 = \beta_2$ and $\alpha_2 = \beta_1$, the velocity triangles are symmetric, equal pressure rise in the rotor and the stator
  - $R_x=1.0, \alpha_2 = -\alpha_1$, entire pressure rise takes place in the rotor while the stator has no contribution.

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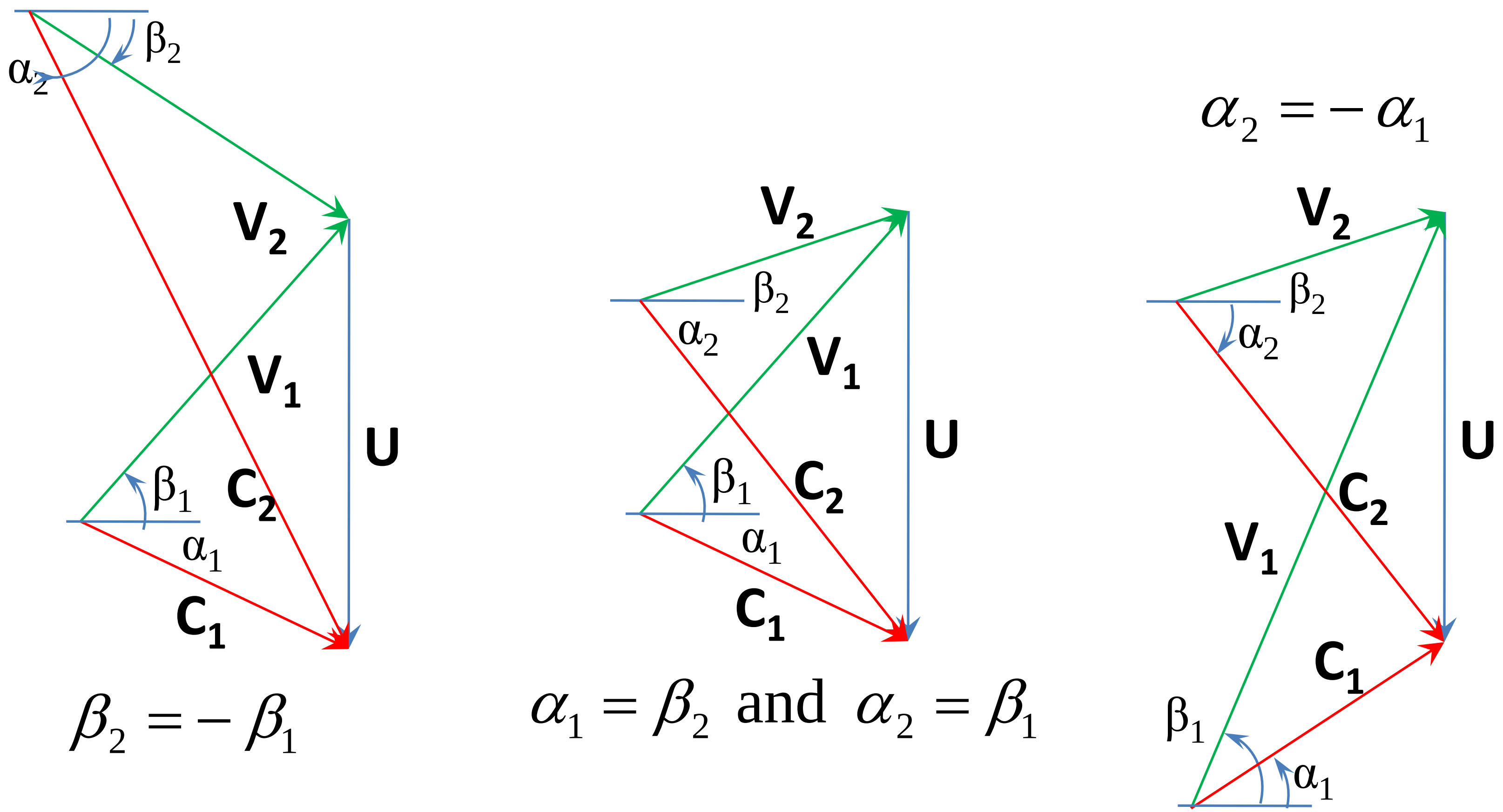
Degree of reaction



$\beta_2 = -\beta_1$ $\quad$ $\alpha_1 = \beta_2$ and $\alpha_2 = \beta_1$ $\quad$ $\alpha_2 = -\alpha_1$

$R_x = 0.0$ $\quad$ **$R_x = 0.5$** $\quad$ **$R_x = 1.0$**

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Diffusion factor

- Fluid deflection (β_2-β_1)is an important parameter that affects the stage pressure rise.
- Excessive deflection, which means high rate of diffusion, will lead to blade stall.
- Diffusion factor is a parameter that associates blade stall with deceleration on the suction surface of the airfoil section.
- Diffusion factor, D*, is defined as

$D^* = \dfrac{V_{\max} - V_2}{V_1}$ Where, $V_{\max}$ is the ideal surface velocity at the minimum pressure point and V_2 is the ideal velocity at the trailing edge and V_1 is the velocity at the leading edge.

