Jet Aircraft Propulsion

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Lect-19

In this lecture...

- Performance characteristics of centrifugal compressors
- Surging and choking
- Tutorial on centrifugal compressors

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Performance characteristics

- The centrifugal compressor performance characteristics can be derived in the same way as an axial compressor.
- Performance is evaluated based on the dependence of pressure ratio and efficiency on the mass flow at different operating speeds.
- Centrifugal compressors also suffer from instability problems like surge and rotating stall.

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Performance characteristics

- The compressor outlet pressure, P_{02}, and the isentropic efficiency, $\eta_{C,}$ depend upon several physical variables

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

In terms of non-dimensionless parameters,

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

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

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, $\theta = \dfrac{T_{01}}{\left(T_{01}\right)_{\text{Std. day}}}$ and $\delta = \dfrac{P_{01}}{\left(P_{01}\right)_{\text{Std. day}}}$

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

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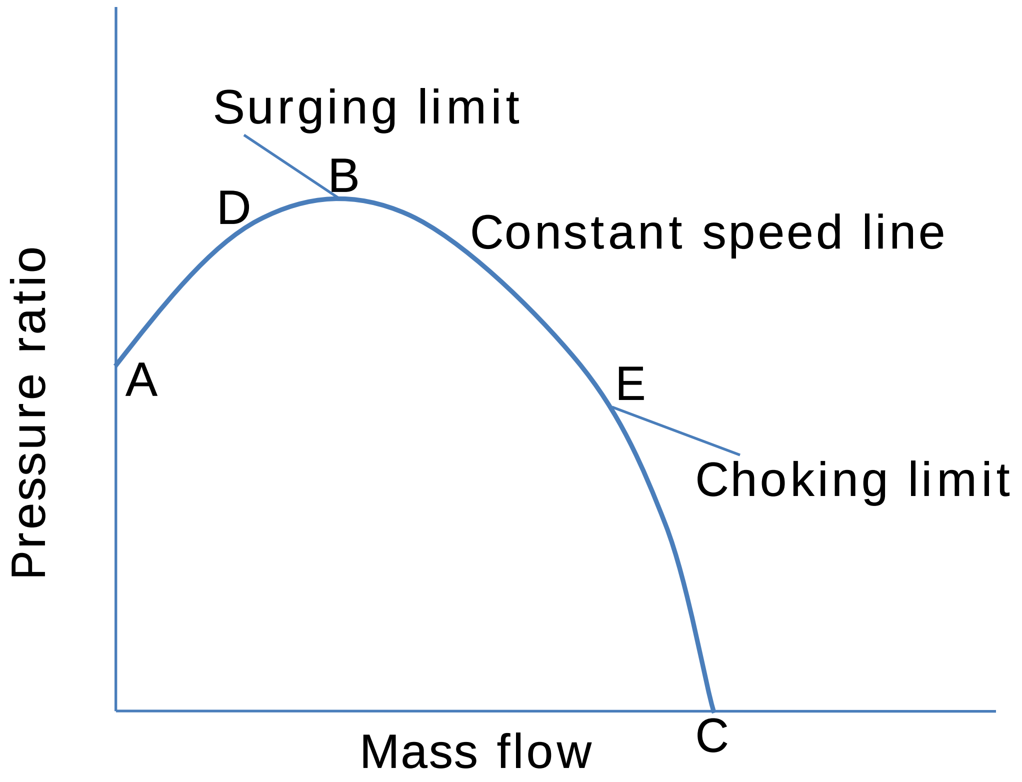
Performance characteristics



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Performance characteristics

- There are two limits to the operation of the compressor.
- Operation between A and B are limited due to occurrence of surge.
- Surging: sudden drop in delivery pressure and violent aerodynamic pulsations.
- Operation on the positive slope of the performance characteristics: unstable
- Surging usually starts to occur in the diffuser passages.

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Performance characteristics

- Rotating stall might also affect the compressor performance.
- In this case a stall cell (that might cover one or more adjacent blades) rotates within the annulus.
- Full annulus rotating stall may eventually lead to surge.
- Rotating stall may also lead to aerodynamically induced vibrations and fatigue failure of the compressor components.

