TURBOMACHINERY AERODYNAMICS

Lect- 4

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

In this lecture...

- Performance parameters: cascade analysis
- 2-D losses in axial compressor stage – primary losses

Performance parameters

- Measurements from cascade: velocities, pressures, flow angles …
- Loss in total pressure expressed as total pressure loss coefficient

$$\overline{\omega}_{PLC} = \frac{P_{01} - P_{02}}{\frac{1}{2}\rho V_1^2}$$

- Total pressure loss is very sensitive to changes in the incidence angle.
- At very high incidences, flow is likely to separate from the blade surfaces, eventually leading to stalling of the blade.

Performance parameters

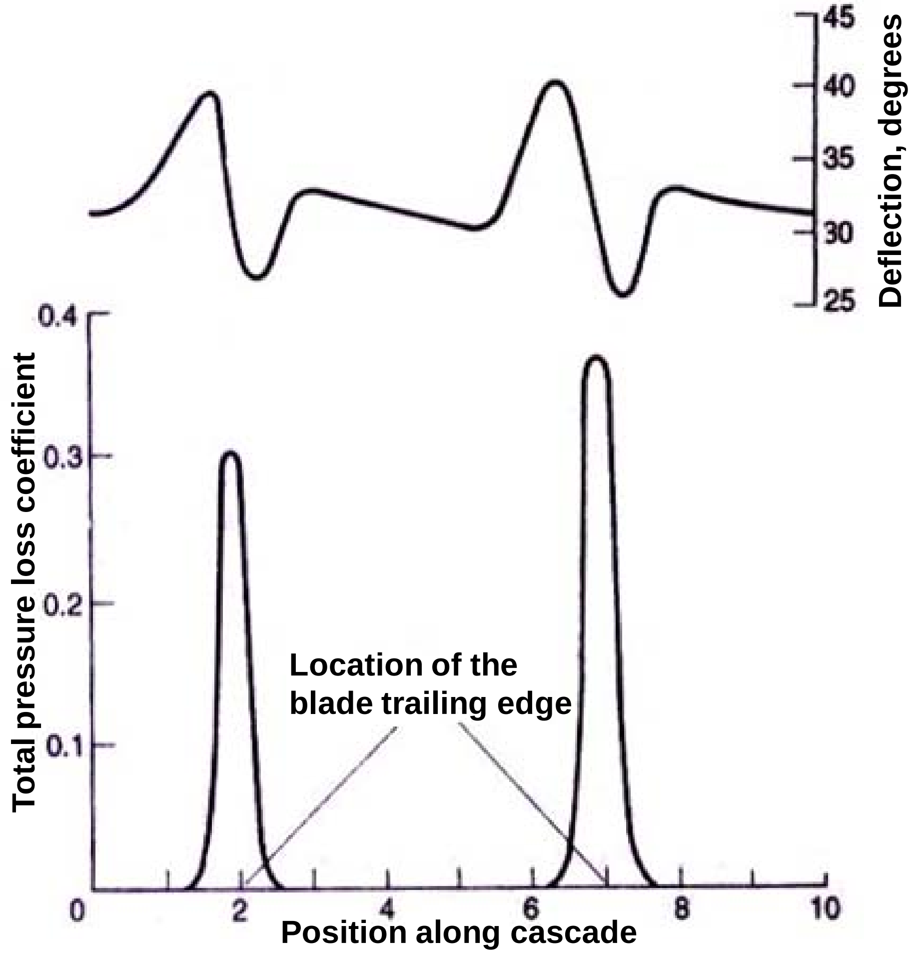
- Blade performance/loading can be assessed using static pressure coefficient:

