Jet Aircraft Propulsion

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Lect-16

In this lecture...

- Free vortex theory
- Single and multi-stage axial compressor characteristics

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Radial equilibrium

- For a realistic design of an axial compressor blade, it is necessary to take into account radial variations in
  - Blade speed, U
  - Axial velocity, C_a
  - Tangential velocity, C_w
  - Static pressure
- Maintain a reasonably uniform flow at the exit of the compressor → uniform radial work input

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Free vortex design

- Since $\Delta h_0 = U\Delta C_\theta = \Omega r \Delta C_\theta$
- This means that for a given rotational speed, $r\Delta C_\theta$ must be a constant.
- One such configuration that satisfies the above is the Free Vortex Design.
- In this approach, the product rC_θ is held a constant across the exit of each blade row.
- From the axial velocity and the blade speeds at various radial sections, the velocity triangle can be completed.

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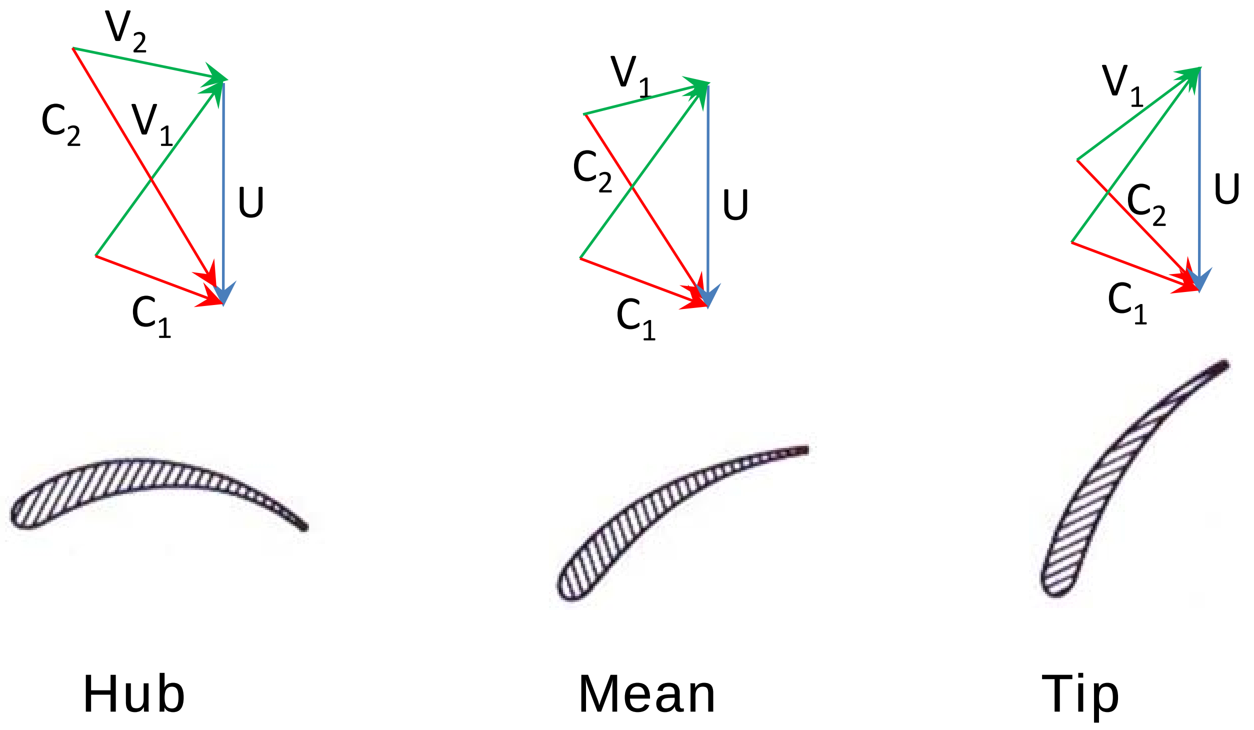
Free vortex design



