TURBOMACHINERY AERODYNAMICS

Lect- 20

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.

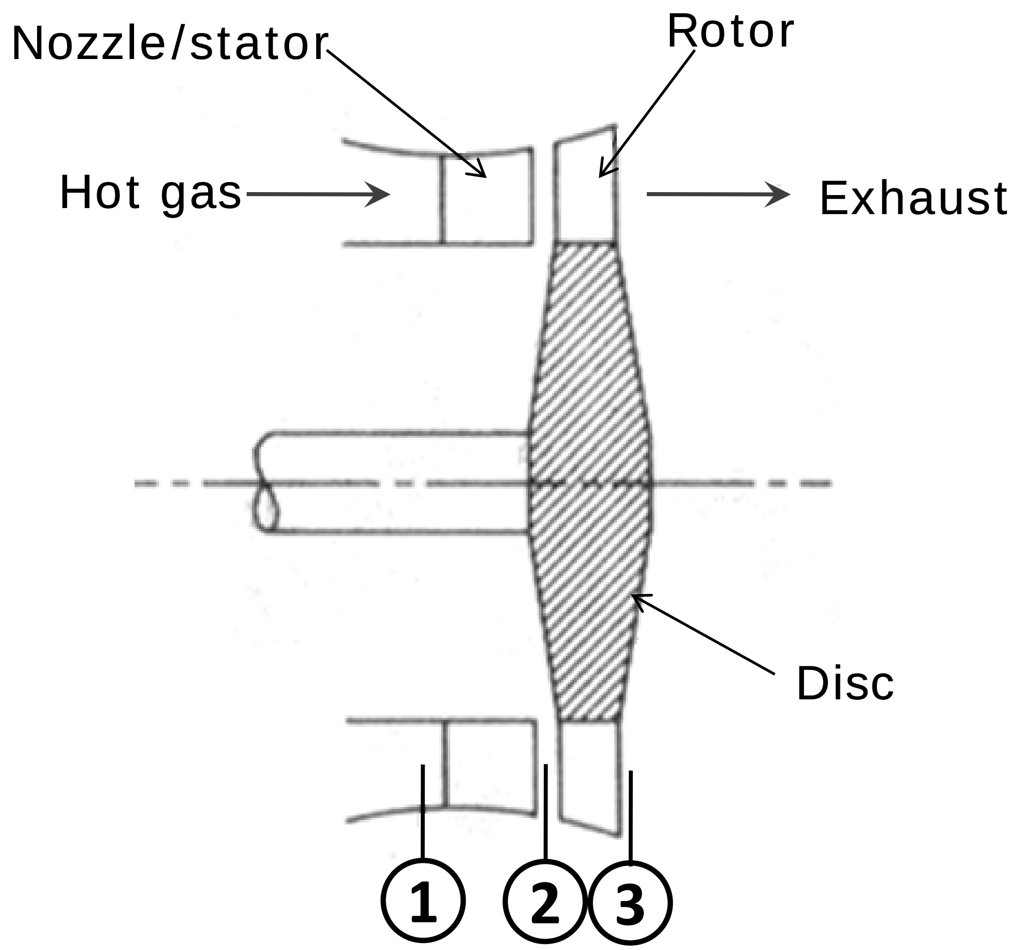
Axial flow turbines

- 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