$$C_P = \frac{P_{local} - P_{ref}}{\frac{1}{2}\rho V_1^2}$$

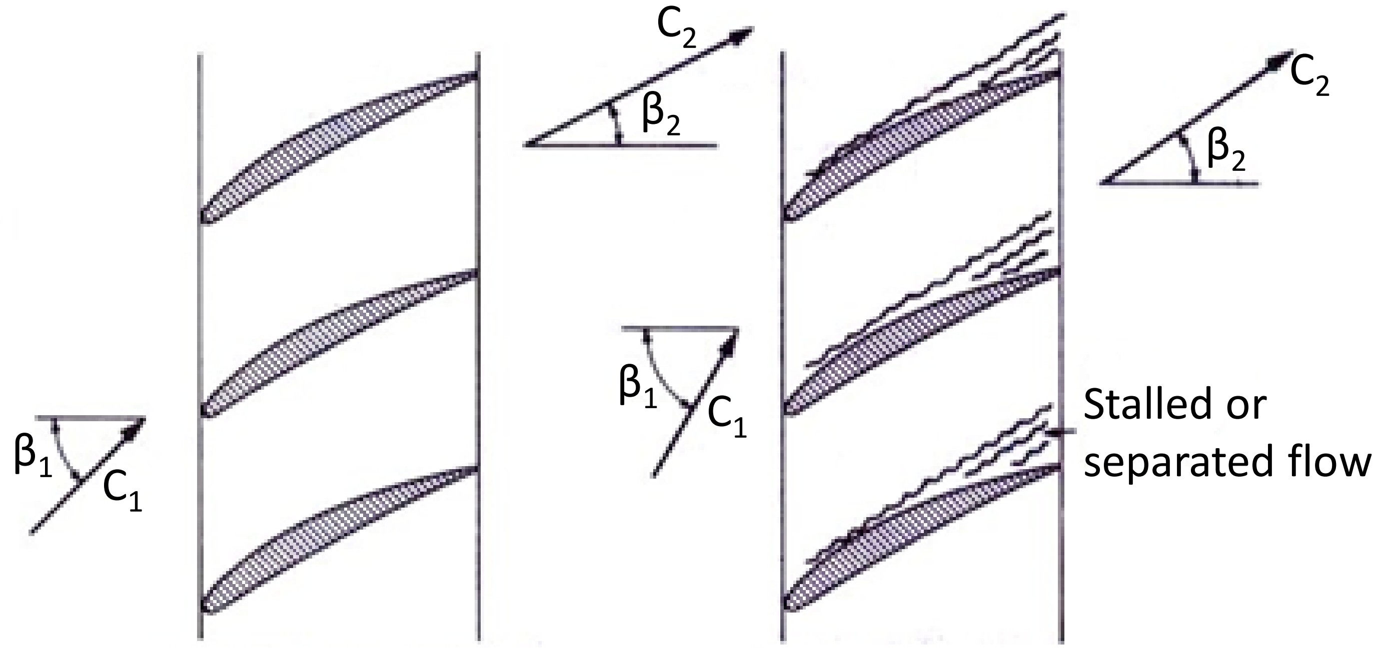
Where, P_{local} is the blade surface static pressure and P_{ref} is the reference static pressure (usually measured at the cascade inlet)

- The C_P distribution (usually plotted as C_P *vs. x/C*) gives an idea about the chordwise load distribution.