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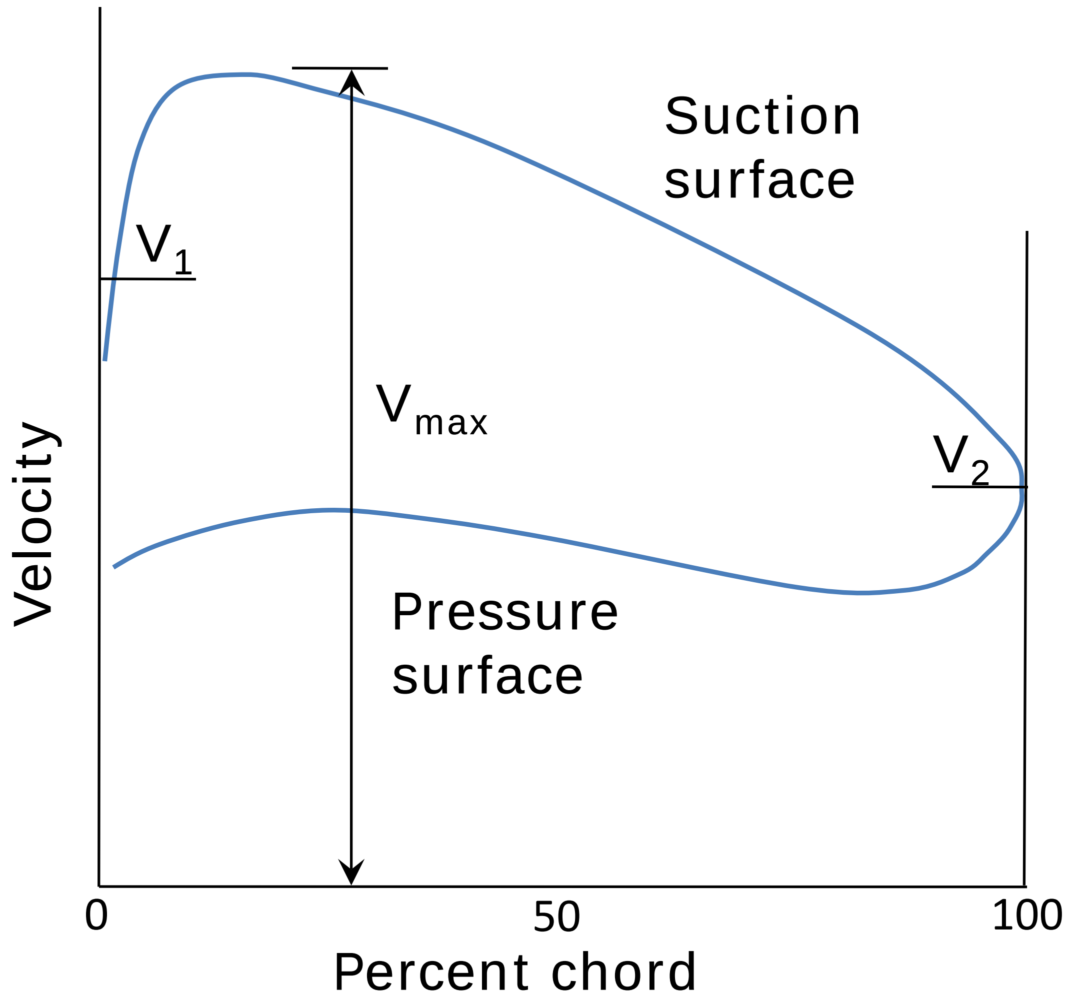
Diffusion factor



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Diffusion factor

- Lieblein (1953) proposed an empirical parameter for diffusion factor.
  - It is expressed entirely in terms of known or measured quantities.
  - It depends strongly upon solidity (C/s).
  - It has been proven to be a dependable indicator of approach to separation for a variety of blade shapes.
  - D^* is usually kept around 0.5.

$$D^* = 1 - \frac{V_2}{V_1} + \frac{V_{w1} - V_{w2}}{2\left(\frac{C}{s}\right)V_1}$$

Where, C is the chord of the blade and s is the spacing between the blades.

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In the next lecture...

- Cascade analysis
  - Cascade nomenclature
  - Loss and blade performance estimation