• Recap: Lecture 7: 11th August 2015, 1530-1655 hrs.
  
  – Losses in a compressor blade
    • Overall losses and loss components
  
  – 2-D losses in a compressor
    • Profile losses
    • Profile + mixing losses
  
  – 3-D losses in an axial compressor
3-D flow in axial compressors

• Flow in axial compressors considered so far was 2-D: no radial component of velocity.

• Three dimensionality is caused by inviscid and viscous effects.

• Some of the inviscid effects are due to
  – Compressibility and radial pressure gradients
  – Radial variation in blade geometry
  – Tip leakage flow
  – Presence of shock
  – Secondary flows
3-D flow in axial compressors

- These inviscid effects can be analysed using the inviscid governing equations.
- The most dominant effect is the radial variation in velocity.
- The viscous and inviscid effects compliment each other.
- For eg. Tip leakage flow is essentially an inviscid effect, but is propagation and formation of leakage vortex is controlled by viscous effects.
3-D flow in axial compressors

• The equations of motion for 3-D analysis of flow through turbomachines is highly non-linear.
• Analytical solutions exist for simple flow fields.
• Depending upon the analysis, one may take up an axisymmetric analysis or a non-axisymmetric analysis.
• Axisymmetric analysis
  – Simple radial equilibrium analysis
  – Actuator disc theories
  – Passage averaged equations
3-D flow in axial compressors

• Non-axisymmetric analysis
  – Lifting line and lifting surface approach
  – Quasi-3-D approach
  – Numerical solution of exact equations
    (Euler or Navier-Stokes)

• Axisymmetric analysis is used to predict the radial or spanwise variation of properties far downstream of the blade.

• In the blade passage, cascade theories can be used to determine variation in properties at a given spanwise location.
Axisymmetric analysis

From Lakshminarayana, Chap 4, P 264
3-D flow in axial compressors

Local flow field decides blade shape
3-D flow in axial compressors

- Axial flow acquires rotational component on entering the blades
- Axial compressors blades are normally highly twisted
- Airfoils used may significantly vary in camber and stagger settings from hub to tip
- Solidity and spacing between the airfoils vary from root to tip
- As a result of the above, Cp distributions on the blade surfaces vary from root to tip
3-D flow in axial compressors

Fabricated Blades

Top View

Typical 3-D blade shapes
3-D flow in axial compressors

The flow, in passing through the curved, twisted blades, develop asymmetric boundary layers on its bounding surface, which promote strong passage vortex development.
• Secondary flows
  – Occur in flow through curvatures.
  – Flow through curved diffusers, compressor, turbine blade passages.
  – Flow in a direction perpendicular to the primary flow.
  – Usually appears as a pair of counter-rotating vortices.
  – Due to imbalance between the radial pressure gradient and the centripetal forces.
  – Different analytical methods for understanding secondary flows: inviscid analysis: gyroscope analogy, viscous analysis.
  – Tip leakage flows and secondary flows are often indistinguishable.
Force balance on a fluid element in rotation

\[
\frac{\partial P}{\partial r} = \frac{\rho V^2}{r}
\]
Secondary Flows and associated losses
Secondary flow development (Hawthorne, 1955)
Fig. 1. Secondary flow models in turbine cascades: (a) – model of Hawthorne (1955), (b) – model of Langston (1980), (c) – model of Sharma and Butler (1987), (d) – model of Goldstein and Spores (1988), (e) – model of Doerrfler and Amecke (1994), (f) – model of Wang et al. (1997)
Langston’s secondary flow development model for turbines