TURBOMACHINERY
AERODYNAMICS

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In this lecture...

• Axial flow compressors and fans
  – Thermodynamics of compression
    – P-v and T-s diagrams of compressors
    – Thermodynamics of compression process
    – Multi-stage compression
  – Basic operation of axial compressors/fans
  – Velocity triangles
  – Work and compression
Introduction

- Simplified aero-thermodynamic analysis
- Optimised cycle design to precede the detailed component design
- Prediction of work requirements
- Efficiency of the compressor
- Enables faster design modifications
Thermodynamics of compression

(i) Adiabatic (process $1-2'$), $Pv^\gamma = c$

(ii) Isothermal process ($1-2''$), $Pv = c$

(iii) Isochoric (Process $1-2'''$), $Pv^\infty = c$
Thermodynamics of compressors

i) Isentropic process (1-2/)

ii) Polytropic process (1-2)

iii) Isothermal process (1-2/\)

iv) Isochoric Process (1-2///)
Thermodynamics of compressors

- The compression process is usually expressed in H-s or T-s diagrams.
- The ideal compression process is assumed to be isentropic.
- Deviation from this is expressed as isentropic efficiency.
Thermodynamics of compressors

$X_1$, $X_2$ are the losses in the rotor and the stator respectively.

Compression in terms of static parameters.
Thermodynamics of compressors

Compression in terms of total parameters
Thermodynamics of multi-stage compressors

- The flow at the rotor exit with high kinetic energy is still to be converted to static pressure through diffusion.
- The exit kinetic energy of a compressor is of the same order as the entry kinetic energy and the entire work input is expected to be converted to pressure.
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.
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.
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.
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 $V_w$)
- $\alpha$ denotes the angle between the absolute velocity with the axial direction and $\beta$ the corresponding angle for the relative velocity.
Velocity triangles

\[ \vec{C} = \vec{U} + \vec{V} \]
Velocity triangles

- $C_1$
- $C_2$
- $C_w$
- $\Delta C_w$
- $V_1$
- $V_2$
- $\alpha_1$
- $\alpha_2$
- $\beta_1$
- $\beta_2$
- $V_{w1}$
- $V_{w2}$
- $C_{w1}$
- $C_{w2}$
- $U$
- $C_a$
Property changes across a stage

Total enthalpy

Absolute velocity

Static pressure
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

$$w = U(C_{w2} - C_{w1})$$

where $C_{w1}$ and $C_{w2}$ are the tangential components of the fluid velocity before and after the rotor, respectively.
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.
Work and compression

\[ h_{02} - h_{01} = U \Delta C_w \]

\[ T_{02} - T_{01} = \frac{U \Delta C_w}{c_p} \quad \Rightarrow \quad \Delta T_0 = \frac{U \Delta C_w}{c_p T_{01}} \]

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, \( \eta_{st} \), as

\[ \eta_{st} = \frac{h_{03s} - h_{01}}{h_{03} - h_{01}} \]

This can be expressed as

\[ \frac{T_{03s}}{T_{01}} = 1 + \eta_{st} \frac{\Delta T_0}{T_{01}} \]
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,

$$\frac{p_{03}}{p_{01}} = \left[ 1 + \eta_{st} \frac{U \Delta C_w}{c_p T_{01}} \right]^{\gamma/(\gamma-1)}$$
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 \((\beta_1 - \beta_2)\): Aerodynamic considerations and adverse pressure gradients limit the above.
Work and compression

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In the next lecture...

• Two-dimensional analytical model
• Performance parameters
• Cascade aerodynamics