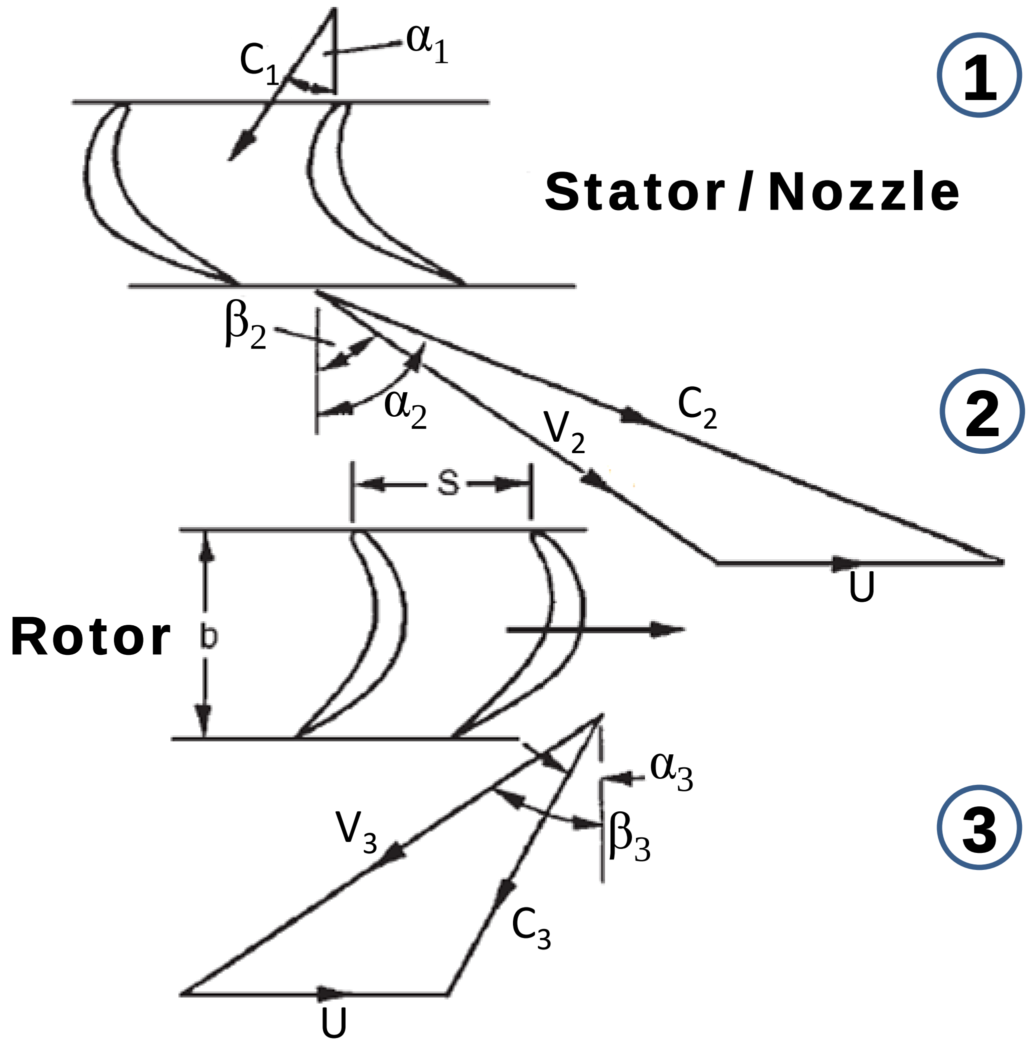


An axial turbine stage

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)
- α denotes the angle between the absolute velocity with the axial direction and β the corresponding angle for the relative velocity.

