TURBOMACHINERY AERODYNAMICS

Lect- 11

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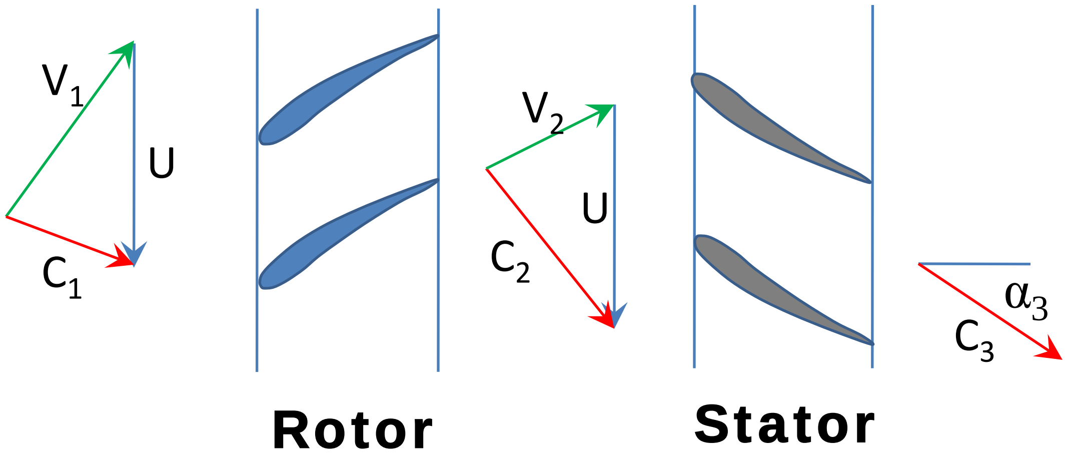
In this lecture...

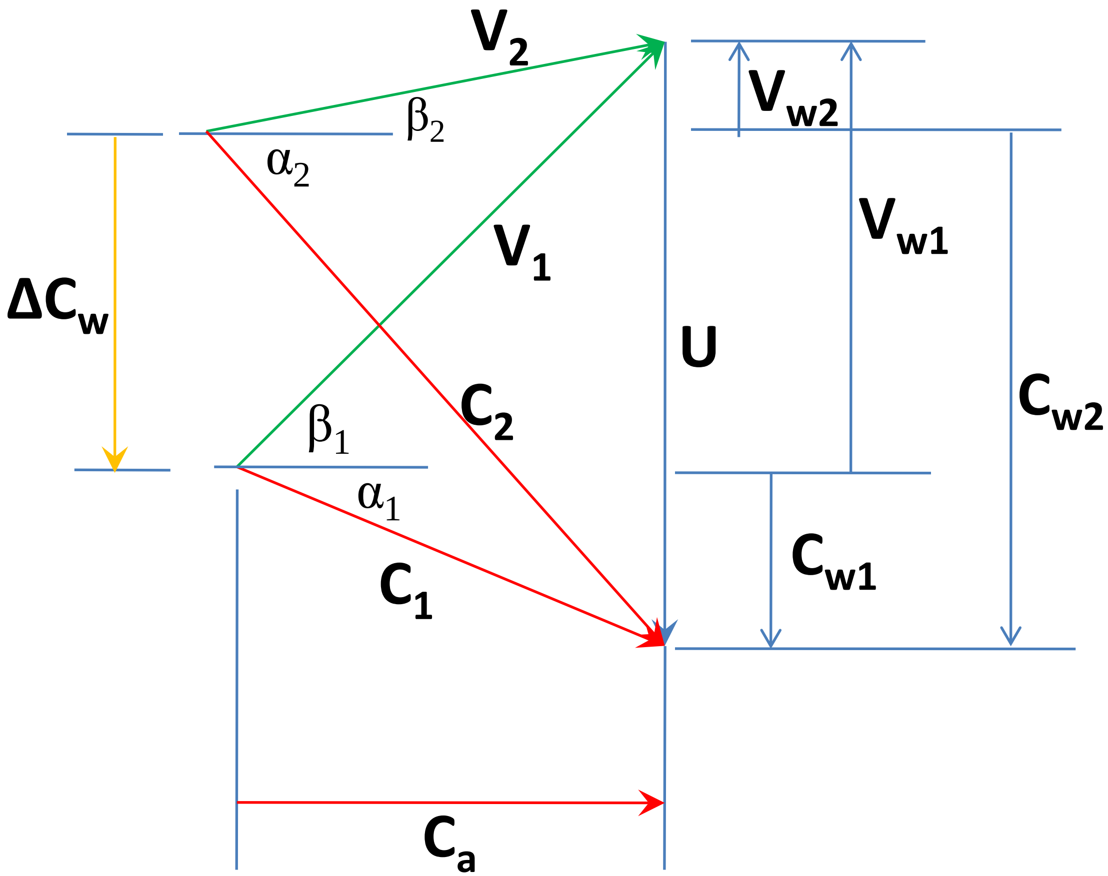
- Performance characteristics of axial flow compressors
  - Single stage characteristics
  - Multi-stage characteristics