Free vortex velocity diagrams at the hub, mean and tip sections

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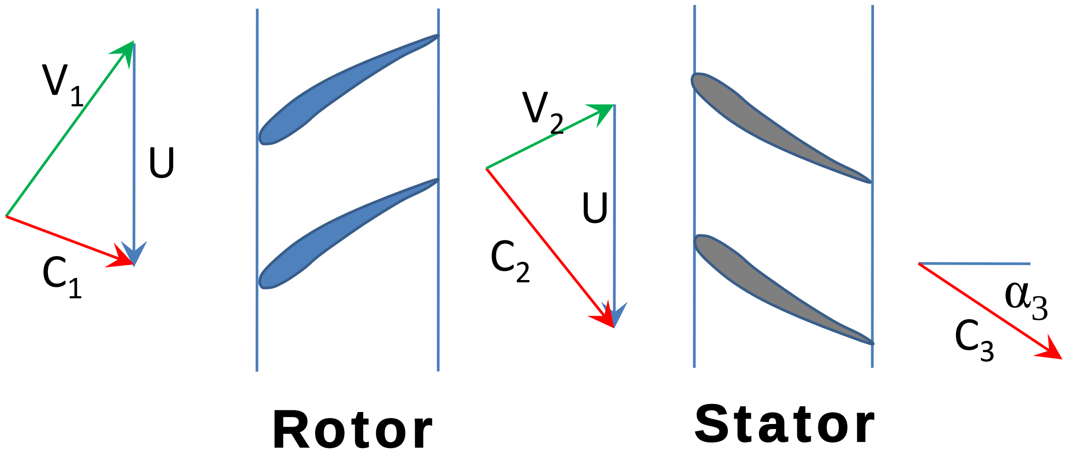
Free vortex design

- The conditions of radial equilibrium, i.e., the satisfaction of the three-dimensional equations of fluid motion must be considered.
- Possible distributions that satisfy the constant specific radial work criterion are:
  - Free vortex, $rC_\theta=a$
  - Forced vortex, $rC_\theta=ar^2$
  - Exponential, $rC_\theta=ar+b$
  - Constant reaction, $rC_\theta=ar^2+b$

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.



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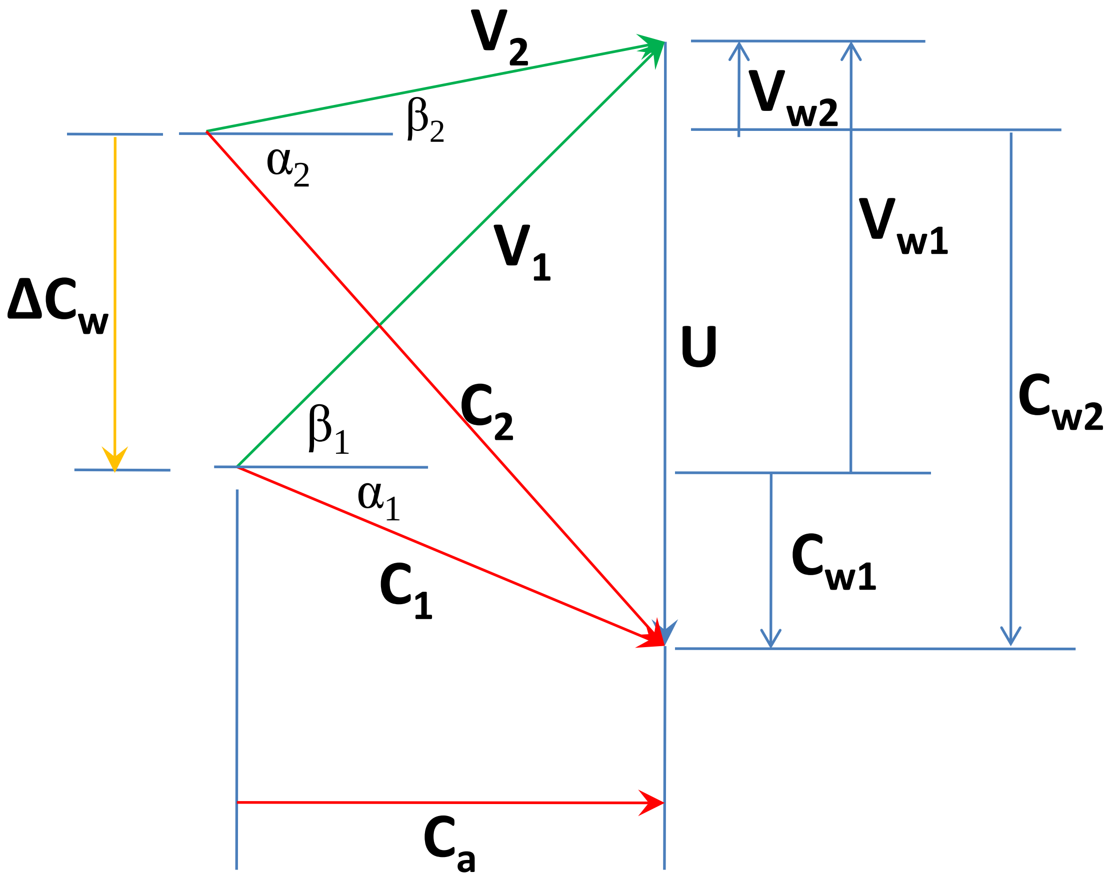
Single stage performance characteristics



Single stage performance characteristics

- From the above velocity triangles,

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

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

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

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

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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.

