Controlling Separation in Turbomachines

Simon Evans, Christoph Himmel
Bronwyn Power, Christian Wakelam
Liping Xu, Tom Hynes, Howard Hodson

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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

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LP Turbine Airfoils with Passive Flow Control

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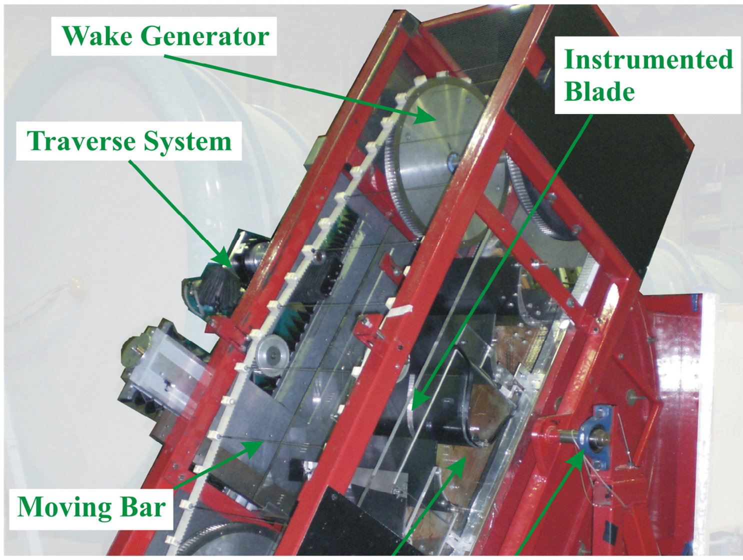
Moving Bar Cascade Facility



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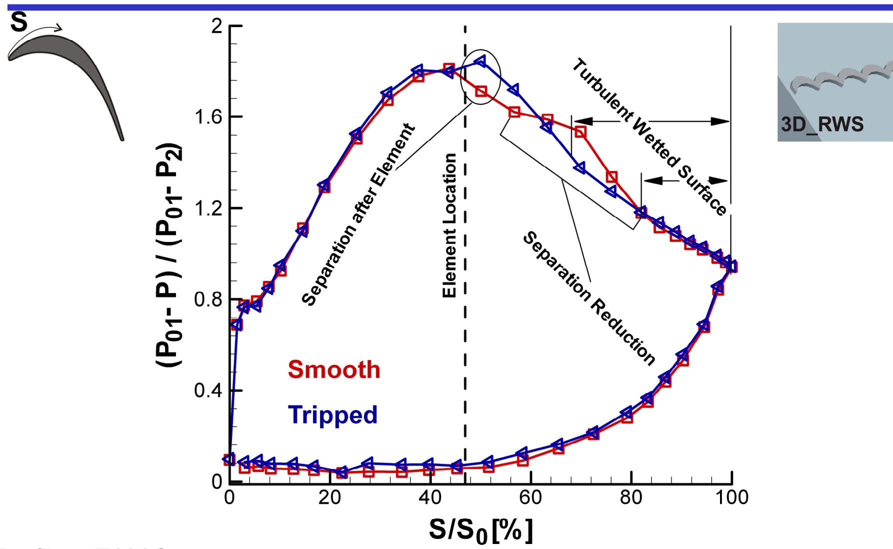
Pressure Coefficient (f_r = 0.57, Tu = 4.0%, Re = 50000)



Profile = T106C

Zweifel Lift Coefficient = 1.3

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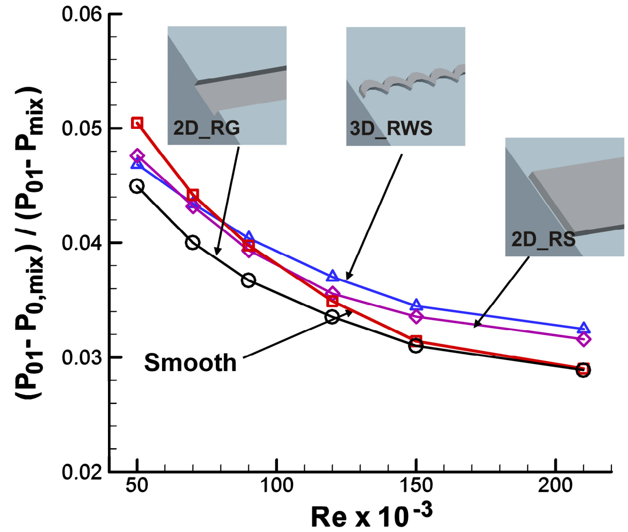
Total Pressure Loss Coefficient (f_r = 0.57, Tu = 4.0%)



