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

\[ \Delta C_w \]

\[ V_1 \]

\[ \beta_1 \]

\[ C_1 \]

\[ \alpha_1 \]

\[ C_a \]

\[ V_2 \]

\[ \beta_2 \]

\[ C_2 \]

\[ \alpha_2 \]

\[ V_w1 \]

\[ V_w2 \]

\[ U \]

\[ C_w1 \]

\[ C_w2 \]
Single stage performance characteristics

• From the above velocity triangles,

\[ C_{w2} = U - C_a \tan \beta_2 \quad \text{and} \quad C_{w1} = C_a \tan \alpha \]

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 $\beta_1$ 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,

$$\text{Stage performance} = f(\psi, \phi, \eta)$$
Single stage performance characteristics

\[ \frac{\Delta h_0}{U^2} = \frac{\Delta C_w}{U} \]

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

Stage loading

\[ \left( \frac{C_a}{U} \right)_{\text{design}} \]

\[ \left( \frac{C_a}{U} \right) \]

Stage efficiency

\[ \eta_{st} \]

Measured

1.0

Measured

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

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

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

In terms of non-dimensional parameters,

\[ \frac{P_{02}}{P_{01}}, \eta_C = f\left(\frac{m\sqrt{\gamma RT_{01}}}{P_{01}D^2}, \frac{\Omega D}{\sqrt{\gamma RT_{01}}}, \frac{\Omega D^2}{\nu}, \gamma, \text{design} \right) \]

For a given design, we can assume that \( \gamma \) and \( \nu \) do not affect the performance significantly. Also, \( D \) and \( R \) are fixed. Therefore the above reduces to

\[ \frac{P_{02}}{P_{01}}, \eta_C = f\left(\frac{m\sqrt{T_{01}}}{P_{01}}, \frac{N}{\sqrt{T_{01}}} \right) \]
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 \(\delta = \frac{P_{01}}{(P_{01})_{\text{Std. day}}}\)

\((T_{01})_{\text{Std. day}} = 288.15 \, K \quad \text{and} \quad (P_{01})_{\text{Std. day}} = 101.325 \, \text{kPa}\)
Multi-stage performance characteristics

\[ \eta \]

\[ \frac{P_{02}}{P_{01}} \]

Surge line

\[ \frac{N}{\sqrt{\theta}} \text{ rel} \]

\[ \frac{\dot{m}\sqrt{\theta}}{\delta} \]
Multi-stage performance characteristics

\[ \frac{P_{02}}{P_{01}} \]

\[ \frac{m\sqrt{\theta}}{\delta} \]
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

Design velocity triangles

First stages

Last stages
Multi-stage performance characteristics

- Decreased $C_a$ with $\alpha_1$ and $\beta_2$ constant, results in increased $\alpha_2$ and $\beta_1$ 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.
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

\[ \frac{P_{02}}{P_{01}} \]

\[ \frac{m\sqrt{\theta}}{\delta} \]
Multi-stage performance characteristics

\[ \frac{\Delta P_0}{\rho U^2} \]

\[ \frac{C_a}{U} \]

Stage characteristics

Throttle characteristics
In this lecture...

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