TURBOMACHINERY
AERODYNAMICS

Lect- 31

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In this lecture...

• Centrifugal compressors
  • Thermodynamics of centrifugal compressors
  • Components of a centrifugal compressor
Centrifugal compressors

- Centrifugal compressors were used in the first jet engines developed independently by Frank Whittle and Hans Ohain.
- Centrifugal compressors still find use in smaller gas turbine engines.
- For larger engines, axial compressors need lesser frontal area and are more efficient.
- Centrifugal compressors can develop higher per stage pressure ratios.
Centrifugal compressors

• Besides small aero engines, centrifugal compressors are used in the auxiliary power units (APUs) in many aircraft.
• Some of the aircraft air conditioning systems employ centrifugal compressors.
• In a few engines, centrifugal compressors are used as the final stage of the compression process downstream of a multi-stage axial compressor. Eg. GE T700, P&W PT6, Honeywell T53.
Centrifugal compressors stage

Typical centrifugal compressor rotors
Centrifugal compressors stage

Schematic of a typical centrifugal compressor
Centrifugal compressors stage

T-s diagram for a centrifugal compressor

- **Total losses**
- **Impeller losses**

- $T_{02} = T_{03}$
- $P_{02}$
- $P_{03}$
- $P_3$
- $P_2$
- $P_{01}$
- $P_1$

- $C_2^2 / 2c_p$
- $C_i^2 / 2c_p$
- $C_3^2 / 2c_p$
Centrifugal compressors stage

The torque applied on the fluid by the rotor
$$\tau = \dot{m}[(rC_w)_2 - (rC_w)_1]$$
where 1 and 2 denotes the compressor inlet and outlet, respectively.

The total work per unit mass is therefore,
$$w = \Omega \tau / \dot{m} = \Omega[(rC_w)_2 - (rC_w)_1]$$
or,
$$w = (UC_w)_2 - (UC_w)_1$$
in which, \(U = \Omega r\)

From the steady flow energy equation,
$$w = h_{02} - h_{01} = h_2 - h_1 + \frac{C_2^2}{2} - \frac{C_1^2}{2}$$
or,
$$h_2 - h_1 = (UC_w)_2 - (UC_w)_1 - \frac{C_2^2}{2} + \frac{C_1^2}{2}$$
Centrifugal compressors stage

Diagram showing centrifugal compressor components with variables $r_1$, $r_2$, $b$, $U_1$, $U_2$, and $\Omega$. The diagram illustrates the geometry and flow direction in a centrifugal compressor stage.
Centrifugal compressors stage

The above equation gets transformed to,

\[ h_2 - h_1 = \frac{U_2^2}{2} - \frac{U_1^2}{2} - \left( \frac{V_2^2}{2} - \frac{V_1^2}{2} \right) \]

i.e., \( dh = d\left(\frac{\Omega^2 r^2}{2}\right) - \frac{dV^2}{2} \)

Since, \( Tds = dh - \frac{dP}{\rho} \)

\[ \frac{dP}{\rho} = d\left(\frac{\Omega^2 r^2}{2}\right) - \frac{dV^2}{2} - Tds \]

For an isentropic flow, \( \frac{dP}{\rho} = d\left(\frac{\Omega^2 r^2}{2}\right) - d\left(\frac{V^2}{2}\right) \)
Centrifugal compressors stage

• For axial compressors, \( dr \approx 0 \) and the above equation reduces to \( \frac{dP}{\rho} = -d\left(\frac{V^2}{2}\right) \).

• Thus in an axial compressor rotor, pressure rise can be obtained only by decelerating the flow.

• In a centrifugal compressor, the term \( d\left(\Omega^2r^2/2\right) > 0 \), means that pressure rise can be obtained even without any change in the relative velocity.

• With no change in relative velocity, these rotors are not liable to flow separation.
Centrifugal compressors stage

• However most centrifugal compressors do have deceleration and hence are liable to boundary layer separation.

• Centrifugal compressor rotor is not essentially limited by separation the way axial compressor is.

• It is therefore possible to obtain higher per stage pressure rise from a centrifugal compressor as compared to axial flow compressors.
Conservation of Rothalpy

• If we were to assume steady, viscous flow without heat transfer

\[ h_1 + \frac{C_1^2}{2} - U_1 C_{w1} = h_2 + \frac{C_2^2}{2} - U_2 C_{w2} = I \]

• Here, \( I \), is the rotational enthalpy or rothalpy.
• It is now known that rothalpy is conserved for the flow through the impeller.
• Any change in rothalpy is due to the fluid friction acting on the stationary shroud (if considered in the analysis).
Impeller

• Impeller draws in the working fluid. It is the rotating component of the centrifugal compressor.
• The diverging passages of the impeller diffuses the flow to a lower relative velocity and higher static pressure.
• Impellers may be single-sided or double-sided, shrouded or un-shrouded.
• In the impeller, the working fluid also experiences centripetal forces due to the rotation.
Impeller

- In principle, there are three possibilities for a centrifugal compressor rotor.
  - Straight radial
  - Forward leaning
  - Backward leaning
- Forward leaning blades are not used due inherent dynamic instability.
- Straight and backward leaning blades are commonly used in modern centrifugal compressor rotors.
Impeller

Forward leaning blades ($\beta_2$ is negative)

Straight radial

Backward leaning blades ($\beta_2$ is positive)
Inducer

• Inducer is the impeller entrance section where the tangential motion of the fluid is changed in the radial direction.
• This may occur with a little or no acceleration.
• Inducer ensures that the flow enters the impeller smoothly.
• Without inducers, the rotor operation would suffer from flow separation and high noise.
Inducer

Section m-m

Leading edge velocity triangles
Inducer

• It can be seen from the above that
  \[ V'_t = V_{it} \cos \beta_{1t} \]
  Where, \( V' \) denotes the relative velocity at the inducer outlet.

• It can be seen that \( V' < V_1 \), which indicates diffusion in the inducer.

• Similarly, we can see that the relative Mach number from the velocity triangle is,
  \[ M_{1rel} = M_1 / \cos \beta_{1t} \]
The diffuser

• High impeller speed results in a high absolute Mach number leaving the impeller.
• This high velocity is reduced (with an increase in pressure) in a diffuser.
• Diffuser represents the fixed or stationary part of the compressor.
• The diffuser decelerates the flow exiting the impeller and thus reduces the absolute velocity of the working fluid.
• The amount of deceleration depends upon the efficiency of the diffusion process.
The diffuser

- The fluid flows radially outwards from the impeller, through a vaneless region and then through a vaned diffuser.
- Both vaned and the vaneless diffusers are controlled by boundary layer behaviour.
- Pipe and channel type diffusers are used in aero engines due to their compatibility with the combustors.
The diffuser

Diffuser vanes

Vaneless space

Impeller

$r_3 > r_2 > r_1$
The diffuser

Streamlines in a radial diffuser

Logarithmic spiral
The diffuser

Let us consider an incompressible flow in a vaneless region of constant axial width.
From continuity, \( \dot{m} = \rho(2\pi rh)C_r = \text{constant} \).
From conservation of angular momentum,
\( rC_w = \text{constant} \)
\( \therefore \frac{C_w}{C_r} = \text{constant} = \tan \alpha \), where \( \alpha \) is the angle between the velocity and the radial direction.
Thus, the velocity is inversely proportional to radius. This means that there is diffusion taking place in the vaneless space.
In the next lecture...

- Centrifugal compressors
  - Coriolis acceleration
  - Slip factor
  - Performance characteristics
  - Stall and surge
In this lecture...

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  - Thermodynamics of centrifugal compressors
  - Components of a centrifugal compressor