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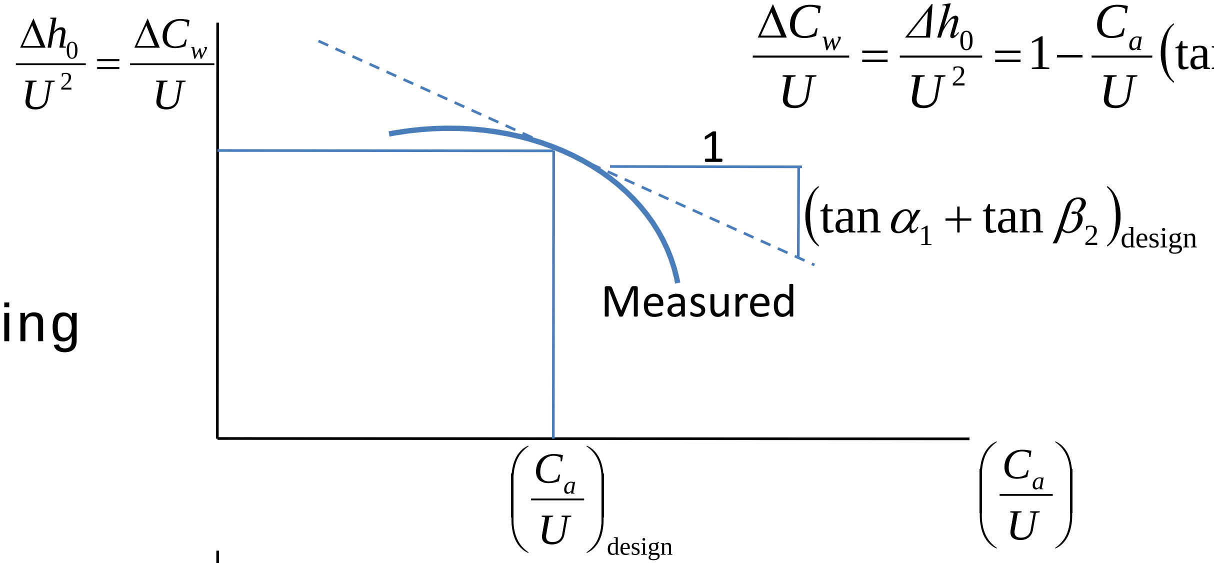
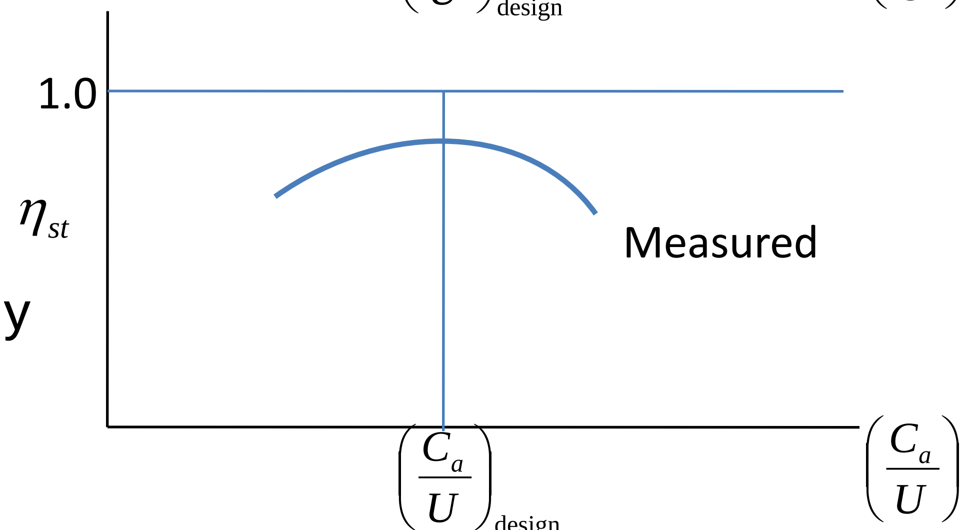
Single stage performance characteristics