Velocity triangles



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,

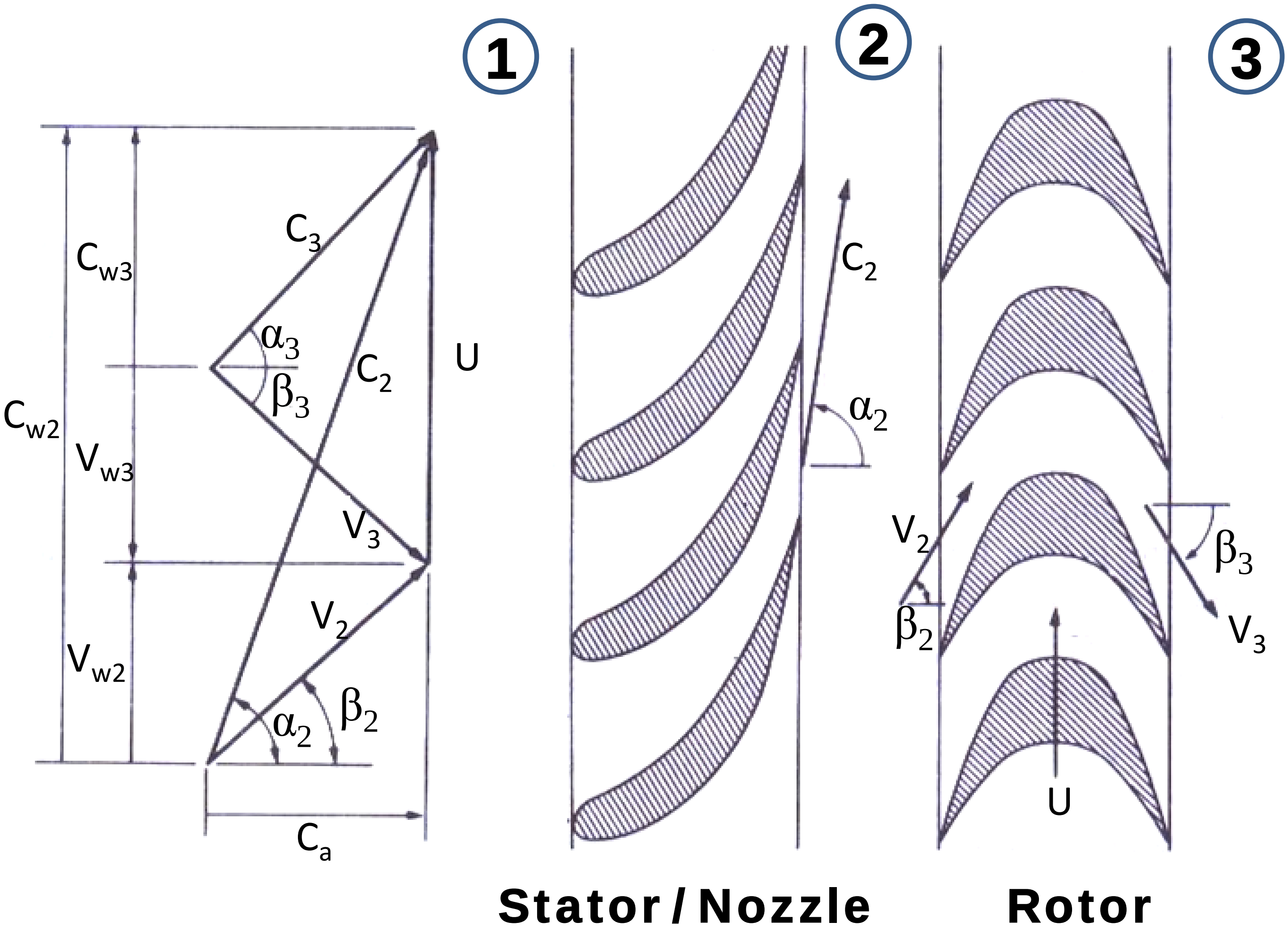
$$\frac{\Delta T_0}{T_{01}} = \frac{U(C_{w2} - C_{w3})}{c_p T_{01}}$$

