Controlling Separation in Turbomachines

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Outline

- Four examples of flow control
  - Passive control of LP turbine blades
    - Laminar separation control
  - Aspiration of a conventional axial compressor blade
    - Turbulent separation control
  - Compressor blade designed for aspiration
    - Turbulent separation control

Control of intakes in crosswinds
  - Turbulent separation control
LP Turbine Airfoils with Passive Flow Control
Moving Bar Cascade Facility

Wake Generator

Traverse System

Instrumented Blade

Moving Bar
Pressure Coefficient \((f_r = 0.57, \, Tu = 4.0\%, \, Re = 50000)\)

Profile = T106C

Zweifel Lift Coefficient = 1.3

Moving Bar Cascade Facility
Total Pressure Loss Coefficient \((f_t = 0.57, \, \text{Tu} = 4.0\%)\)
Passive Vortex Generator Jets
Total Pressure Loss Coefficient \((f_s = 0.57, \, \text{Tu} = 4.0\%)\)
Comparison of LP Turbine Blades

Normalized Loss Coefficient vs. Re x 10^-3

- T106C, Smooth
- U2, Smooth
- U2
- 2D_RG
- H2, Ra = 5
- H2, Smooth

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Conclusions

- For laminar flow control investigations, need:
  - Incoming wakes
  - Realistic FSTI

- Important influences
  - Scale and shape of roughness elements
  - Reynolds number
  - Blade design

- Controlled ultra high lift airfoils have higher loss than lower lift airfoils
Turbulent Separation on Compressor Blades

1. Conventional Design with Aspiration

2. Design for Aspiration
Problem statement

- Risk of high Reynolds number turbulent separation from suction surface due to
  - Low solidity
  - High Incidence

- Flow control can
  - Prevent separation
  - Increase blade loading
  - Act as Virtual VGV?
Conventional Compressor Blade with Aspiration
Jet hole plug on flat plate surface. Variable skew angle achieved by rotating plug.
Aspirated Blade & Siren Valve

- \( V_{\text{jet}} \leq V_{\text{i}} \)
- Jets at 54% chord
- Jet pitch angle = 30 degrees
- Jet skew angle = 60 degrees
- Jet spacing 8 diameters
- AVDR=1 achieved by endwall suction
Influence of boundary layer blowing (Cascade, $i=12.5^\circ$)

**Midspan velocity distribution**

- No boundary layer control
- Steady blowing

- Jets at 54% Chord
- Plateau due to corner separation

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Definition of loss coefficient

\[ Y_p = \frac{p_{01} - p_{02M}}{\frac{1}{2} \rho V_1^2} + \left( \frac{\dot{m}_1}{\dot{m}_2} \right) \left( \frac{p_{01} - p_{02M}}{\frac{1}{2} \rho V_1^2} \right) + \left( \frac{-\dot{m}_2}{\dot{m}_2} \right) \left( \frac{p_{01} - p_{02M}}{\frac{1}{2} \rho V_1^2} \right) \]

measured loss term  jet loss term  suction loss term
Pulsed vs. Steady Blowing (flat plate; equiv i=12.5°)

\[ C_\mu = \frac{2A_j}{bs \cos(\alpha_1)} \left( \frac{V_j}{V_1} \right)^2 \]

\[ F^* = \frac{f(U_{in} - U_{separation})}{V_1} \]
Exit stagnation pressure loss (cascade; $i=12.5^\circ$)

- Uncontrolled case
  - Endwall separation removes mid-span separation

- Endwall suction only
  - Midspan separated

- Endwall suction & blade surface steady blowing
2D Loss vs Incidence - Steady Blowing (cascade)

With Endwall Suction, AVDR = 1
2D Steady Suction vs. Blowing (cascade; $i=12.5^\circ$)

With Endwall Suction, AVDR = 1
Influence of flow control on the engine cycle

- At realistic velocity ratios
  - Unsteady blowing not worthwhile of steady blowing
  - Optimal skew angle approx 60 deg

- Endwall flow control
  - Required when using blade flow control

- For a conventional airfoil, flow control
  - offers benefit only over a limited range of incidence
  - could reduce solidity from 1.5 to 1.0 but at cost to efficiency (0.3%)
Compressor Blade Designed for Aspiration
Aspiration

- 2D profiles optimised using MISES
- Bleed mass flow rate ~1%
- Results:
  - High loading
  - High turning
  - Very low profile loss (excluding cost to cycle)
Isentropic Mach Number Distribution with Aspiration

\[ M_{\text{inlet}} = 0.75 \]
3D CFD of Flow Inside Blade Bleed Slot

- Aspect ratio ~1
- Endwall flow control removes corner separation
- Slot optimisation is essential for uniform bleed flow
• Good efficiency achievable due to
  – Relatively low cost of bleed flow (2.6% of mass flow)
  – High loading/low solidity
3D Core Loss – Measured – Low Speed Cascade

- Above excludes bleed loss
- “Soft failure” when aspiration reduces
3D Core Loss – Measured – Low Speed Cascade

- Excludes bleed loss
Conclusions

- Must design with control in mind
- Experimental results from low speed cascade show design is viable
- “Soft failure” when aspiration mass flow reduces
Separation Control on Intakes in Cross Winds
Intake Operation in a Crosswind

Windward Lip Stagnation Point

Separation and Low Stagnation Pressure Region

Overspeed Around Leading Edge

Shock Wave

Strong Crosswind (35 Knots)
Sector Rig Fan Face Traverses

Vortex Generator Jets
Naturally Separated Cases: Fan Stagnation Pressure Profiles

\[ \frac{P_{\text{inlet}} - P_{\text{fan}}}{P_{\text{inlet}}} \]

- No Control
  - Re = 4.4 \times 10^5
- No Control
  - Re = 5.9 \times 10^5
- Sp/D 8.5, VR 4.5
  - Re = 5 \times 10^5
- Sp/D 8.5, VR 4.5
  - Re = 5.8 \times 10^5

\[ M_{\text{fan}} = 0.53 \]

Distance From Lip / Passage Width at Fan
Conclusions

- Vortex generator jets positioned between the stagnation point and intake highlight delay shock induced separation
- Distortion is reduced over the full range of operating conditions
- A ratio formed from appropriate lip static pressures is a good indicator of when to apply control
Conclusions

- In the case of LP turbines
  - Problem is one of laminar separation control
  - Incoming wakes & realistic turbulence levels needed for tests
  - Increasing lift+flow control does not improve efficiency

- In the case of compressors
  - Problem is one of turbulent separation control
  - Unsteady blowing not worthwhile compared to steady blowing
  - Suction better than blowing
  - Endwall flow control necessary
  - For a conventional airfoil, benefit is limited
  - Aggressive designs for use with aspiration are viable
Conclusions (cont)

- In the case of intakes
  - Shock induced separation occurs as the fan face Mach number is increased (exact value depends on Reynolds No.)
  - VGJs between the stagnation point and intake highlight delay shock induced separation over a range of Mach No.
  - The distortion resulting from separation is reduced over full range of operating conditions
  - A ratio formed from appropriate lip static pressures is good indicator of when to apply control