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

Stage loading



Stage efficiency



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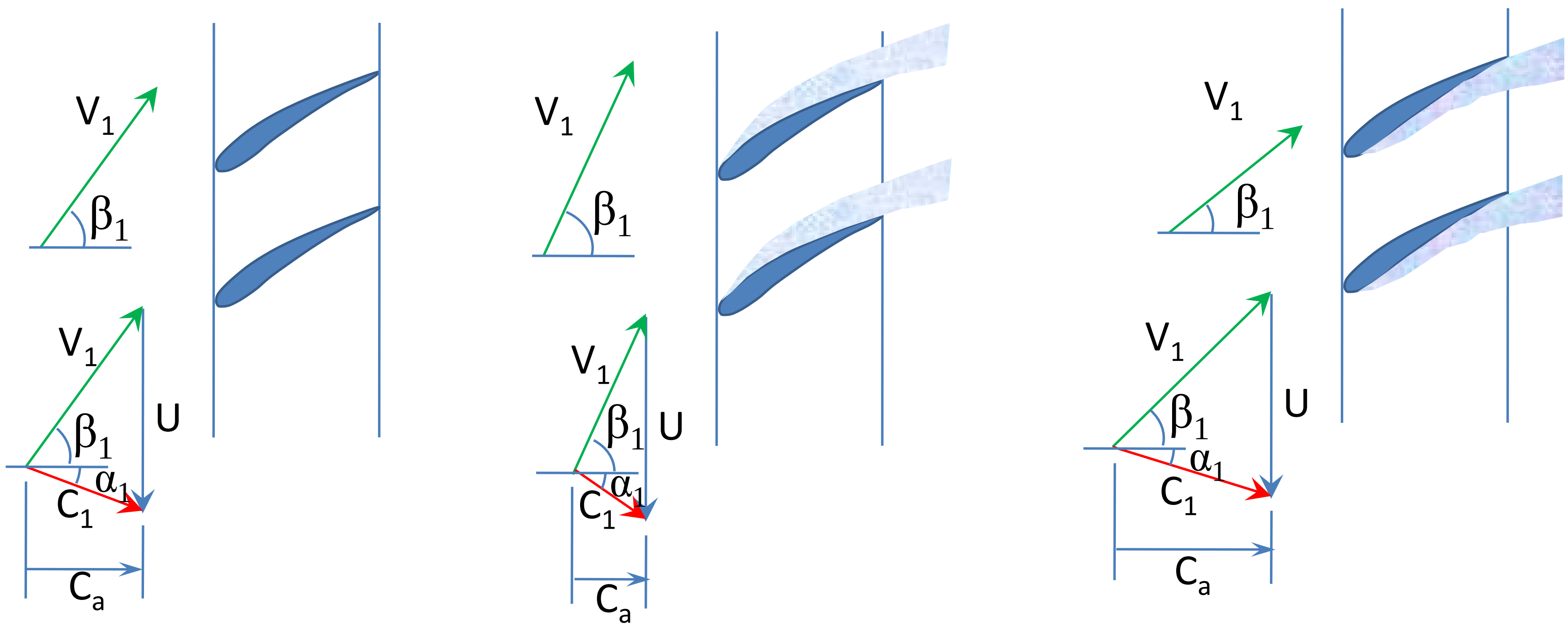
Single stage performance characteristics



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

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

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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

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

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.

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

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

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

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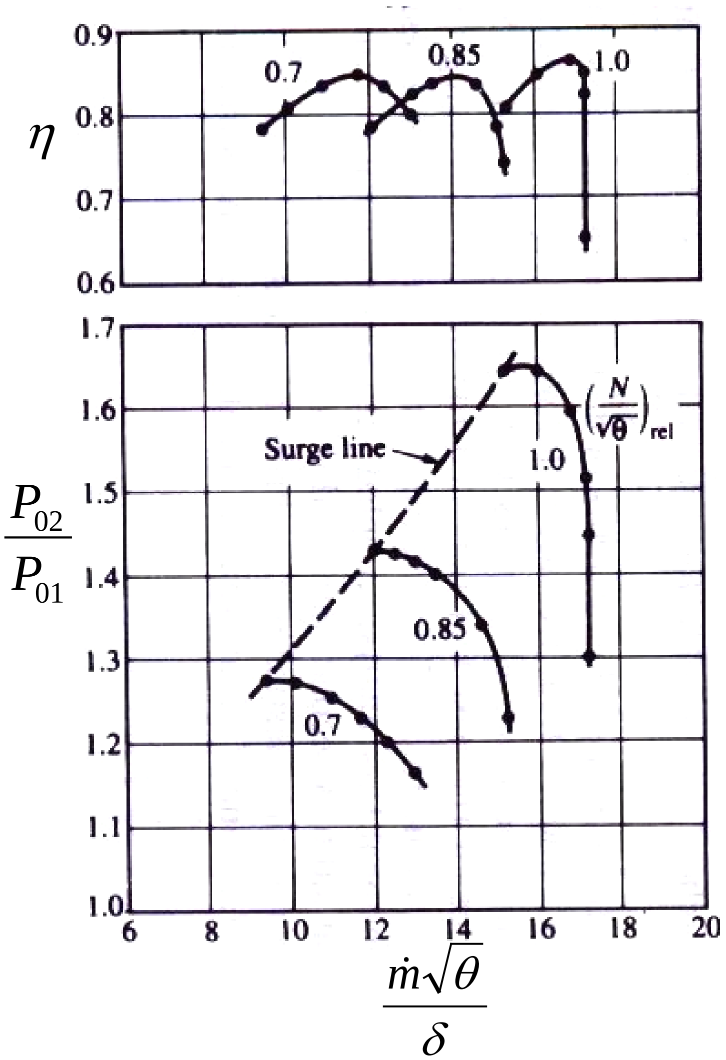
Multi-stage performance characteristics