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



Impulse turbine stage

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

$$\beta_3 = -\beta_2 \Rightarrow V_{w3} = -V_{w2}$$

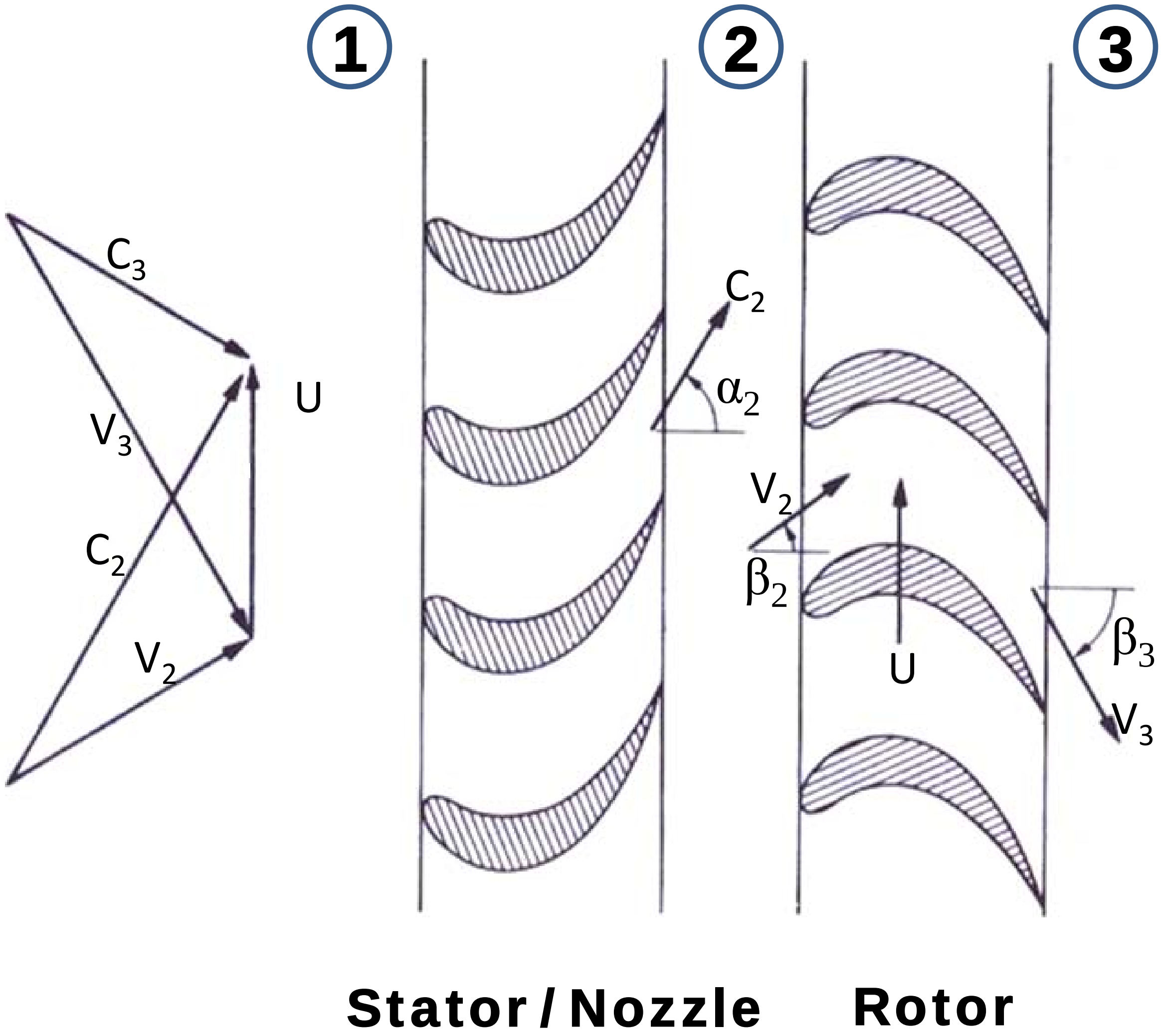
and $C_{w2} - C_{w3} = 2V_{w2} = 2(C_{w2} - U)$