Performance parameters

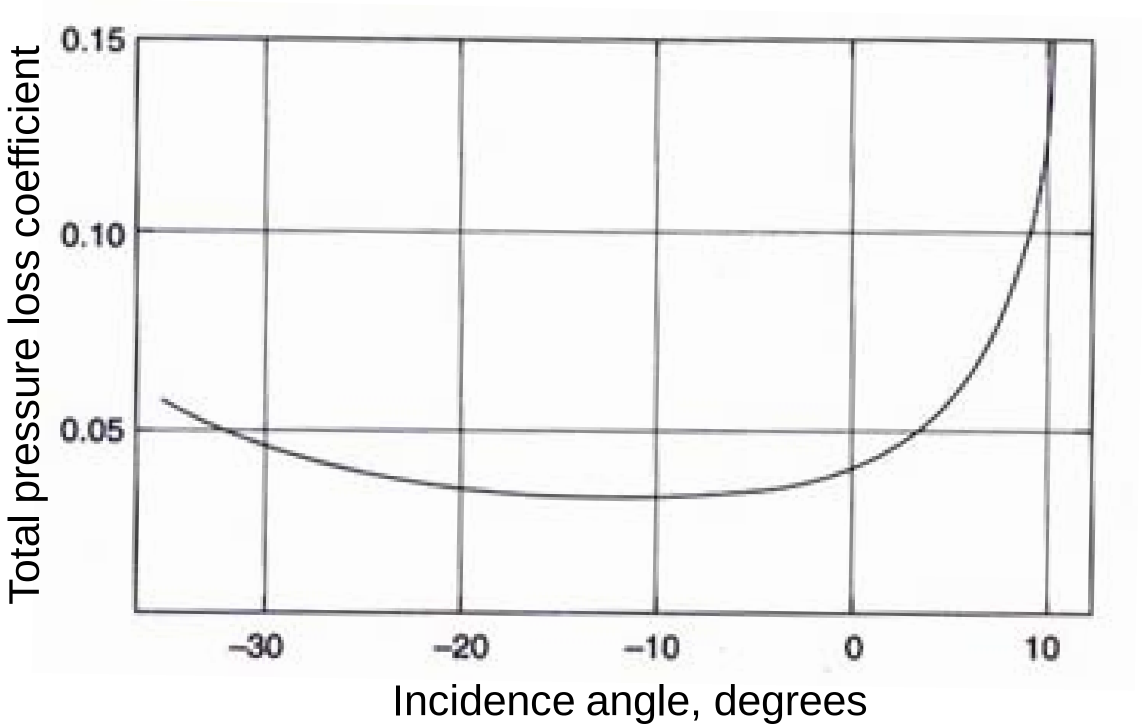


Performance parameters



(a) Normal operation (b) Stalled operation

Performance parameters



Losses in a compressor blade

- Nature of losses in an axial compressor
  - Viscous losses
  - 3-D effects like tip leakage flows, secondary flows etc.
  - Shock losses
  - Mixing losses
- Estimating the losses crucial designing loss control mechanisms.
- However isolating these losses not easy and often done through empirical correlations.
- Total losses in a compressor is the sum of the above losses.

Losses in a compressor blade

- Viscous losses
  - Profile losses: on account of the profile or nature of the airfoil cross-sections
  - Annulus losses: growth of boundary layer along the axis
  - Endwall losses: boundary layer effects in the corner (junction between the blade surface and the casing/hub)
- 3-D effects:
  - Secondary flows: flow through curved blade passages
  - Tip leakage flows: flow from pressure surface to suction surface at the blade tip

Losses in a compressor blade

- The loss manifests itself in the form of stagnation pressure loss (or entropy increase).

$$\frac{\Delta s}{R} = -\ln\frac{P_{02}}{P_{01}} = -\ln\left[1 - \frac{(\Delta P_o)_{loss}}{P_{01}}\right]$$

Expanding the above equation in an infinite series,

$$\frac{\Delta s}{R} = \frac{(\Delta P_o)_{loss}}{P_{01}} + \frac{1}{2}\left(\frac{(\Delta P_o)_{loss}}{P_{01}}\right)^2 + \ldots$$

Neglecting higher order terms, $\frac{\Delta s}{R} = \frac{(\Delta P_o)_{loss}}{P_{01}}$

Since, $\omega = \frac{(\Delta P_o)_{loss}}{\frac{1}{2}\rho V_1^2} = \frac{\Delta s}{R}\frac{P_{01}}{\frac{1}{2}\rho V_1^2}$

or, $\frac{\Delta s}{R} = \left(\frac{\omega\rho V_1^2}{2P_{01}}\right)$

Losses in a compressor blade

- The overall losses in a turbomachinery can be summarised as:

$$\omega = \omega_P + \omega_{sh} + \omega_s + \omega_L + \omega_E$$

Where, ω_P : profile losses

ω_{sh} : shock losses

ω_s : secondary flow loss

ω_L : tip leakage loss

ω_E : Endwall losses

2-D Losses in a compressor blade

- 2-D losses are relevant only to axial flow turbomachines.
- These are mainly associated with blade boundary layers, shock-boundary layer interactions, separated flows and wakes.
- The mixing of the wake downstream produces additional losses called mixing losses.
- The maximum losses occur near the blade surface and minimum loss occurs near the edge of the boundary layer.

2-D Losses in a compressor blade

- 2-D losses can be classified as:
  - Profile loss due to boundary layer, including laminar and/or turbulent separation.
  - Wake mixing losses
  - Shock losses
  - Trailing edge loss due to the blade.

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

2-D Losses in a compressor blade

- The profile loss depends upon:
  - Flow parameters like Reynolds number, Mach number, longitudinal curvature of the blade, inlet turbulence, free-stream unsteadiness and the resulting unsteady boundary layers, pressure gradient, and shock strength
  - Blade parameters like: thickness, camber, solidity, sweep, skewness of the blade, stagger angle and blade roughness.

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

2-D Losses in a compressor blade

- The mixing losses arise as a result of the mixing of the wake with the freestream.
- This depends upon, in addition to the parameters mentioned in the previous slide, the distance downstream.
- The physical mechanism is the exchange of momentum and energy between the wake and the freestream.
- This transfer of energy results in the decay of the free shear layer, increased wake centre line velocity and increased wake width.