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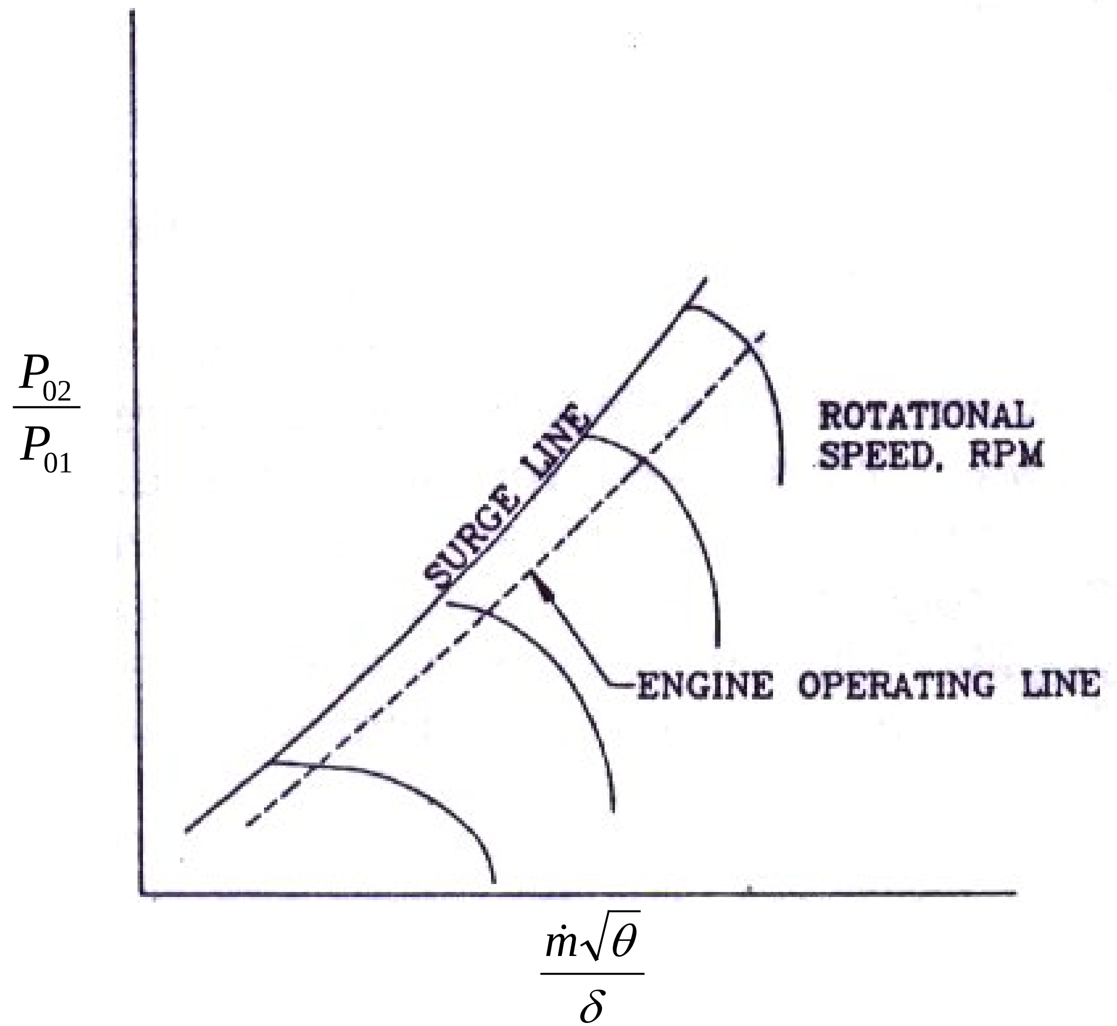
Multi-stage performance characteristics



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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.