Single stage performance characteristics

- Let us consider a typical axial compressor stage comprising of a set of rotor blades followed by a set of stator blades.



Single stage performance characteristics



Single stage performance characteristics

- From the above velocity triangles,

$$C_{w2} = U - C_a \tan\beta_2 \quad and \quad C_{w1} = C_a \tan\alpha$$

$$\text{Since, } \Delta h_0 = U \Delta C_w$$

$$\Delta h_0 = U\left[U - C_a\left(\tan\alpha_1 + \tan\beta_2\right)\right]$$

$$or,\ \frac{\Delta C_w}{U} = \frac{\Delta h_0}{U^2} = 1 - \frac{C_a}{U}\left(\tan\alpha_1 + \tan\beta_2\right)$$

Single stage performance characteristics

- Change in the design mass flow rate affects C_a, change in rotor speed affects U.
- Change of either C_a or U changes the inlet angle β_1 at which the flow approaches the rotor.
- The above equation shows that the blade performance depends upon the ratio C_a/U.

The stage performance is a function of the loading coefficient, flow coefficient and the efficiency.

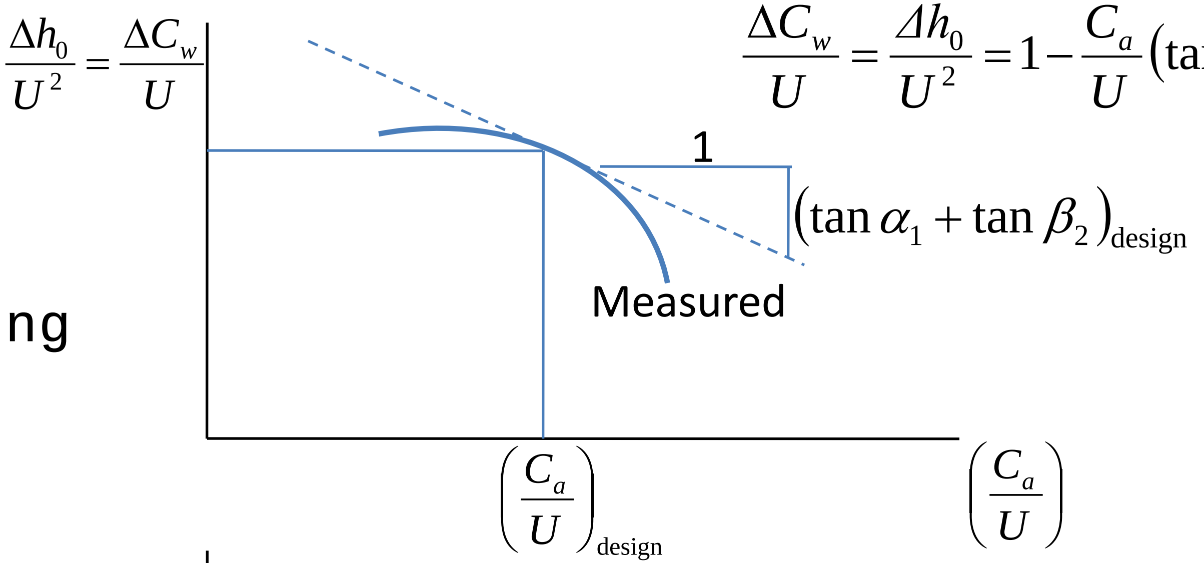
Thus,

$$\text{Stage performance} = f(\psi, \varphi, \eta)$$

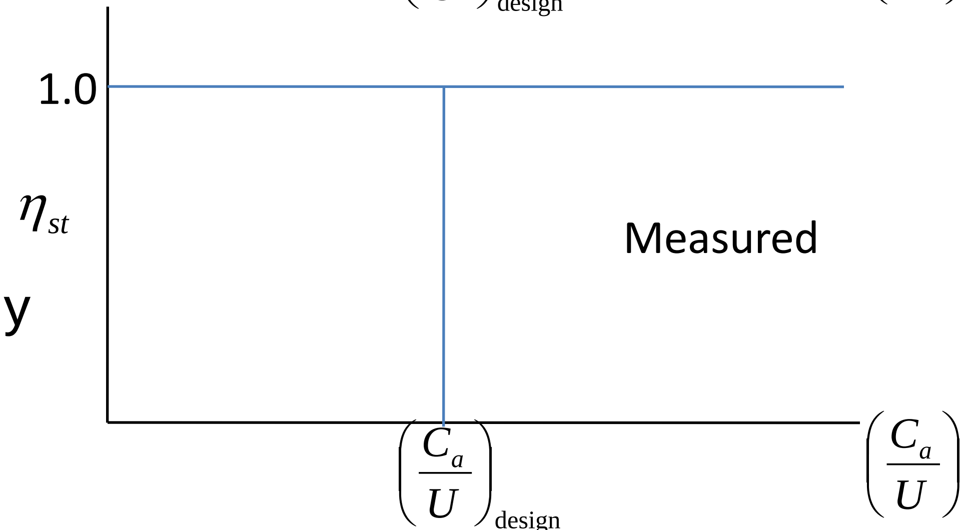
Single stage performance characteristics

$$\frac{\Delta C_w}{U} = \frac{\Delta h_0}{U^2} = 1 - \frac{C_a}{U}\left(\tan\alpha_1 + \tan\beta_2\right)$$

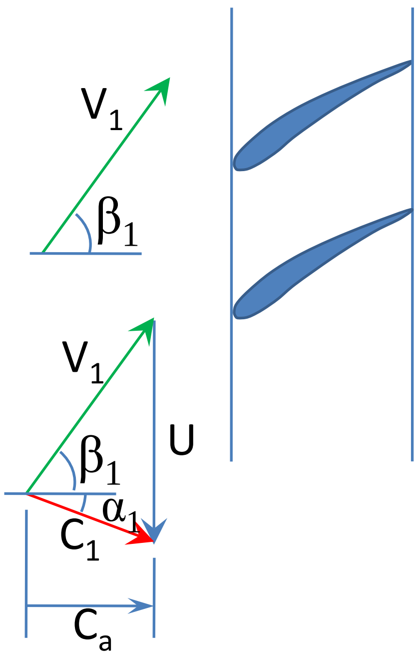
Stage loading



Stage efficiency



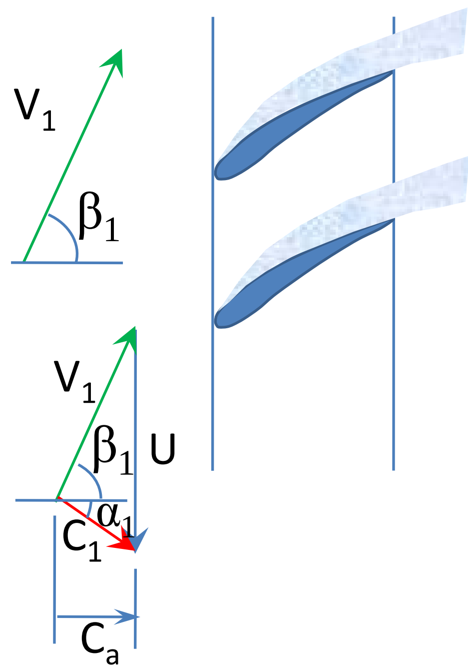
Single stage performance characteristics



Design condition :

Normal operation

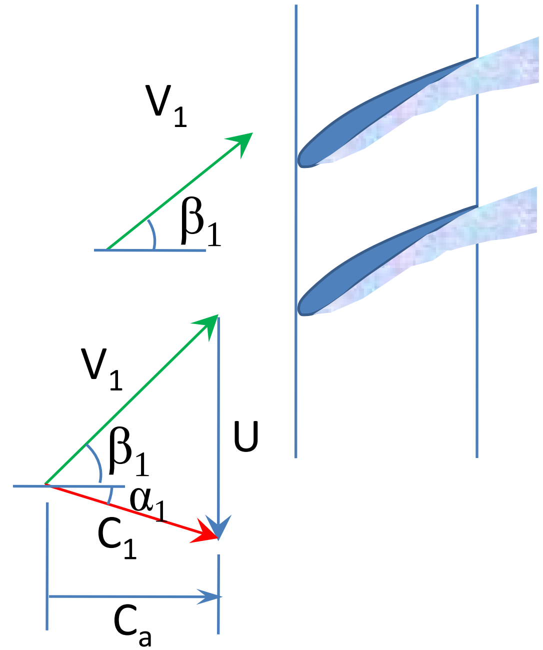
$$\left(\frac{C_a}{U}\right)=\left(\frac{C_a}{U}\right)_{\text{design}}$$