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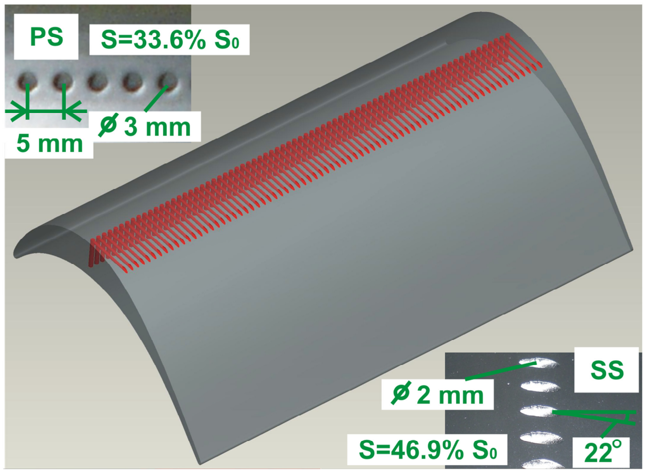
Passive Vortex Generator Jets



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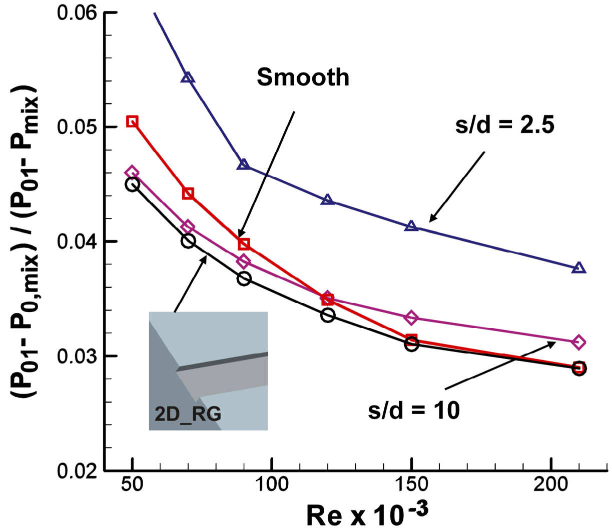
Total Pressure Loss Coefficient (f_r = 0.57, Tu = 4.0%)



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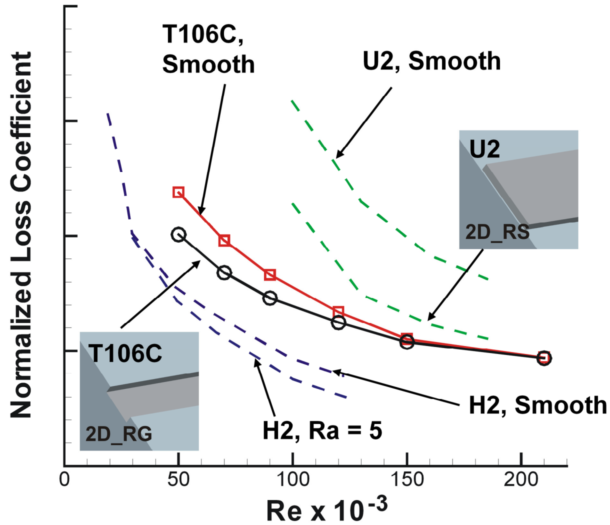
Comparison of LP Turbine Blades



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Conclusions

- For laminar flow control investigations, need:
  - Incoming wakes
  - Realistic FSTI
- Importrant influences
  - Scale and shape of roughness elements
  - Reynolds number
  - Blade design
- Controlled ultra high lift airfoils have higher loss than lower lift airfoils

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Turbulent Separation on Compressor Blades

1. Conventional Design with Aspiration

2. Design for Aspiration

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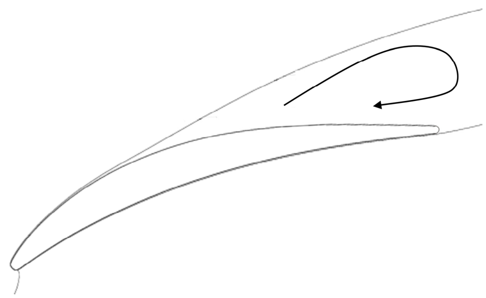
Problem statement

- 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?



