TURBOMACHINERY
AERODYNAMICS

Prof. Bhaskar Roy, Prof. A M Pradeep
Department of Aerospace Engineering,
IIT Bombay
In this lecture...

- Axial flow turbine
  - Impulse and reaction turbine stages
  - Work and stage dynamics
  - Turbine blade cascade
Axial flow turbines

• Axial turbines like axial compressors usually consists of one or more stages.
• The flow is accelerated in a nozzle/stator and then passes through a rotor.
• In the rotor, the working fluid imparts its momentum on to the rotor, that converts the kinetic energy to power output.
• Depending upon the power requirement, this process is repeated in multiple stages.
Axial flow turbines

- Due to motion of the rotor blades, two distinct velocity components: absolute and relative velocities in the rotor.
- This is very much the case in axial compressors that was discussed earlier.
- Since turbines operate with a favourable pressure gradient, it is possible to have much higher pressure drop per stage as compared with compressors.
- Therefore, a single turbine stage can drive several stages of an axial compressor.
Axial flow turbines

- Turbines can be either axial, radial or mixed.
- Axial turbines can handle large mass flow rates and are more efficient.
- Axial turbine have same frontal area as that of the compressor.
- They can also be used with a centrifugal compressor.
- Efficiency of turbines higher than that of compressors.
- Turbines are in general aerodynamically “easier” to design.
Axial flow turbines

An axial turbine stage
Velocity triangles

• Elementary analysis of axial turbines too 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

1. Rotor

2. Stator/Nozzle

3. Exit conditions
Types of axial turbines

• There are two types of axial turbine configurations: Impulse and reaction

• Impulse turbine
  • Entire pressure drop takes place in the nozzle.
  • Rotor blades simply deflect the flow and hence have symmetrical shape.

• Reaction turbine
  • Pressure drop shared by the rotor and the stator
  • The amount of pressure drop shared is given by the degree of reaction.
Work and stage dynamics

Applying the angular momentum equation,
\[ P = \dot{m}(U_2 C_{w2} - U_3 C_{w3}) \]
In an axial turbine, \( U_2 \approx U_3 = U \).
Therefore, the work per unit mass is
\[ w_t = U(C_{w2} - C_{w3}) \quad \text{or} \quad w_t = c_p (T_{01} - T_{03}) \]
Let \( \Delta T_0 = T_{01} - T_{03} = T_{02} - T_{03} \)
The stage work ratio is,
\[ \frac{\Delta T_0}{T_{01}} = \frac{U(C_{w2} - C_{w3})}{c_p T_{01}} \]
Work and stage dynamics

• Turbine work per stage is limited by
  – Available pressure ratio
  – Allowable blade stresses and turning

• Unlike compressors, boundary layers are generally well behaved, except for local pockets of separation

• The turbine work ratio is also often defined in the following way:

$$\frac{W_t}{U^2} = \frac{\Delta h_0}{U^2} = \frac{C_{w2} - C_{w3}}{U}$$
Impulse turbine stage

Stator/Nozzle

Rotor
Impulse turbine stage

In an impulse turbine, the rotor simply deflects the flow. Therefore,

\[ \beta_3 = -\beta_2 \implies V_{w3} = -V_{w2} \]

and \[ C_{w2} - C_{w3} = 2V_{w2} = 2(C_{w2} - U) \]

\[ = 2U \left( \frac{C_a}{U} \tan \alpha - 1 \right) \]

Or, the turbine work ratio is

\[ \frac{\Delta h_0}{U^2} = 2U \left( \frac{C_a}{U} \tan \alpha_2 - 1 \right) \]
50% Reaction turbine stage

Stator/Nozzle  Rotor
Impulse turbine stage

In a 50% reaction turbine, the velocity triangles are symmetrical. Therefore, for constant axial velocity,

\[ C_{w3} = -(C_a \tan \alpha_2 - U) \]

And the turbine work ratio becomes

\[ \frac{\Delta h_0}{U^2} = \left( 2 \frac{C_a}{U} \tan \alpha_2 - 1 \right) \]
Turbine Cascade