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

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



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

$$\frac{\Delta h_0}{U^2} = \left(2\frac{C_a}{U}\tan\alpha_2 - 1\right)$$

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

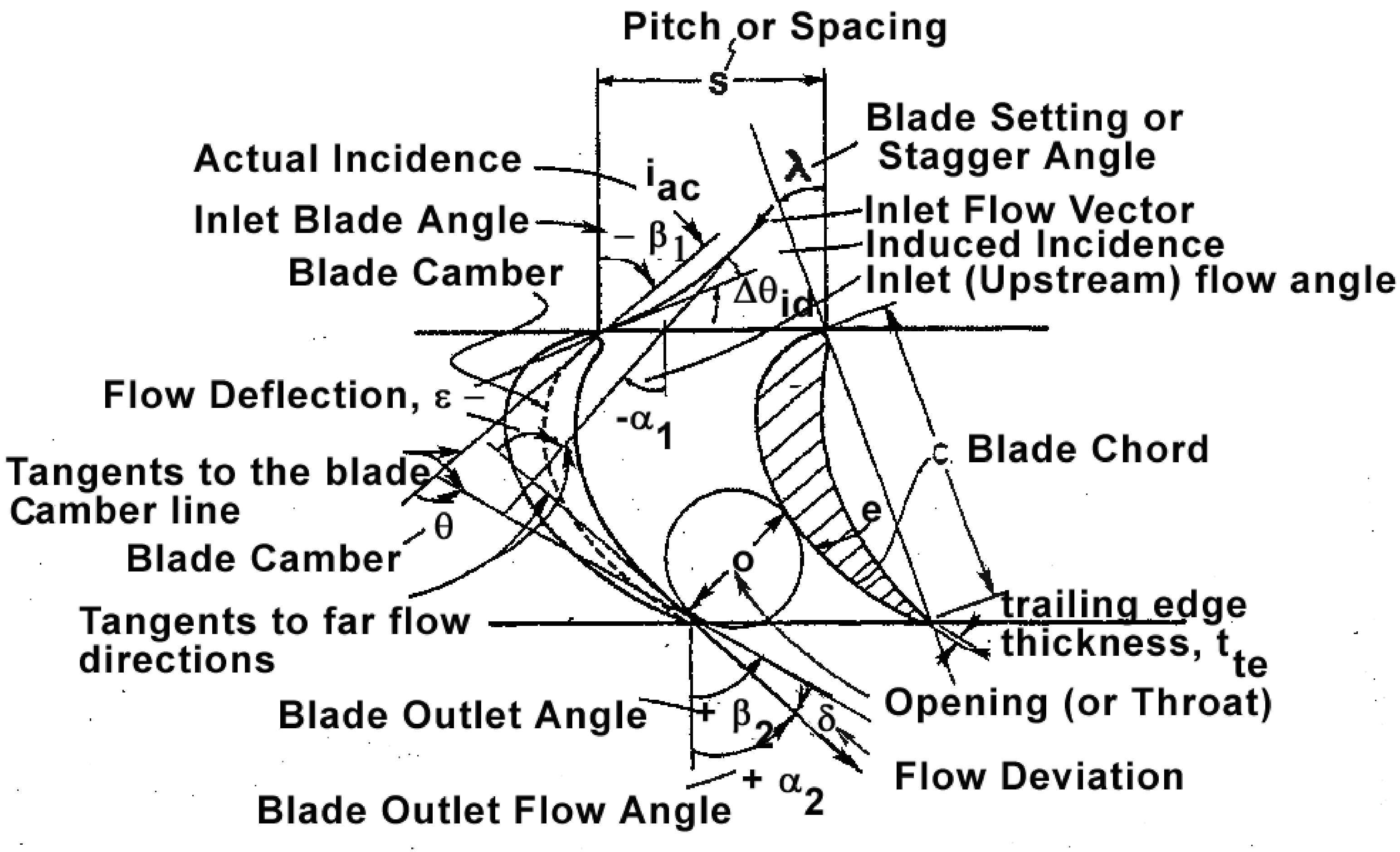
Turbine Cascade

- 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.

