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
Profile = T106C
Zweifel Lift Coefficient = 1.3
Moving Bar Cascade Facility
Total Pressure Loss Coefficient \( (f_e = 0.57, \text{Tu} = 4.0\%) \)

\[
\frac{P_{01} - P_{01,\text{mix}}}{P_{01} - P_{\text{mix}}} \quad \text{vs} \quad \text{Re} \times 10^{-3}
\]

Graph showing different profiles (2D_RG, 3D_nWS, 2D_RS) for varying Re with a smooth profile indicated.
Passive Vortex Generator Jets
Total Pressure Loss Coefficient ($f_i = 0.57, \text{Tu} = 4.0\%$)

![Graph showing the relationship between Total Pressure Loss Coefficient and Re $\times 10^{-3}$](image)

- **Smooth**
- $s/d = 2.5$
- $s/d = 10$

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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

- $V_{\text{jet}} \leq V_1$
- 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°)

Midspan velocity distribution

- No boundary layer control
- Steady blowing

Jets at 54% Chord
Plateau due to corner separation
Definition of loss coefficient

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

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

\[
C_\mu = \frac{2A_j}{b \cos(\alpha_i)} \left(\frac{V_j}{V_1}\right)^2 F^+ = \frac{f(U_{kr} - U_{separation})}{V_1}
\]
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°)

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

- At realistic velocity ratios
  - Unsteady blowing not worthwhile cf 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

\[ M_{\text{inlet}} = 0.75 \]

- High loading
- Sharp diffusion controlled by aspiration

Suction

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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
3D Loss Breakdown (Fluent + SA Tu model)

- 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
Naturally Separated Cases: Fan Stagnation Pressure Profiles

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

- 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