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Conventional Compressor Blade with Aspiration

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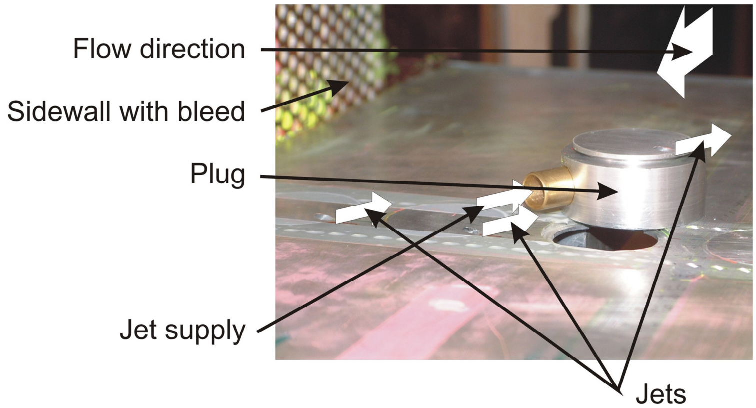
Variable Skew Jet Holes on Flat Plate



- Pitch angle set to 30 degrees
- Optimal skew angle approximately 60 degrees
- Simulates suction surface of compressor blade at i = 12.5 deg

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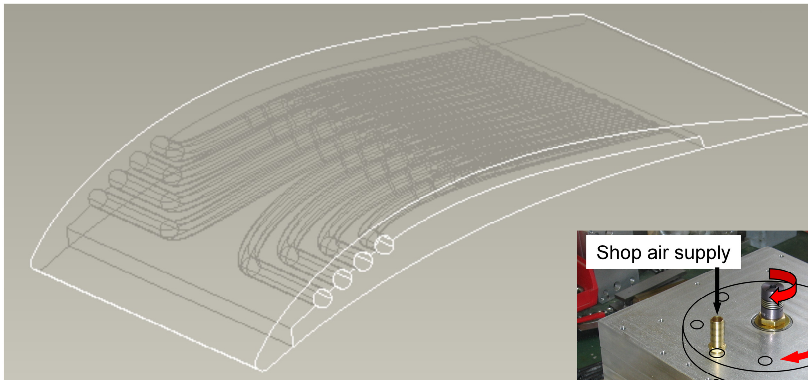
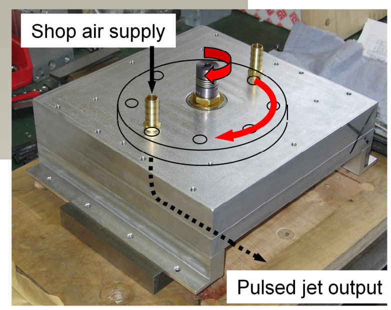
Jet hole plug on flat plate surface. Variable skew angle achieved by rotating plug.

Aspirated Blade & Siren Valve





- $V_{jet} \leq V_1$
- Jets at 54% chord
- Jet pitch angle = 30 degrees
- Jet skew angle = 60 degrees
- Jet spacing 8 diameters
- AVDR=1 achieved by endwall suction

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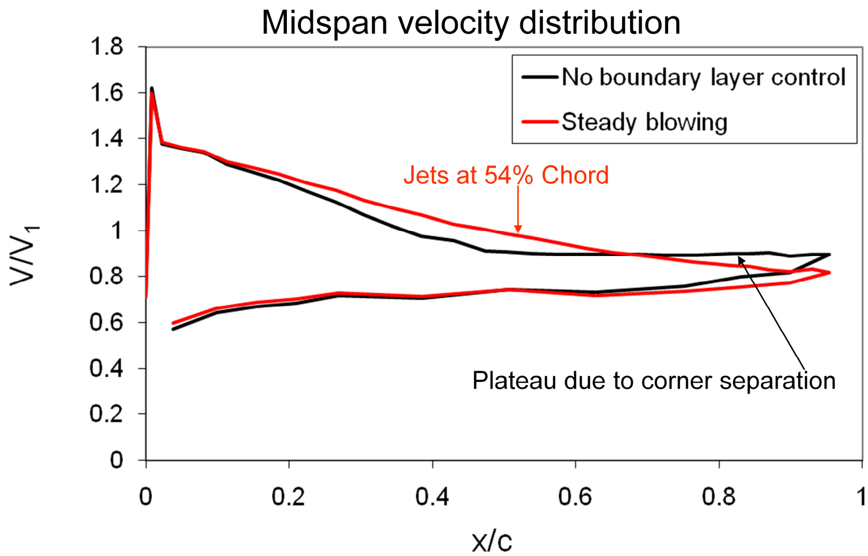
Influence of boundary layer blowing (Cascade, i=12.5°)



Definition of loss coefficient

$$Y_p = \underbrace{\frac{p_{01} - p_{02M}}{\frac{1}{2}\rho V_1^2}}_{\text{measured loss term}} + \underbrace{\left(\frac{\dot{m}_j}{\dot{m}_2}\right)\left(\frac{p_{0j} - p_{02M}}{\frac{1}{2}\rho V_1^2}\right)}_{\text{jet loss term}} + \underbrace{\left(-\frac{\dot{m}_s}{\dot{m}_2}\right)\left(\frac{p_{0s} - p_{02M}}{\frac{1}{2}\rho V_1^2}\right)}_{\text{suction loss term}}$$