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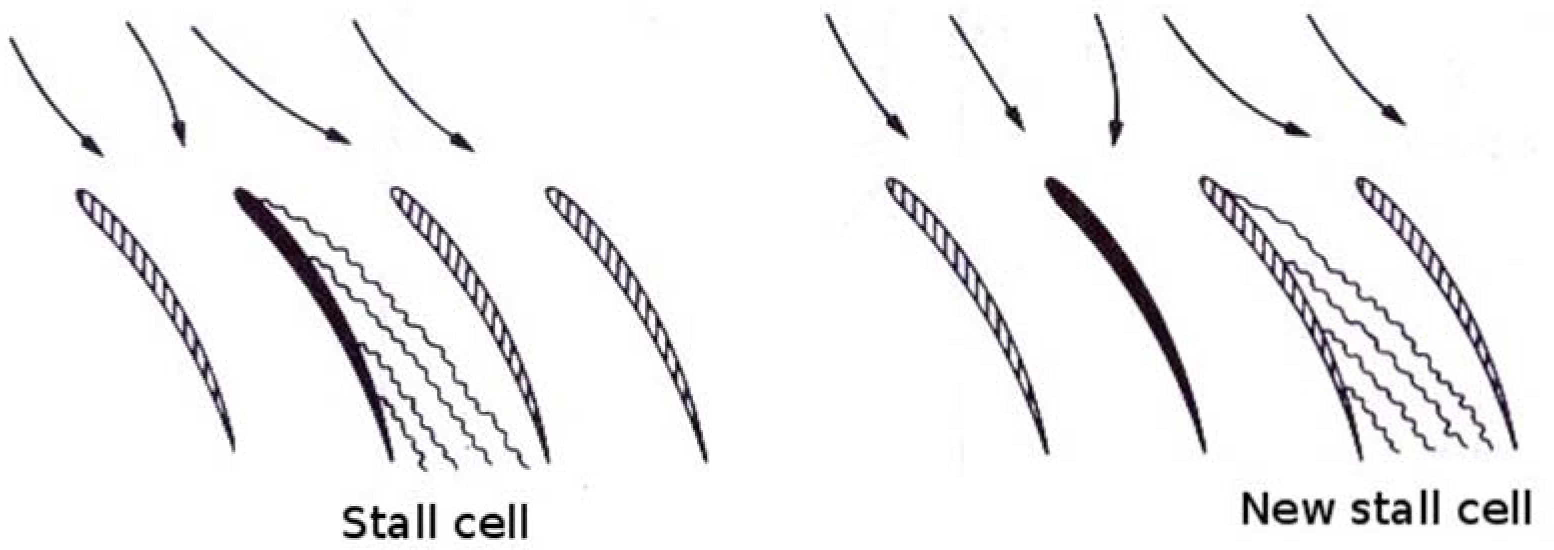
Performance characteristics