- A cascade is a stationary array of blades.
- Cascade is constructed for measurement of performance similar to that used in axial turbines.
- Cascade usually has porous end-walls to remove boundary layer for a two-dimensional flow.
- Radial variations in the velocity field can therefore be excluded.
- Cascade analysis relates the fluid turning angles to blading geometry and measure losses in the stagnation pressure.
Turbine Cascade

• Turbine cascades are tested in wind tunnels similar to what was discussed for compressors.
• However, turbines operate in an accelerating flow and therefore, the wind tunnel flow driver needs to develop sufficient pressure to cause this acceleration.
• Turbine blades have much higher camber and are set at a negative stagger unlike compressor blades.
• Cascade analysis provides the blade loading from the surface static pressure distribution and the total pressure loss across the cascade.
Turbine Cascade

Actual Incidence
Inlet Blade Angle
Blade Camber

Flow Deflection, $\varepsilon$
Tangets to the blade
Camber line
Blade Camber

Tangents to far flow directions
Blade Outlet Angle
Blade Outlet Flow Angle

Pitch or Spacing
Blade Setting or Stagger Angle
Inlet Flow Vector
Induced Incidence
Inlet (Upstream) flow angle

$\Delta \theta_{ic}$
$c$
$\theta$
$\phi$
$\alpha_1$
$\beta_1$
$\alpha_2$
$\beta_2$
$\delta$

trailing edge thickness, $t_{te}$
Opening (or Throat)
Flow Deviation

Prof. Bhaskar Roy, Prof. A M Pradeep, Department of Aerospace, IIT Bombay
Turbine Cascade

• From elementary analysis of the flow through a cascade, we can determine the lift and drag forces acting on the blades.

• This analysis could be done using inviscid or potential flow assumption or considering viscous effects (in a simple manner).

• Let us consider $V_m$ as the mean velocity that makes and angle $\alpha_m$ with the axial direction.

• We shall determine the circulation developed on the blade and subsequently the lift force.

• In the inviscid analysis, lift is the only force.
Turbine Cascade

Inviscid flow through a turbine cascade
Turbine Cascade

Circulation, \( \Gamma = S(V_{w2} - V_{w1}) \)
and lift, \( L = \rho V_m \Gamma = \rho V_m S(V_{w2} - V_{w1}) \)

Expressing lift in a non-dimensional form,

Lift coefficient, \( C_L = \frac{L}{\frac{1}{2} \rho V_m^2 C} = \frac{\rho V_m S(V_{w2} - V_{w1})}{\frac{1}{2} \rho V_m^2 C} \)

\[ = 2 \frac{S}{C} (\tan \alpha_2 - \tan \alpha_1) \cos \alpha_m \]
Turbine Cascade

• Viscous effects manifest themselves in the form to total pressure losses.
• Wakes from the blade trailing edge lead to non-uniform velocity leaving the blades.
• In addition to lift, drag is another force that will be considered in the analysis.
• The component of drag actually contributes to the effective lift.
• We define total pressure loss coefficient as:

\[ \frac{\bar{\omega}}{\omega} = \frac{P_{01} - P_{02}}{\frac{1}{2} \rho V_2^2} \]
Turbine Cascade

Viscous flow through a turbine cascade
Turbine Cascade

Drag is given by, \( D = \bar{\omega}S \cos \alpha_m \)

The effective lift

\[ L + \bar{\omega}S \cos \alpha_m = \rho V_m \Gamma + \bar{\omega}S \cos \alpha_m \]

Therefore, the lift coefficient,

\[ C_L = 2 \frac{S}{C} (\tan \alpha_2 - \tan \alpha_1) \cos \alpha_m + C_D \tan \alpha_m \]
Turbine Cascade

- Based on the calculation of the lift and drag coefficients, it is possible to determine the blade efficiency.

- Blade efficiency is defined as the ratio of ideal static pressure drop to obtain a certain change in KE to the actual static pressure drop to produce the same change in KE.

\[
\eta_b = \frac{1 - \frac{C_D}{C_L} \tan \alpha_m}{1 + \frac{C_D}{C_L} \cot \alpha_m}
\]

If we neglect the \( C_D \) term in the lift definition,

\[
\eta_b = \frac{1}{1 + \frac{2C_D}{C_L \sin 2\alpha_m}}
\]
In this lecture...

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In the next lecture...

• Axial flow turbine
  • Degree of Reaction, Losses and Efficiency