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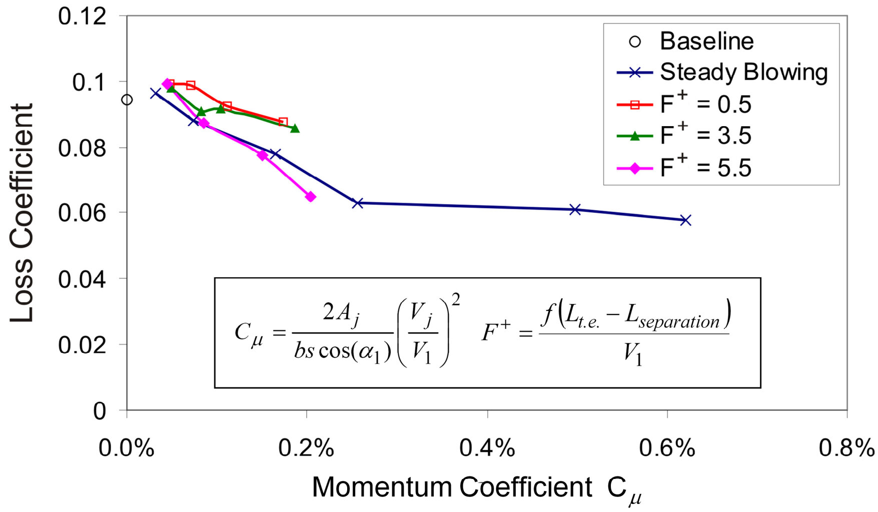
Pulsed vs. Steady Blowing (flat plate; equiv i=12.5°)



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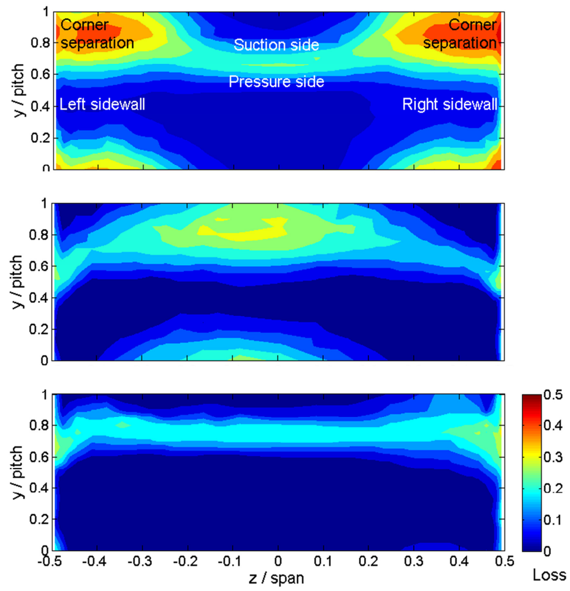
Exit stagnation pressure loss (cascade; i=12.5°)



- Uncontrolled case
  - Endwall separation removes mid-span separation
- Endwall suction only
  - Midspan separated
- Endwall suction & blade surface steady blowing

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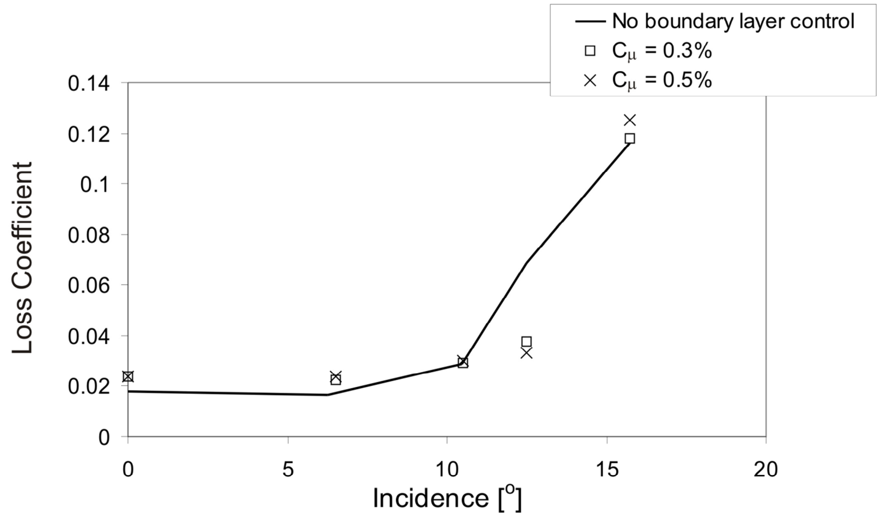
2D Loss vs Incidence - Steady Blowing (cascade)