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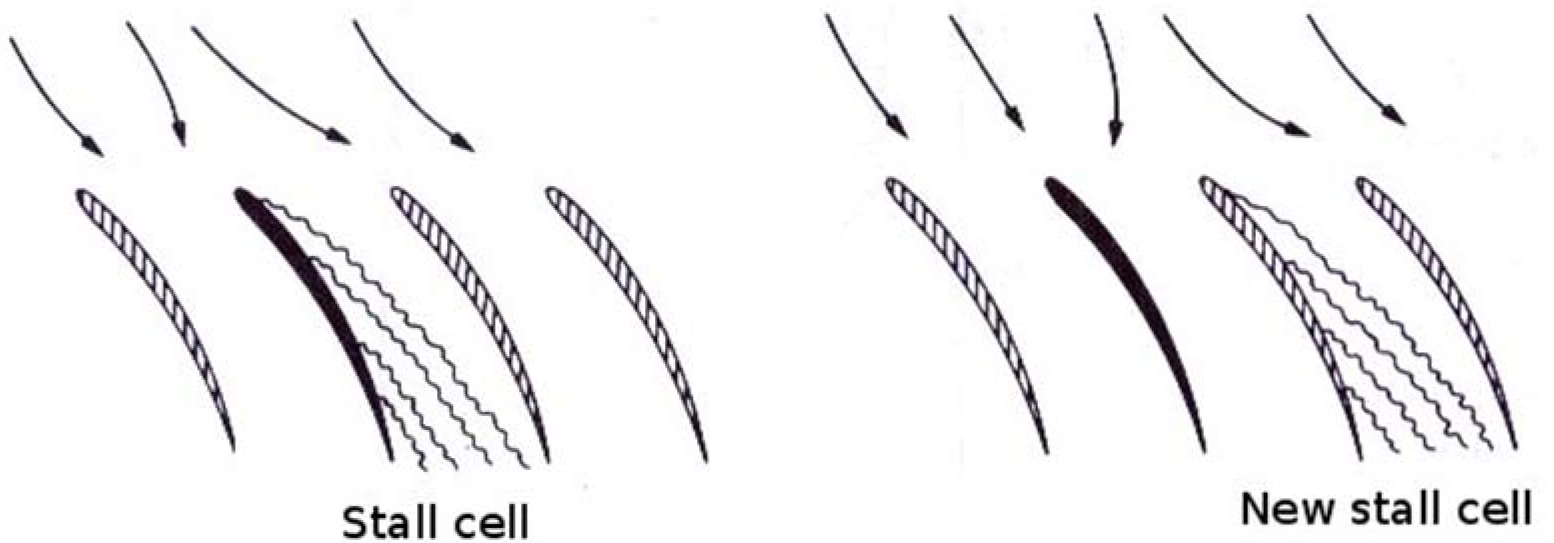
Multi-stage performance characteristics



Propagation of rotating stall

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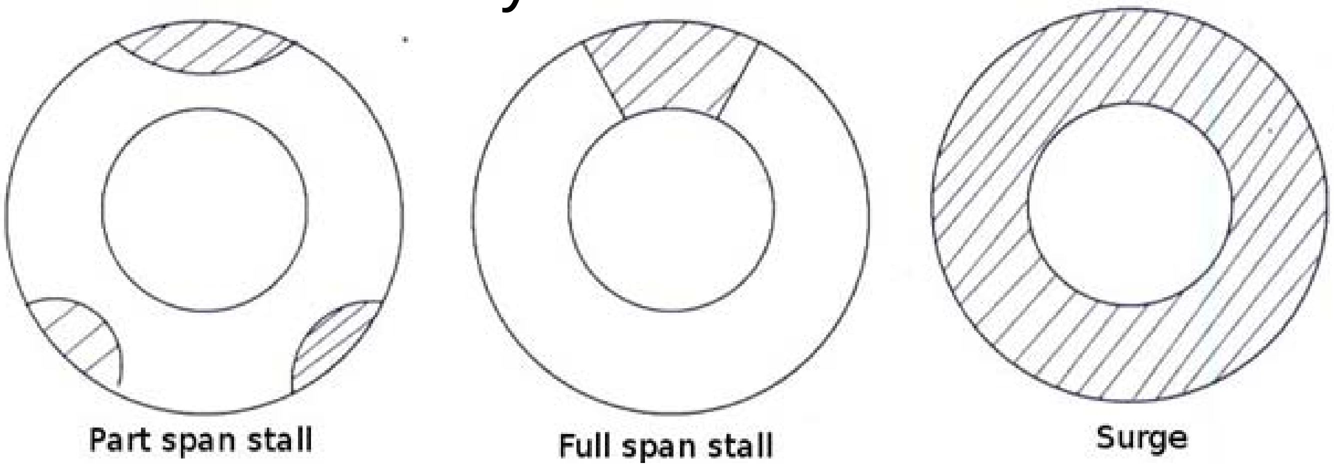
Multi-stage performance characteristics