Off - design condition :

Positive incidence flow separation

$$\left(\frac{C_a}{U}\right)<\left(\frac{C_a}{U}\right)_{\text{design}}$$



Off - design condition :

Negative incidence flow separation

$$\left(\frac{C_a}{U}\right)>\left(\frac{C_a}{U}\right)_{\text{design}}$$

Multi-stage performance characteristics

- Let us know consider a multi-stage compressor. Inlet station is denoted by 1 and exit of the compressor by 2.
- Therefore the overall pressure ratio of the compressor is P_{02}/P_{01}.
- The compressor outlet pressure, P_{02}, and the isentropic efficiency, $\eta_{C,}$ depend upon several physical variables

Multi-stage performance characteristics

$$P_{02},\eta_C = f(\dot{m}, P_{01}, T_{01}, \Omega, \gamma, R, \nu, \text{design}, D)$$

In terms of non-dimensionless parameters,

$$\frac{P_{02}}{P_{01}},\eta_C = f\left(\frac{\dot{m}\sqrt{\gamma R T_{01}}}{P_{01}D^2}, \frac{\Omega D}{\sqrt{\gamma R T_{01}}}, \frac{\Omega D^2}{\nu}, \gamma, \text{design}\right)$$

For a given design, we can assume that γ and ν do not affect the performance significantly. Also, D and R are fixed. Therefore the above reduces to

$$\frac{P_{02}}{P_{01}},\eta_C = f\left(\frac{\dot{m}\sqrt{T_{01}}}{P_{01}}, \frac{N}{\sqrt{T_{01}}}\right)$$

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Multi-stage performance characteristics

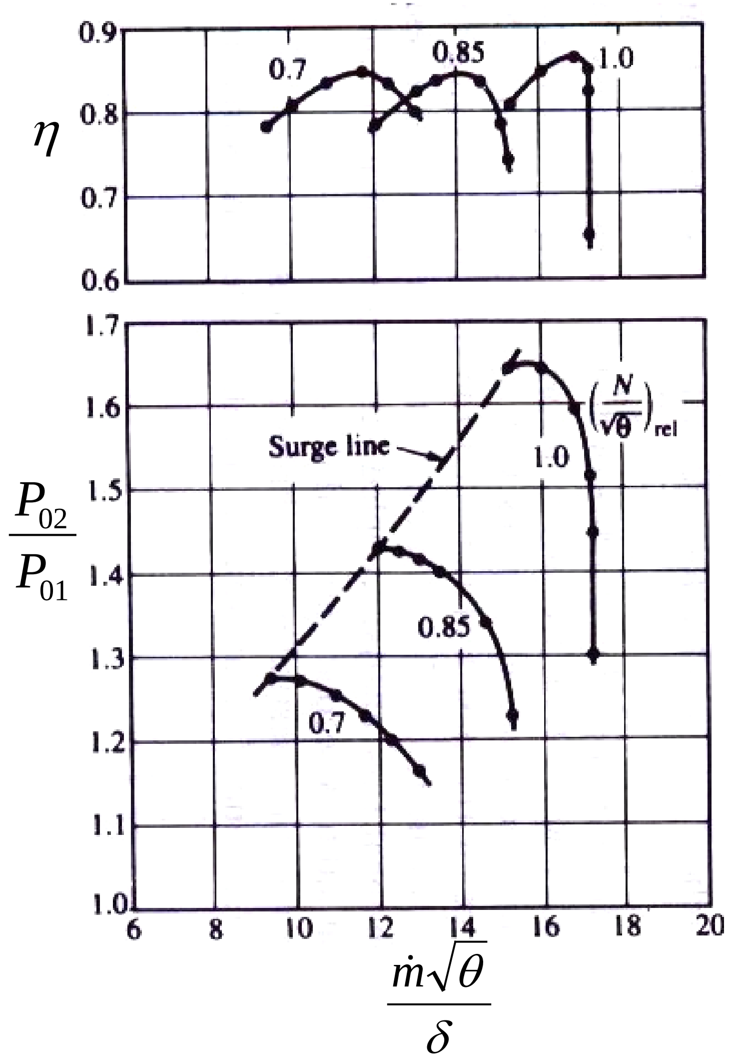
Usually, this is further processed in terms of the standard day pressure and temperature.