With Endwall Suction, AVDR = 1

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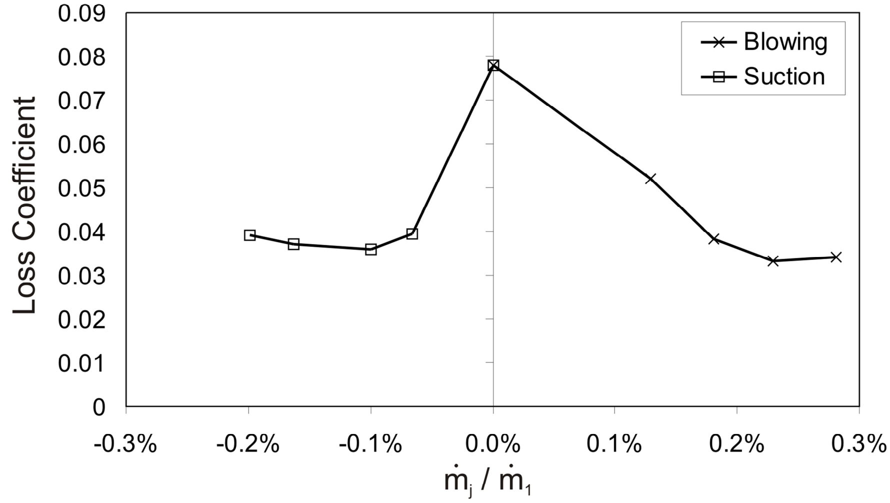
2D Steady Suction vs. Blowing (cascade; i=12.5°)



With Endwall Suction, AVDR = 1

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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%)

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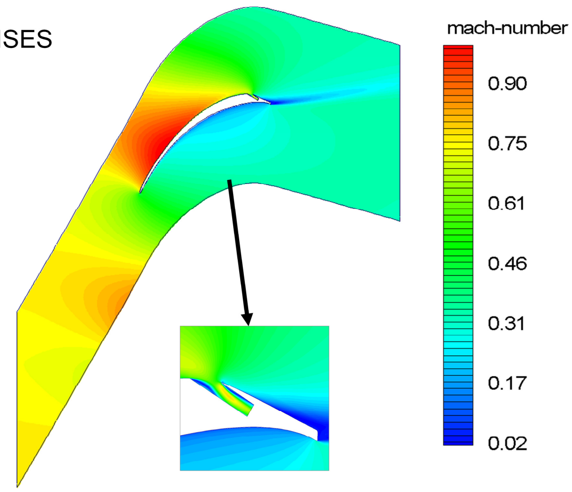
Compressor Blade Designed for Aspiration

Aspiration

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



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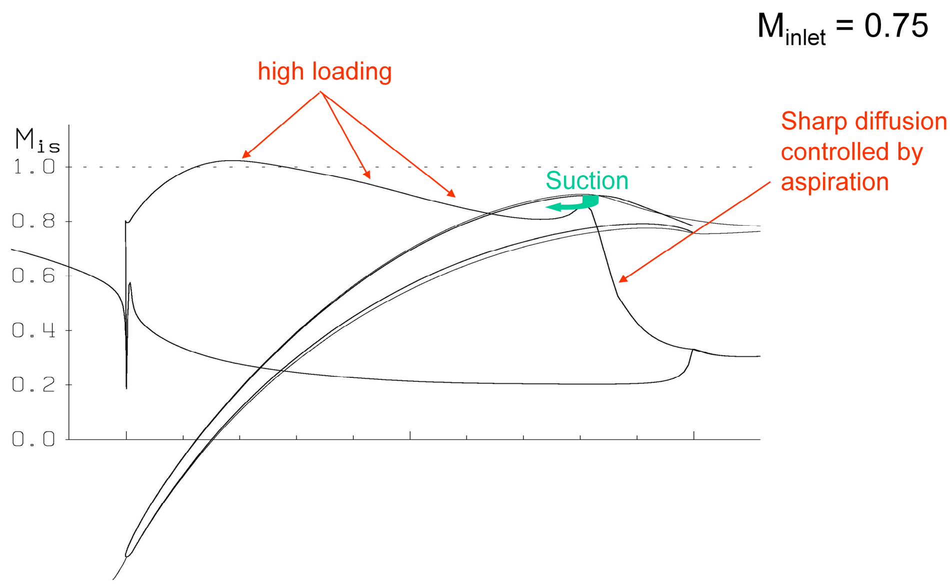
Isentropic Mach Number Distribution with Aspiration