- Rotating stall often precedes surge.
- The stall patterns move in a direction opposite to that of the rotor revolution.
- The stall frequency can be as high as 50% of the rotor frequency.
- Rotating stall may be initiated by an incoming flow non-uniformity.



Multi-stage performance characteristics

- Surge line denotes the locus of unstable operation of the compressor.
- Surge is characterised by violent, periodic oscillations in the flow.
- Surge might lead to flame blow-out in the combustion chamber.
- Surge can lead to substantial damage to compressors and must be avoided.
- The operating line of the compressor is therefore kept slightly away from the surge line: surge margin.

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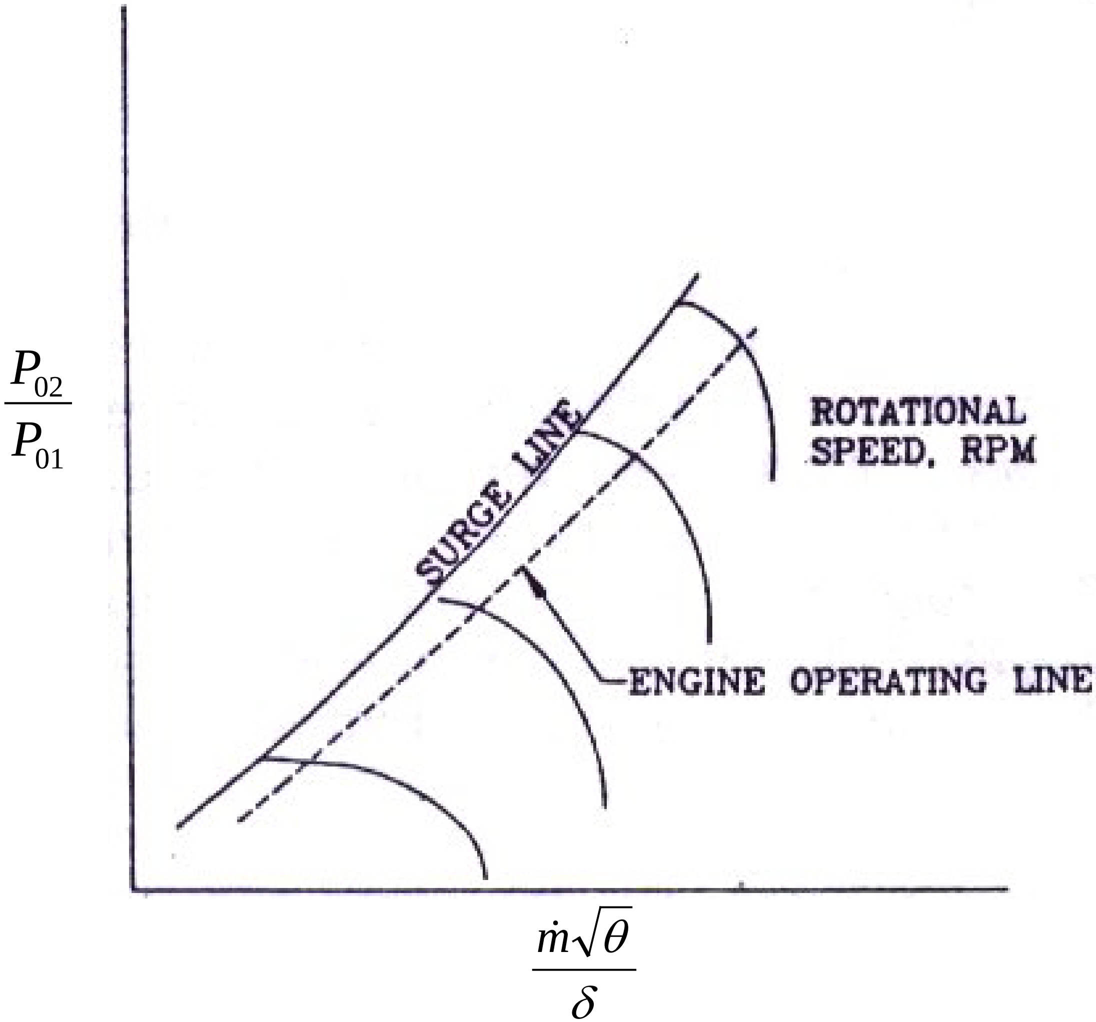
Multi-stage performance characteristics