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

2-D Losses in a compressor blade

- At far downstream, the flow becomes uniform.
- Theoretically, the difference between the stagnation pressure far downstream and the trailing edge represents the mixing loss.
- Most loss correlations are based on measurements downstream of the trailing edge (1/2 to 1 chord length) and therefore do not include all the mixing losses.
- If there is flow separation, the losses would include losses due to this zone and at its eventual mixing downstream.

2-D Losses in a compressor blade

The profile and mixing losses along a streamline can be written as :

$$\overline{\omega}_{p+m} = \frac{2(P_{0t} - P_{02})}{\rho V_1^2}$$

To determine the above, it is necessary to relate the static pressure difference and velocities to the displacement and momentum thickness of the blade boundary layer at the trailing edge.

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

2-D Losses in a compressor blade

Detailed derivation of these correlations are given in Lakshminarayana's book (Chapter 6).

$$\overline{\omega}_{p+m} = \frac{2(P_{0t} - P_{02})}{\rho V_1^2} = \frac{2(p_t - p_2)}{\rho V_1^2} + \frac{V_t^2 - V_2^2}{V_1^2}$$

This is further expressed as :

$$\overline{\omega}_{p+m} \sec^2 \alpha_1 = \left[\frac{2\Theta + \Delta^2}{(1-\Delta)^2} + \tan^2 \alpha_2 \left\{ \frac{(1-\Delta)^2}{(1-\Theta-\Delta)^2} - 1 \right\} \right]$$

Neglecting higher order terms,

$$\overline{\omega}_{p+m} \sec^2 \alpha_1 = 2(\Theta + \Theta \tan^2 \alpha_2)$$

Where, Δ is the blockage (related to displacement thickness) and Θ is the momentum thicknesss.

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

2-D Losses in a compressor blade

- Thus, in a simplified manner, we see that the profile loss can be estimated based on the momentum thickness.
- The above loss correlation includes both profile and wake mixing loss.
- If flow separation occurs, additional losses are incurred. This is because the pressure distribution is drastically altered beyond the separation point.
- The losses increase due to increase in boundary layer displacement and momentum thicknesses.

2-D Losses in a compressor blade

- In addition to the losses discussed above, boundary layer growth and subsequent decay of the wake causes deviation in the outlet angle.
- An estimate of this is given as:

$$\tan \alpha_2 \approx (1 - \Theta - \Delta) \tan \alpha_t$$

- Hence, viscous effect in a turbomachine always leads to decrease in the turning angle.
- The values of displacement and momentum thicknesses, depend upon, variation of freestream velocity, Mach number, skin friction, pressure gradient, turbulence intensity and Reynolds number.

2-D Losses in a compressor blade

- In general, the loss estimation may be carried out using one of the following methods:
  - Separate calculation of the potential or inviscid flow and the displacement and momentum thicknesses. Subsequently, use the equation discussed previously.
  - Using a Navier-Stokes based computational code. Here the local and the integrated losses can be computed directly.

Mach number and shock losses

- The static pressure rise in a compressor increases with Mach number.
- Thus the pressure gradient increases with increase in Mach number.
- This means that the momentum thickness and hence the losses increase with Mach number.
- Increasing Mach numbers also lead to increase in shock losses.
- At transonic speeds, the shock losses are very sensitive to leading and trailing edge geometries.

Mach number and shock losses

- An estimate of the 2-D shock losses for a compressor must include:
  - The losses due to the leading edge bluntness with supersonic upstream Mach number.
  - The location of the passage shock can be determined from inviscid theories. If the shock strength is known, the losses can be estimated.
  - The losses due to boundary layer growth and the shock-boundary layer interaction are most difficult to estimate. The contribution however is small for weak shocks.

Mach number and shock losses

- One of the empirical correlations for the shock loss was given by Freeman and Cumpsty (1989).

$$\omega_{sh} = \frac{(\Delta P_0)_{loss}}{P_{01} - p_1} = \left[\frac{(\Delta P_0)_{loss}}{P_{01} - p_1}\right]_{normal\,shock} + \left[2.6 + 0.18(\alpha_1' - 65^0)\right]10^{-2}(\alpha_1 - \alpha_1')$$

where, α_1' is the blade inlet angle.

- This is valid for an incidence angle upto 5°.
- These empirical correlations are however, derived using the 2-D assumption.
- Actual flows are seldom 2-D in nature.

In this lecture...

- Performance parameters: cascade analysis
- 2-D losses in axial compressor stage – primary losses

In the next lecture…

- Tutorial: solved examples and tutorial problems.