$$\frac{P_{02}}{P_{01}}, \eta_C = f\left(\frac{\dot{m}\sqrt{\theta}}{\delta}, \frac{N}{\sqrt{\theta}}\right)$$

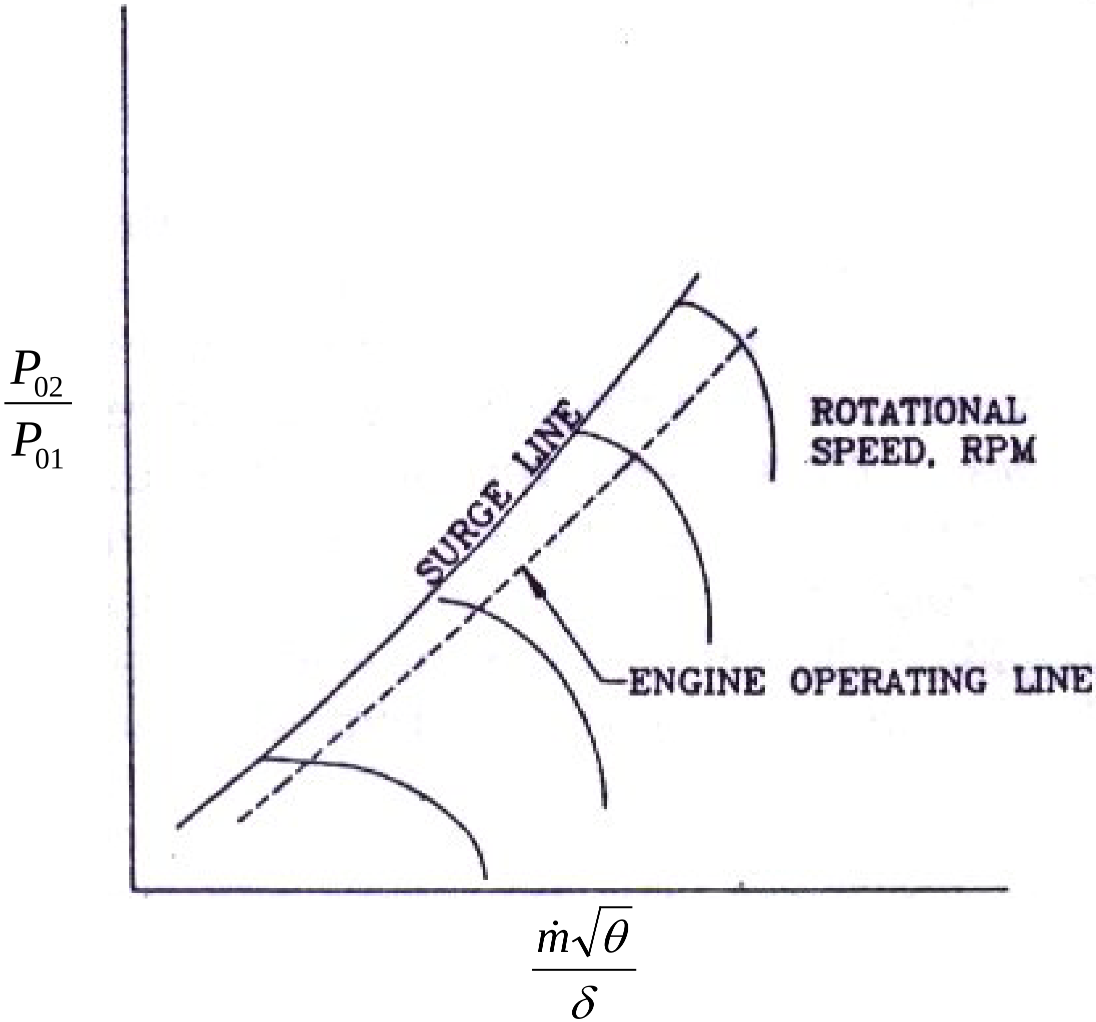
$$\text{Where, } \theta = \frac{T_{01}}{(T_{01})_{\text{Std. day}}} \text{ and } \delta = \frac{P_{01}}{(P_{01})_{\text{Std. day}}}$$

$$(T_{01})_{\text{Std. day}} = 288.15\, K \;\; and \;\; (P_{01})_{\text{Std. day}} = 101.325\; kPa$$