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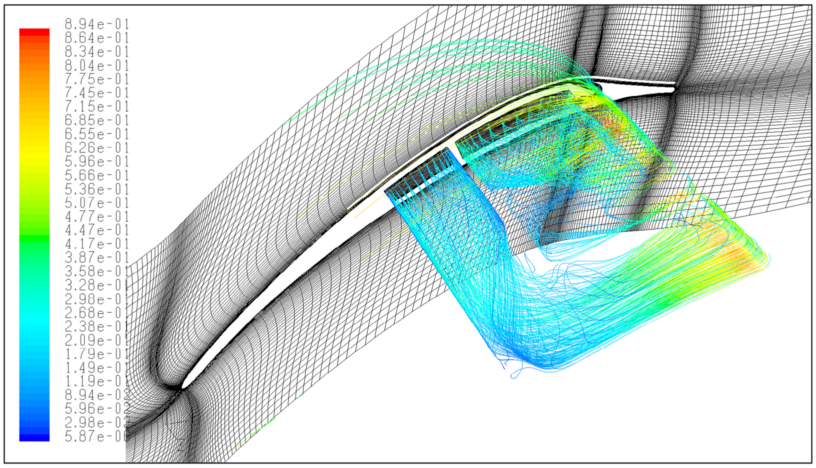
3D CFD of Flow Inside Blade Bleed Slot



- Aspect ratio ~1
- Endwall flow control removes corner separation
- Slot optimisation is essential for uniform bleed flow

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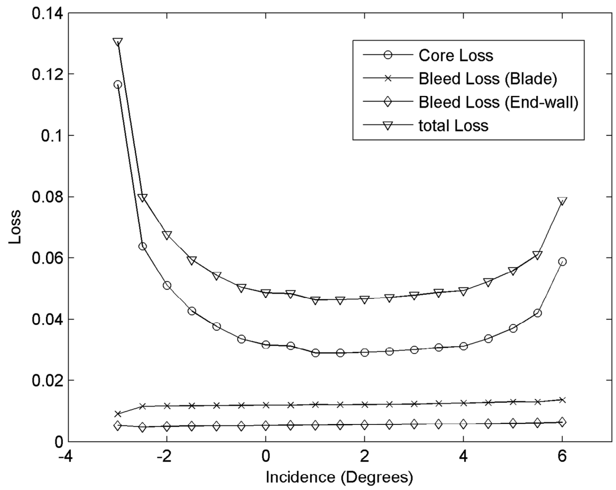
3D Loss Breakdown (Fluent + SA Tu model)



- Good efficiency achievable due to
  - Relatively low cost of bleed flow (2.6% of mass flow)
  - High loading/low solidity

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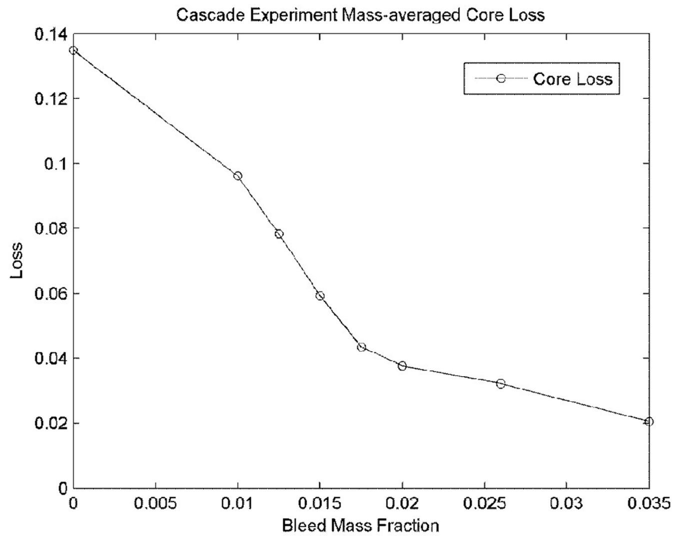
3D Core Loss – Measured – Low Speed Cascade



- Above excludes bleed loss
- “Soft failure” when aspiration reduces

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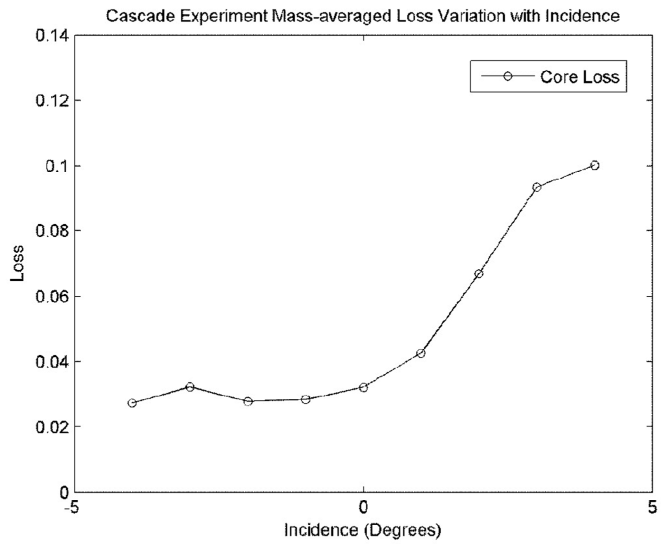
3D Core Loss – Measured – Low Speed Cascade