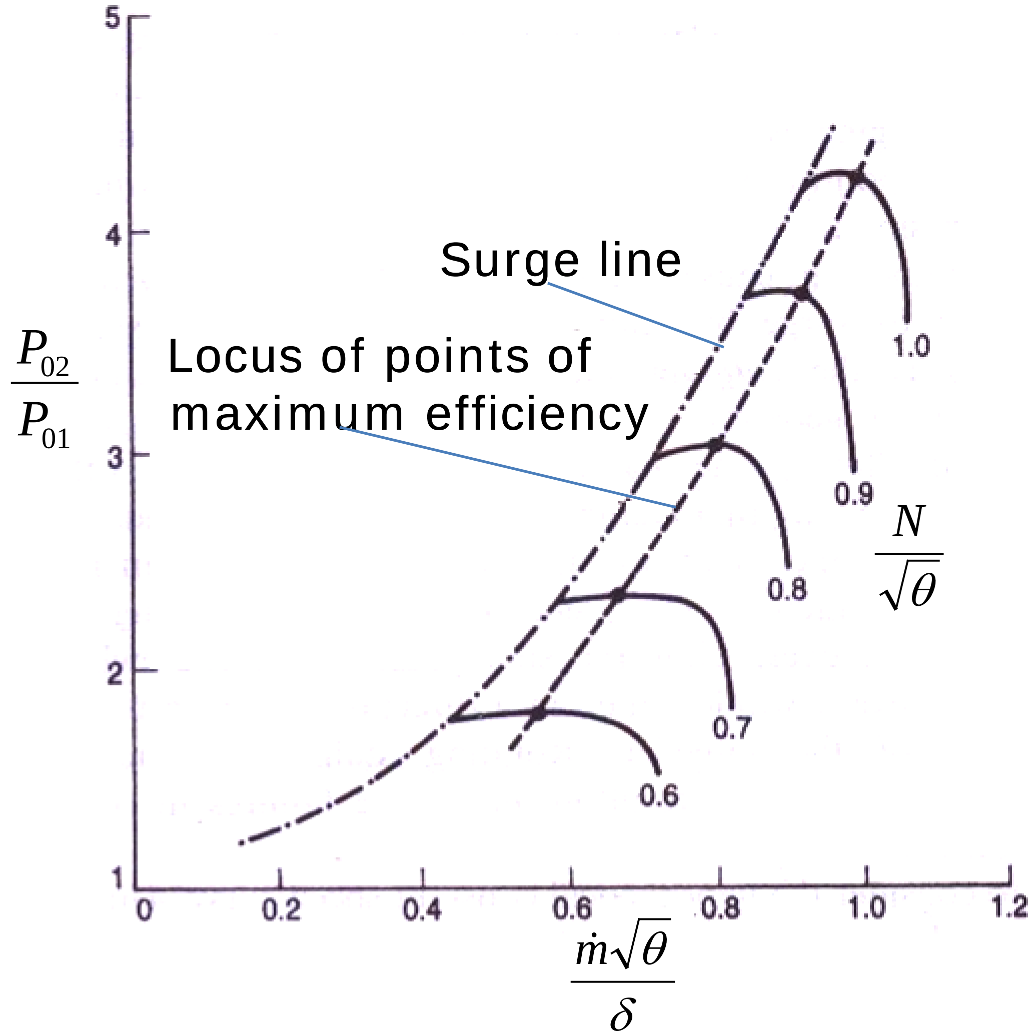


Propagation of rotating stall

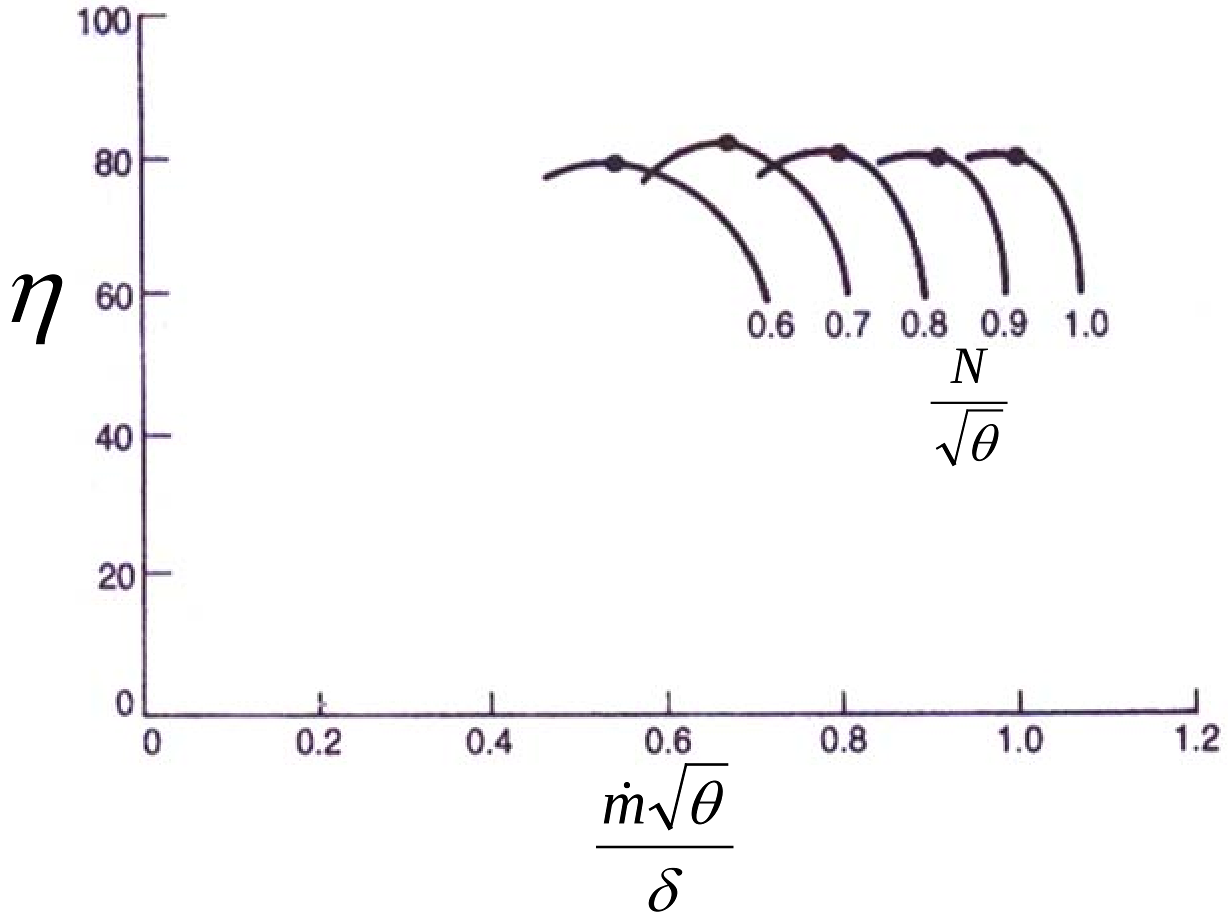
Performance characteristics

- The other limiting aspect of centrifugal compressors is choking.
- As the mass flow increases, the pressure decreases, density reduces.
- After a certain point, no further increase in mass flow will be possible.
- The compressor is then said to have choked.
- The right hand side of the constant speed lines together form the choking line.

Performance characteristics



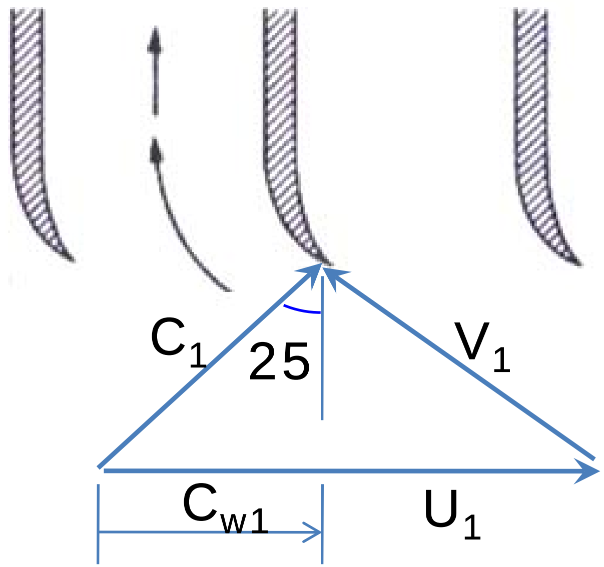
Performance characteristics



Problem # 1

- A centrifugal compressor has a pressure ratio of 4:1 with an isentropic efficiency of 80% when running at 15000 rpm and inducing air at 293 K. Curved vanes at the inlet give the air a prewhirl of 25^{o} to the axial direction at all radii. The tip diameter of the eye of the impeller is 250 mm. The absolute velocity at inlet is 150 m/s and the impeller diameter is 600 mm. Calculate the slip factor.

Problem # 1



Solution: Problem # 1

Exit stagnation temperature is

$$T_{02} = T_{01}\left(\pi_c\right)^{(\gamma-1)/\gamma} = 293\left(4\right)^{(1.4-1)/1.4} = 435.56K$$