Multi-stage performance characteristics



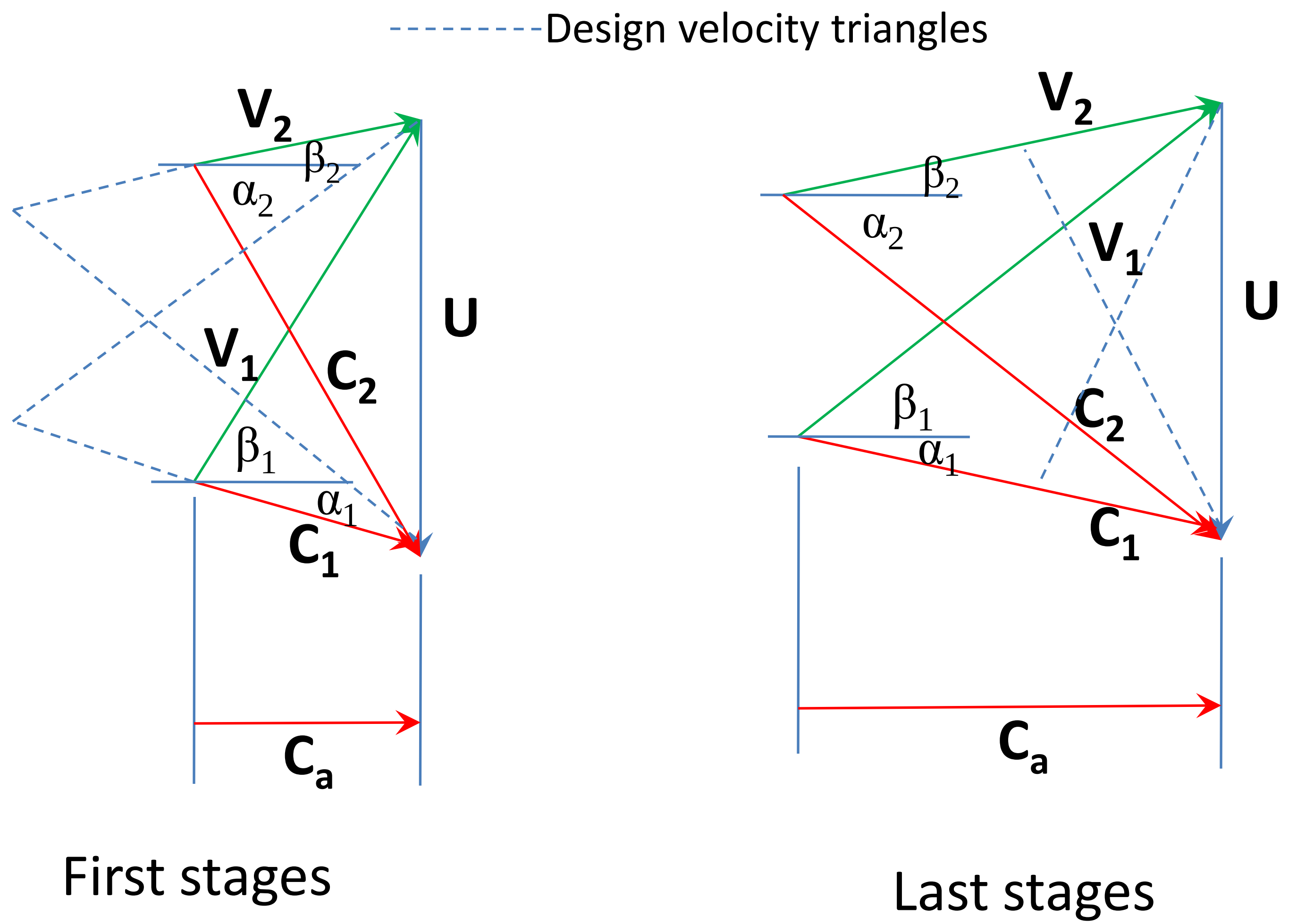
Multi-stage performance characteristics



Multi-stage performance characteristics

- In a multi-stage compressor, a small departure from the design point at the first stage causes progressively increasing departure from design conditions from the first stage onwards.
- Thus, a small reduction in $(c_a/U)_{design}$ at the first stage could lead to positive incidence separation at the last stage.
- Similarly, a small increase in $(c_a/U)_{design}$ could lead to negative incidence separation in the last stage.
- The most extreme mismatching of the front and rear stages occur during starting.