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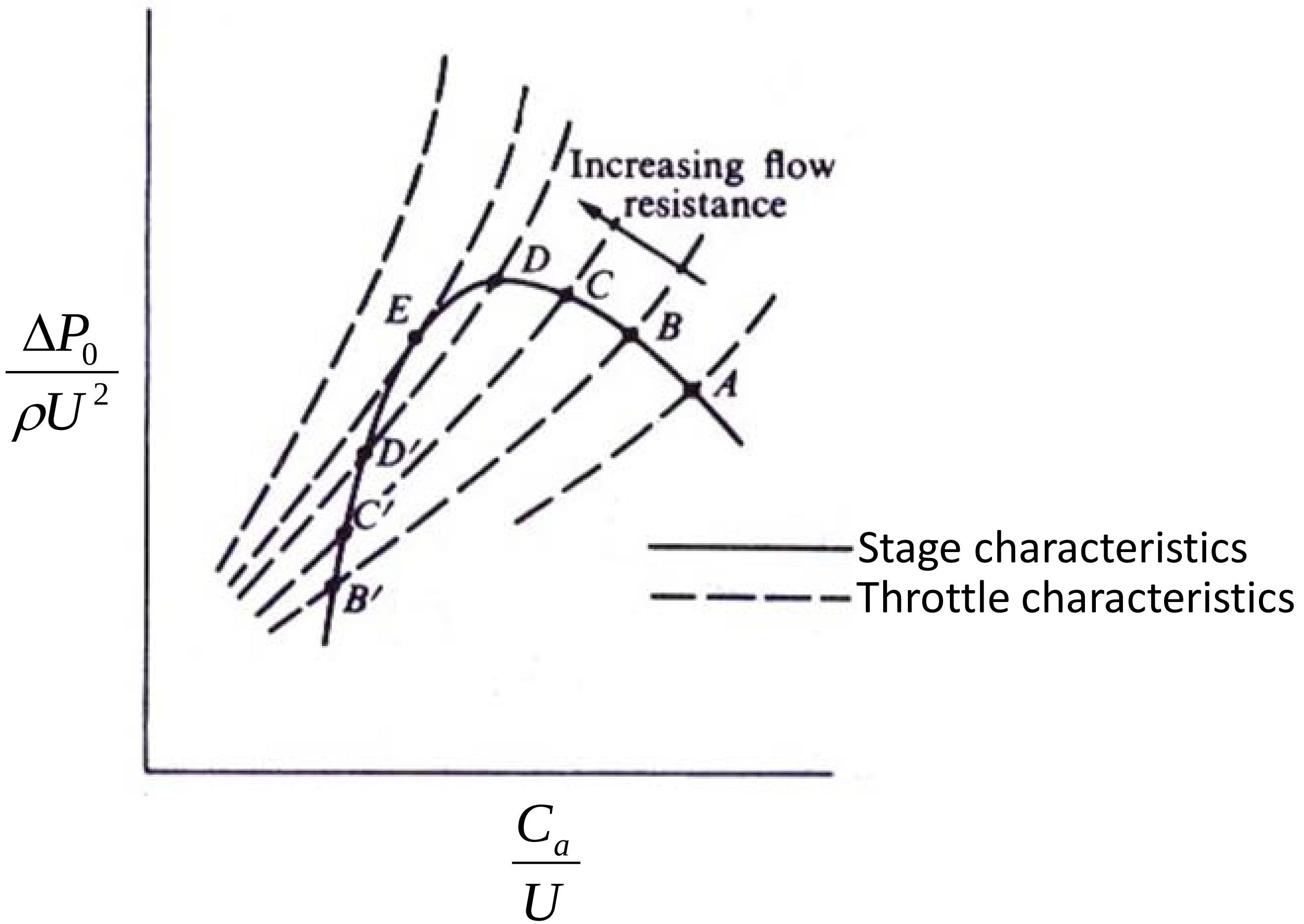
Multi-stage performance characteristics



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In the next lecture…

- Tutorial
  - Axial compressors

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