Therefore the isentropic temperature rise,

$$\Delta T_{0s} = 435.56 - 293 = 142.56K$$

The actual temperature rise, $\Delta T_0 = \Delta T_{0s} / \eta_c$

$$\Delta T_0 = 178.2K$$

Work done per unit mass is, $w = c_P \Delta T_0$

$$w = 1.005 \times 178.2 = 179 \text{ kJ/kg}$$

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Solution: Problem # 1

Peripheral velocity at the tip of the eye,

$$U_1 = \pi dN / 60 = \pi \times 0.25 \times 15000 / 60 = 196.25 m/s$$

$$C_{w1} = C_1 \sin 25 = 63.4 m/s$$

Peripheral velocity at the tip of the impeller,

$$U_2 = \pi DN / 60 = \pi \times 0.60 \times 15000 / 60 = 471.2 m/s$$

Solution: Problem # 1

We know that power input is, $w = U_2 C_{w2} - U_1 C_{w1}$

$$179 \times 10^3 = 471.24 \times C_{w2} - 196.35 \times 63.4$$

$$or, C_{w2} = 406.27 m/s$$

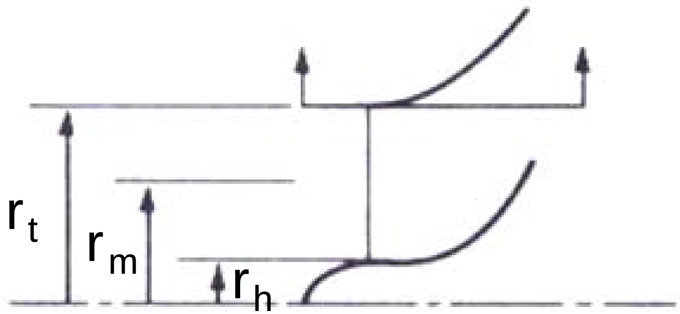
Therefore, the slip factor is,

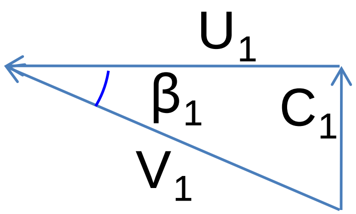
$$\sigma_s = C_{w2} / U_2 = 0.862$$

Problem # 2

- At the inlet of a centrifugal compressor eye, the relative Mach number is to be limited to 0.97. The hub-tip radius ratio of the inducer is 0.4. The eye tip diameter is 20 cm. If the inlet velocity is axial, determine, (a) the maximum mass flow rate for a rotational speed of 29160 rpm, (b) the blade angle at the inducer tip for this mass flow. The inlet conditions can be taken as 101.3 kPa and 288 K.

Problem # 2





Solution: Problem # 2

The rotational speed at the inducer tip is

$$U_1 = \pi dN/60 = \pi \times 0.2 \times 29160/60 = 305.36 m/s$$

From the velocity traingle, we can see that

$$M_{1rel} = \frac{V_1}{\sqrt{\gamma R T_1}} = \frac{\sqrt{C_1^2 + U_1^2}}{\sqrt{\gamma R T_1}}$$

$$T_1 = T_{01} - C_1^2/2c_P = 288 - C_1^2/2010$$

$$M_{1rel} = \frac{\sqrt{C_1^2 + U_1^2}}{\sqrt{\gamma R(288 - C_1^2/2010)}}$$

$$0.97^2 = \frac{C_1^2 + 305.63^2}{115718.4 - 0.2C_1^2}$$

Simplifying, $\mathrm{C}_1 = 114.62 m/s$

Solution: Problem # 2

$$T_1 = T_{01} - C_1^2 / 2c_P = 288 - C_1^2 / 2010 = 281.464K$$

$$\frac{P_{01}}{P_1} = \left(\frac{T_{01}}{T_1}\right)^{\gamma/(\gamma-1)}$$

Substituting, $P_1 = 93.48kPa$

$\therefore \rho_1 = P_1 / RT_1 = 1.157kg / m^3$

Annulus area at the inlet, $A_1 = \frac{\pi}{4} d^2 (1 - r_h / r_t)$

$A_1 = 0.0264m^2$

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Solution: Problem # 2

Since the flow is axial,

$$C_{a1} = C_1$$

$$\therefore \dot{m} = \rho_1 A_1 C_1 = 1.157 \times 0.0264 \times 114.62 = 3.5 kg / s$$

The blade inlet angle at the tip is

$$\tan \beta_1 = C_1 / U_1$$

$$\therefore \beta_1 = 20.57^o$$

Exercise Problem # 1

- The design mass flow rate of a centrifugal compressor is 7.5 kg/s with inlet stagnation temperature of 300 K and pressure of 100 kPa. The compressor has straight radial blades at the outlet. The blade angle at the inducer inlet tip is 50^o and the inlet hub-tip ratio is 0.5. The impeller is designed to have a relative Mach number of 0.9 at the inducer inlet tip. If the tip speed is 450 m/s, determine (a) the air density at inducer inlet, (b) the inducer inlet diameter, (c) the rotor rpm (d) the impeller outlet diameter.
- Ans: 0.988 kg/m3, 0.258 m, 17100 rpm, 0.502 m

Exercise Problem # 2

- A centrifugal compressor runs at 10000 rpm and delivers 600 m^3/min of air at a pressure of 4:1. The isentropic efficiency of the compressor is 0.82. The outer radius of the impeller is twice the inner radius. The axial velocity is 60m/s. If the ambient conditions are 1 bar and 293 K, determine (a) the impeller diameter at inlet and outlet (b) the power input (c) the impeller and diffuser angles at inlet.
- Ans: 0.92, 0.461, 2044 kW, 13.9^o, 7.1^o

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Exercise Problem # 3

- 30 kg of air per second is compressed in a centrifugal compressor at a rotational speed of 15000 rpm. The air enters the compressor axially. The compressor has a tip radius of 30 cm. The air leaves the tip with a relative velocity of 100 m/s at an angle of 80o. Assuming an inlet stagnation pressure and temperature of 1 bar and 300 K, respectively, find (a) the torque required to drive the compressor, (b) the power required (c) the compressor delivery pressure
- Ans: 4085 Nm, 6.417 MW, 6.531 bar

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In the next lecture...

- Intakes for powerplant: Transport and Military

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