Multi-stage performance characteristics



Multi-stage performance characteristics

- Decreased C_a with α_1 and β_2 constant, results in increased α_2 and β_1 or increased loading on both rotor and stator blades.
- In the case of increased C_a, it results in the opposite effect.
- Designers use several solutions to allow compressors to self-start: use of bleed valves allowing some of the incoming air to escape, variable IGVs, multi-spooling.

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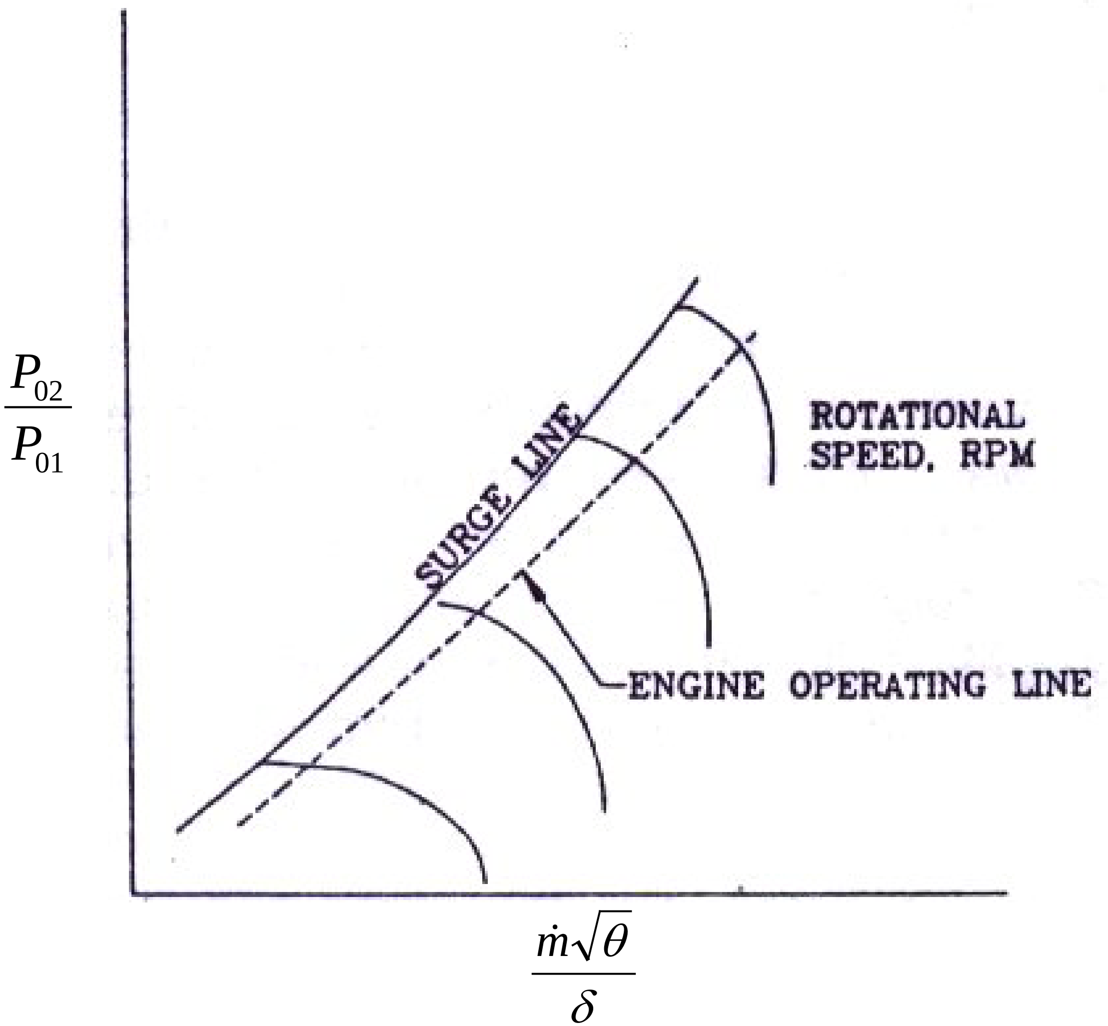
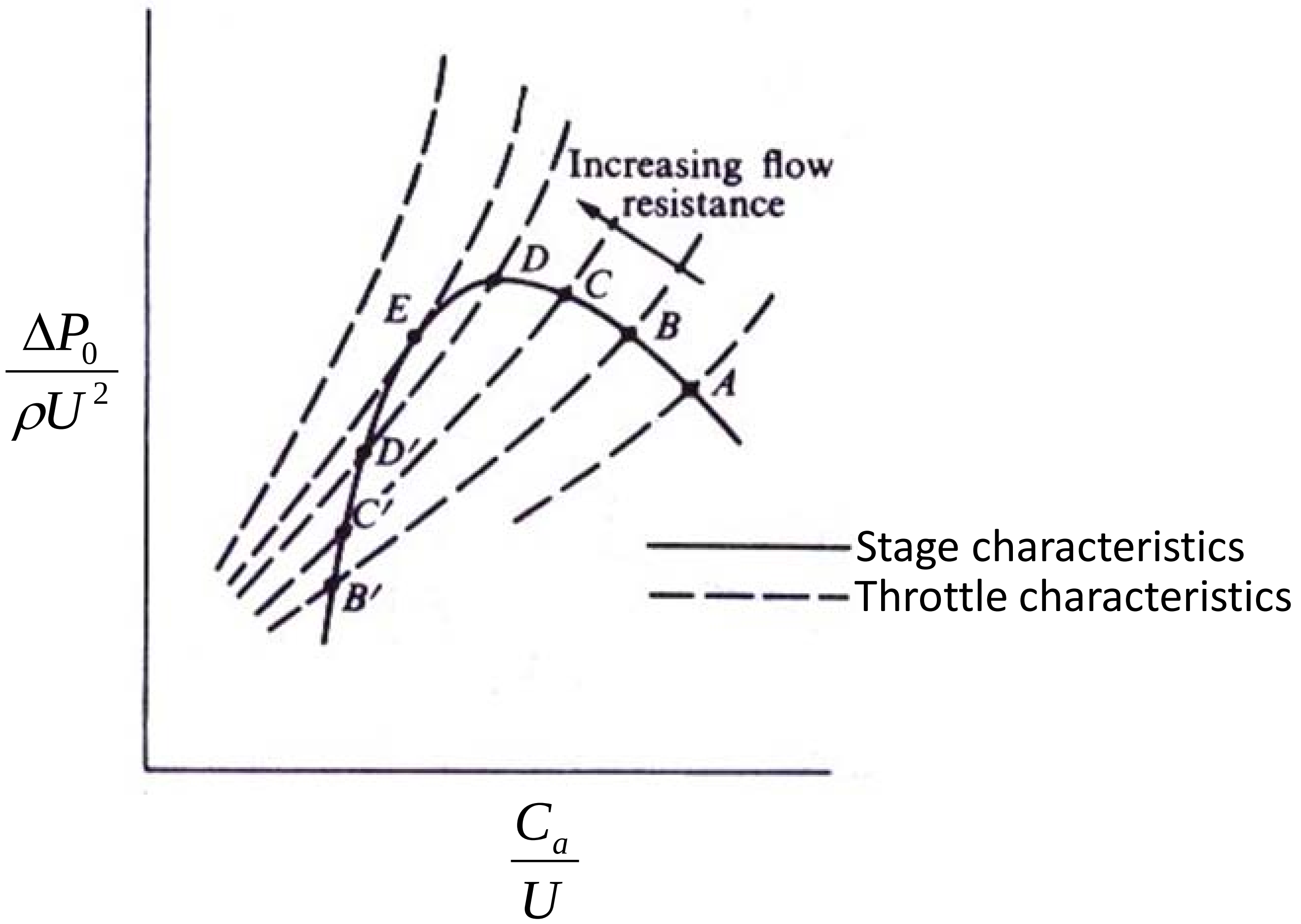
Multi-stage performance characteristics

- Axial compressors suffer from two possible modes of unstable operation
  - Rotating stall: non-axisymmetric, aperiodic
  - Surge: axisymmetric, periodic
- Rotating stall: progression around the blade annulus of a stall pattern, in which one or more adjacent blade passages are instantaneously stalled, then are cleared for unstalled flow as the stall cell progresses.
- Rotating stall causes alternate loading and unloading of the blades: fatigue failure.

Multi-stage performance characteristics



Multi-stage performance characteristics



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