- 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

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Separation Control on Intakes in Cross Winds

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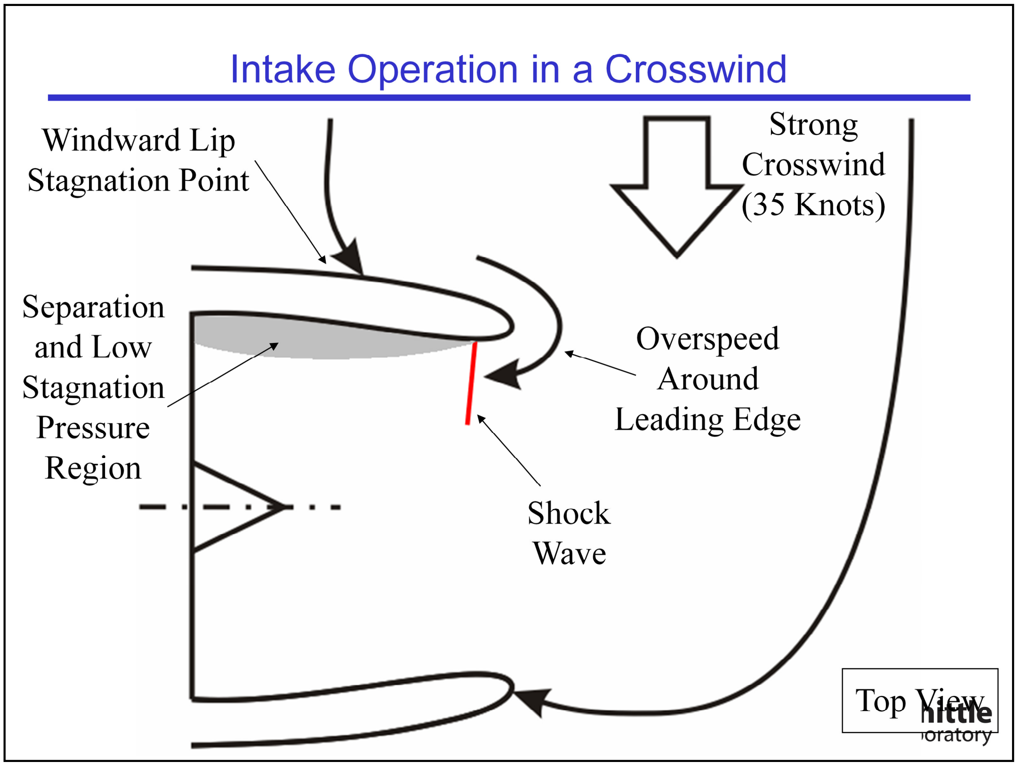
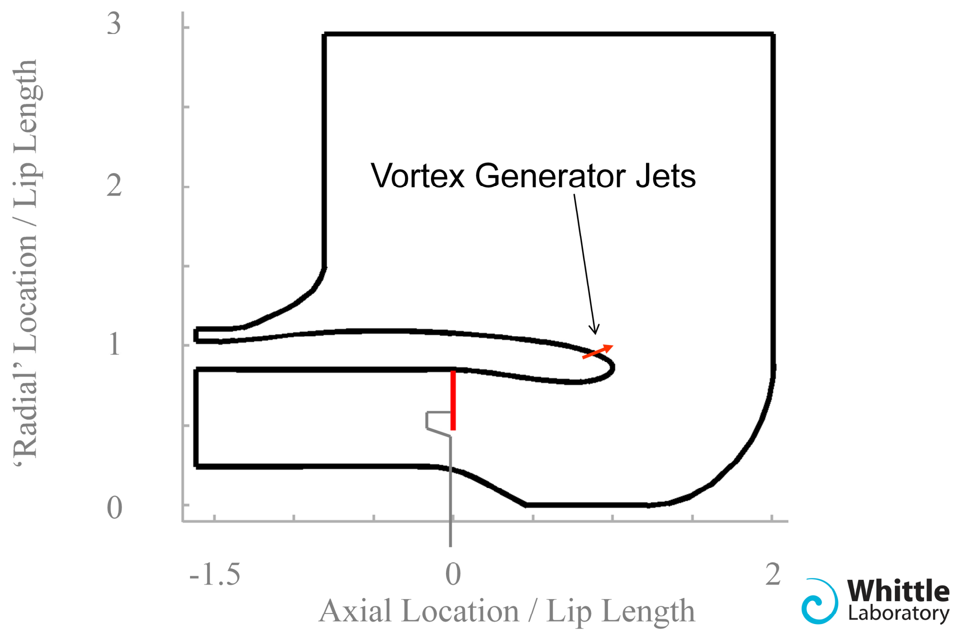
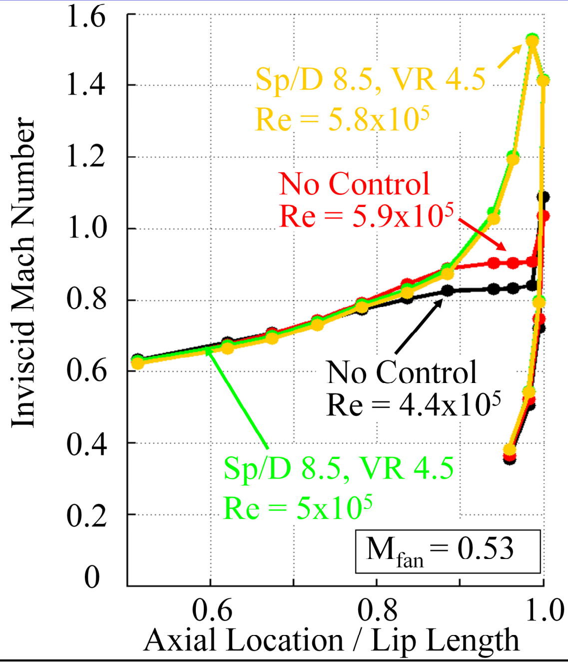
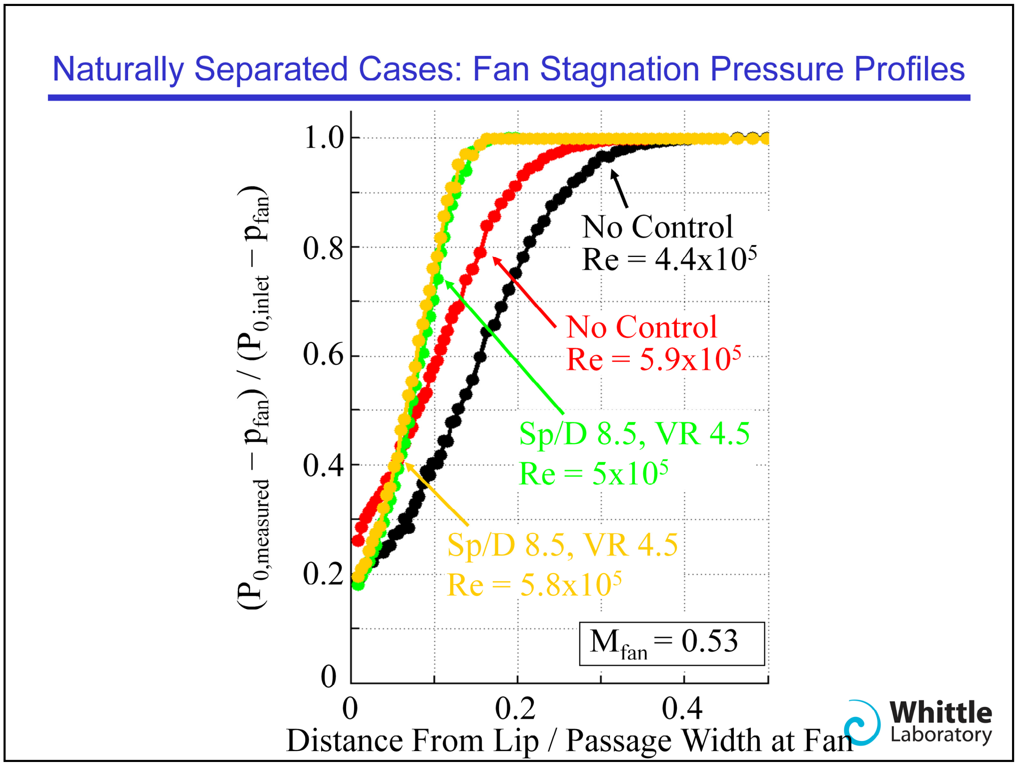

Intake Operation in a Crosswind
Windward Lip Stagnation Point
Strong Crosswind (35 Knots)
Separation and Low Stagnation Pressure Region
Overspeed Around Leading Edge
Shock Wave
Top View

Sector Rig Fan Face Traverses



Lip Mach Number Distribution





Naturally Separated Cases: Fan Stagnation Pressure Profiles
(P0,measured − pfan) / (P0,inlet − pfan)
1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
Distance From Lip / Passage Width at Fan
No Control
Re = 4.4x10^5
No Control
Re = 5.9x10^5
Sp/D 8.5, VR 4.5
Re = 5x10^5
Sp/D 8.5, VR 4.5
Re = 5.8x10^5
Mfan = 0.53
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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

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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

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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

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