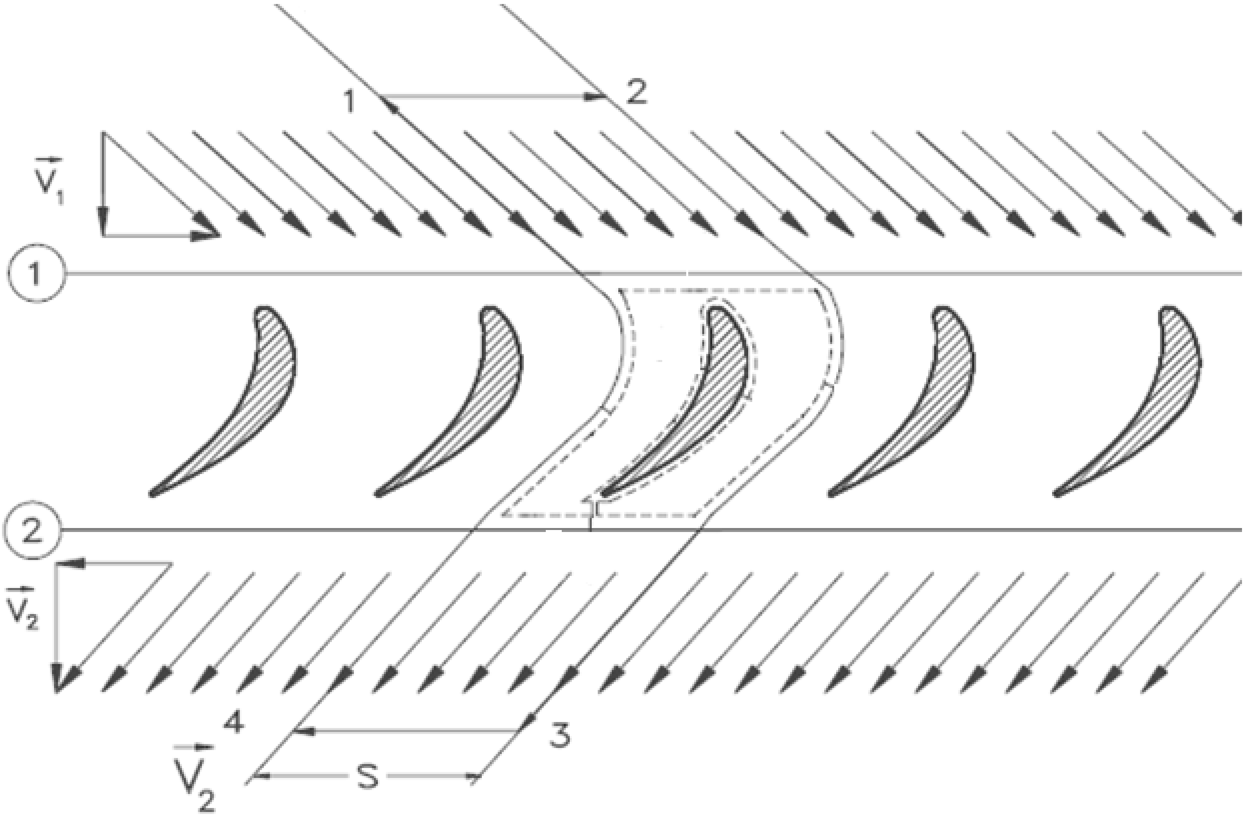
Turbine Cascade



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 α_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

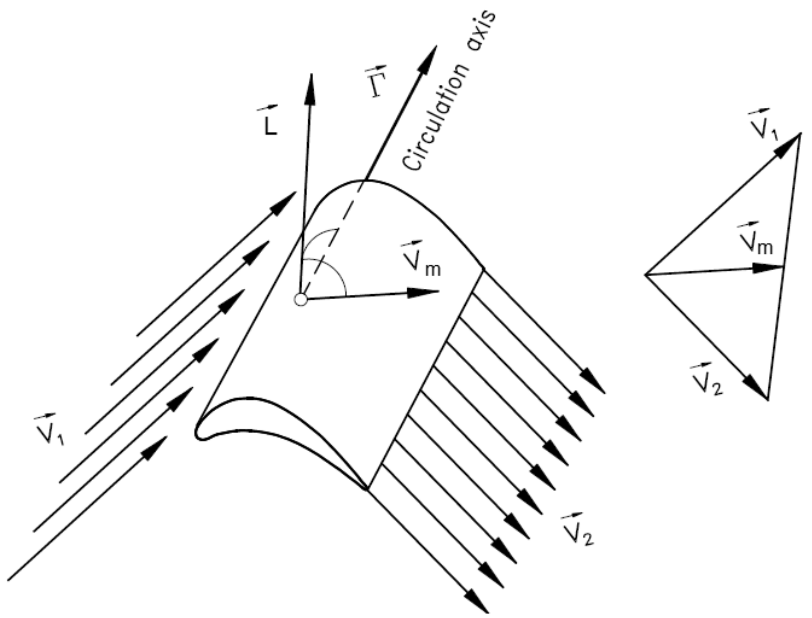
Circulation, $\Gamma = S(V_{w2} - V_{w1})$

