Controlling Separation in Turbomachines

Simon Evans, Christoph Himmel
Bronwyn Power, Christian Wakelam
Liping Xu, Tom Hynes, Howard Hodson
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 \( (f_i = 0.57, \; Tu = 4.0\%, \; Re = 50000) \)

Profile = T106C
Zweifel Lift Coefficient = 1.3
Moving Bar Cascade Facility
Total Pressure Loss Coefficient ($f_r = 0.57, T_u = 4.0\%$)
Passive Vortex Generator Jets
Total Pressure Loss Coefficient \((f_r = 0.57, \, Tu = 4.0\%)\)

![Graph showing Total Pressure Loss Coefficient](image)

**Axes:**
- **X-axis:** Re \(\times 10^{-3}\)
- **Y-axis:** \(\frac{(P_{01} - P_{0,mix})}{(P_{01} - P_{mix})}\)

**Legend:**
- **Smooth**
- s/d = 2.5
- s/d = 10

**Inset Image:** 2D RG
Comparison of LP Turbine Blades

Normalized Loss Coefficient vs. Re x 10^-3

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

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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 0 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

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

measured loss term  jet loss term  suction loss term

[Whittle Laboratory logo]
Pulsed vs. Steady Blowing (flat plate; equiv i=12.5°)

\[ C_\mu = \frac{2A_j}{b_5 \cos(\alpha_t)} \left( \frac{V_j}{V_1} \right)^2 \]
\[ F^* = \frac{fU_{x,t} - L_{separation}}{V_1} \]

- **Baseline**
- **Steady Blowing**
- **F^* = 0.5**
- **F^* = 3.5**
- **F^* = 5.5**
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**

![Whittle Laboratory Logo]
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%)
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

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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
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
Sector Rig Fan Face Traverses

Vortex Generator Jets
Naturally Separated Cases: Fan Stagnation Pressure Profiles

\[
\frac{P_{\text{measured}} - P_{\text{fan}}}{P_{\text{inlet}}} \quad \text{vs} \quad \text{Distance From Lip / Passage Width at Fan}
\]

- 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

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