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

Expressing lift in a non - dimensional form,

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

$$= 2\frac{S}{C}(\tan\alpha_2 - \tan\alpha_1)\cos\alpha_m$$

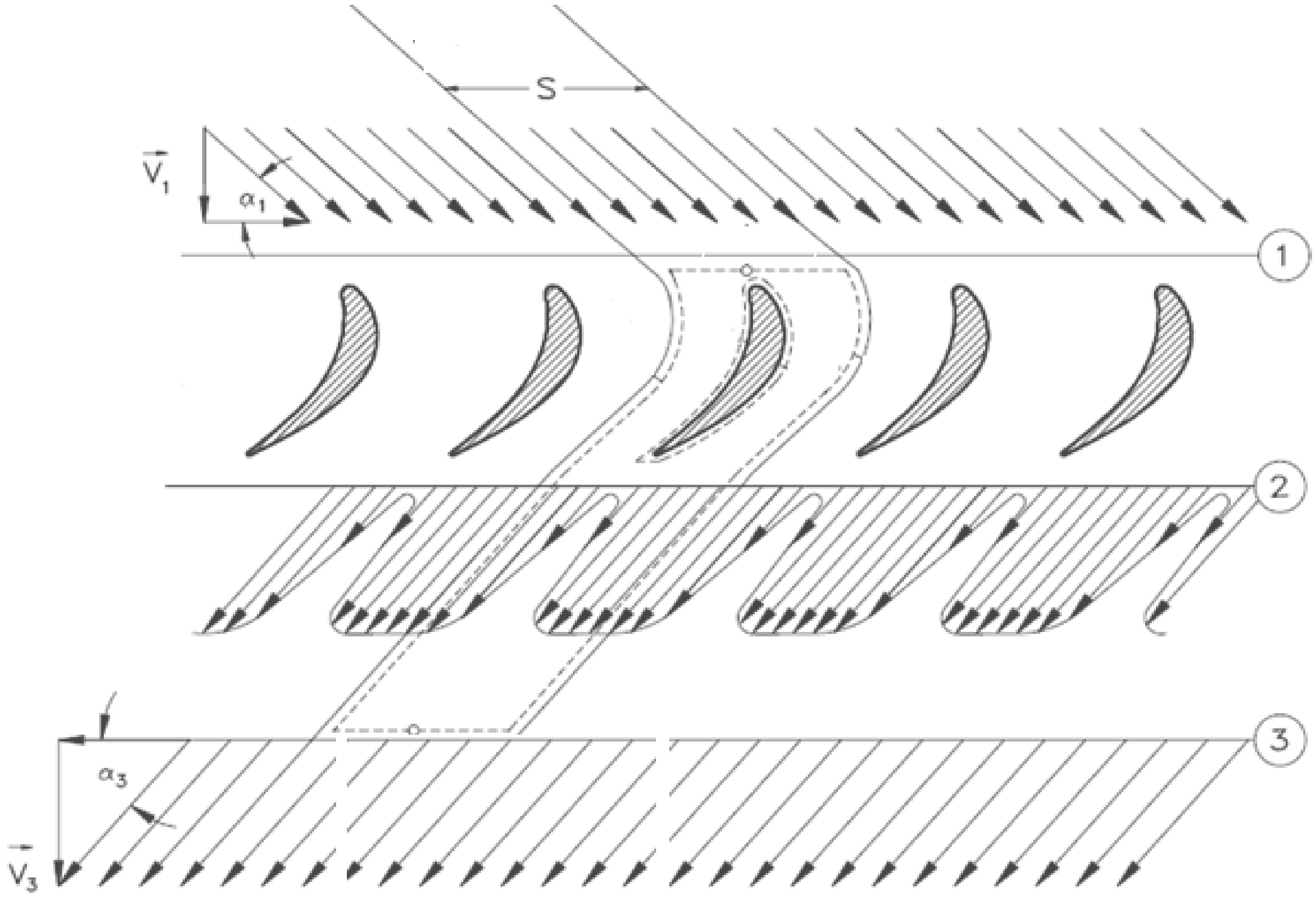


Turbine Cascade

- 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:

$$\overline{\omega} = \frac{P_{01} - P_{02}}{\frac{1}{2}\rho V_2^2}$$

Turbine Cascade



Viscous flow through a turbine cascade

Turbine Cascade

Drag is given by, $D = \overline{\omega} S \cos\alpha_m$

The effective lift

$$L + \overline{\omega} S \cos\alpha_m = \rho V_m \Gamma + \overline{\omega} S \cos\alpha_m$$

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,

$$\eta_b = \frac{1}{1 + \dfrac{2C_D}{C_L \sin 2\alpha_m}}$$

In this lecture...

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

In the next lecture...

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

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