Flow Control on Low-Pressure Turbine Airfoils Using Vortex Generator Jets

Ralph J. Volino
United States Naval Academy
Annapolis, MD

Mounir B. Ibrahim and Olga Kartuzova
Cleveland State University
Cleveland, OH

Minnowbrook VI
August 25, 2009

Sponsor: NASA
Outline

- Background
- Facility
- Results
  - Baseline
  - Vortex Generator Jets
  - Unsteady Wakes
- Conclusions
Background

- Motivation – Higher loading on Low-Pressure Turbine (LPT) airfoils
  - Reduce airfoil count, weight, cost
  - Increase efficiency
  - Limited by suction side separation

- Growing understanding of transition, separation, wake effects
  - Improved models (e.g. Transition-sst, Menter et al., 2006)
  - Take advantage of wakes (e.g. turbulent strips suppress separation)
  - Higher lift airfoils in use

- Further loading increases may require flow control
  - Passive: trips, dimples, etc.
  - Active: plasma actuators, vortex generator jets (VGJs)
  - Can increased loading offset higher losses on high lift airfoils?

- Objectives
  - Advance knowledge of boundary layer separation and transition under LPT conditions
  - Demonstrate, improve understanding of separation control with pulsed VGJs
  - Produce detailed experimental data base
  - Test and develop computational models
Fine screen visible at end of contraction to break up boundary layers and give clean uniform flow into cascade.

Screen replaced by grid for high FSTI cases.

Grid is sheet metal with ¾" square holes spaced 1" apart for 56% open area.

Solenoid valves visible below test section for pulsed jets. Tubes connect to six of the blades.
Holes 0.8 mm dia., spacing about 10 diameter apart.
Angles at 90 degrees to main flow and 30 degrees to surface.
Same jet geometry in present study.

Jets located near the inviscid pressure minimum. Same in present study.
Wake Generator

Click to play animation
filename: 04MOV00477.mpg

Click to play animation
filename: 04MOV00473.mpg and 04MOV00476.mpg

Click to play animation
filename: 04MOV00474.mpg and 04MOV00475.mpg
Conditions

- Freestream turbulence
  TI=0.5%, 4% (integral scale ~0.1Cv)

- VGJ blowing ratio
  B=0.25 – 3.0

- Pulsing frequency
  f=0, 3, 6, 12, 24, 48 Hz
  F=fL/te/Uave=0 – 1.12

- Jet duty cycle
  D=10%, 50%

<table>
<thead>
<tr>
<th>Re=UeL/ν</th>
<th>Re=Uce/ν</th>
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</thead>
<tbody>
<tr>
<td>Exit velocity</td>
<td>Inlet velocity</td>
</tr>
<tr>
<td>Suction surface length</td>
<td>Axial chord</td>
</tr>
<tr>
<td>25,000</td>
<td>10,070</td>
</tr>
<tr>
<td>50,000</td>
<td>20,150</td>
</tr>
<tr>
<td>100,000</td>
<td>40,290</td>
</tr>
<tr>
<td>150,000</td>
<td>60,440</td>
</tr>
<tr>
<td>200,000</td>
<td>80,580</td>
</tr>
<tr>
<td>300,000</td>
<td>120,880</td>
</tr>
</tbody>
</table>
Separation clear at lower Re.
High Re cases show only small separation bubble at s/Ls=0.6, which gets slightly worse as Re drops.
Integrated Cp shows lower lift in separated flow cases.
Do not see large bubble with reattachment in cases such as Re=100,000, as was observed in Pack B studies.
Measured with Kiel probe traversed at midspan 0.6 Cx downstream of trailing edges.

Three highest Re cases show low total pressure loss with almost zero loss between wakes.

At high Re, wakes are in expected positions downstream of blades based on design exit flow angle.

At low Re, separation results in much higher losses and shift of wake to left since flow is not turning as much.

Good periodicity in attached flow cases. Not as good for low Re since tailboard suppresses separation more on closer blades.

Integrated losses for center blade shown in upper right.
Similar behavior at Re=50,000, but transition moves somewhat upstream and is clearer in the intermittency profiles.
Still does not reattach.
Peak in spectra at station 3 is clear.
Small separation, but clearly reattached downstream.
Rms $u'$ peak close to wall.
CFD Predictions

- Most models fail to predict separation
  - Standard k-ε, realizable k-ε, etc.
- A few more successful
  - k-ω SST (Menter, 1994)
  - v2-f (Durbin, 1995)
  - Transition-sst (Menter et al., 2006)
- Transition-sst best
  - Predicts Cp, ψ, velocity, turbulence, transition correctly

Re=100,000

Re=25,000

Re=100,000

Re=300,000
VGJ results

Jet Velocity

- Measured with hot-wire
- $B = \frac{V_{jet}}{V_{freestream}}$
- $V_{jet}$ at jet centerline
- $V_{freestream}$ is local value
- $B$ based on max in cycle

With $B=1$ and steady jets, jet volume flow is 0.04% of main flow

GT2009-59983
Integrated total pressure loss

Low TI
Re=25,000
Re=50,000

High TI
Re=25,000
Re=50,000

Click to play animation

filename: 04bc50f24d10b050.avi
Phase Averaged Velocity, \( Re=25,000, F=0.28, B=1.0 \)

10% Duty Cycle

50% Duty Cycle

\( \nu/T \)

Streamwise station

VGJs most effective when turning on and off

Attached
CFD Predictions

URANS with Transition-sst model fails to capture VGJ effect

LES produces better results but at higher cost

Comparison of experimental (E) and CFD (Cp profiles for Re=50,000 cases

\[ F = 0.56 \]
\[ D = 10\% \]
\[ B = 0.5 \]
Wake results

Rod wake at cascade inlet and airfoil wakes downstream of cascade w/o VGJ's

Re=50,000

Rod wake at cascade inlet and phase averaged airfoil wakes downstream of cascade with VGJ flow control

Re=50,000

Mean Velocity

RM3 streamwise velocity
Wake spectra

- Cascade wake with VGJ8
- Cascade wake with VCLI flow control
- Rod wake

Click to play animation

filename: 04ws50f24d10b100.avi
Pressure results

- Expected wake $F=0.20$
- Partially suppresses separation at $Re=25000$
- More affect at higher $Re$
- Lower $F$ insufficient at $Re=50000$ and below
- Higher $F$ suppresses separation more, VQJe in combination with wakes may be helpful
Phase Averaged Velocity, $F=0.28$

Re=25,000

Re=50,000
Conclusions

- Burst bubble at low Re w/o flow control
  - 20% lower lift
  - 7 times higher total pressure loss
  - Transition does not always cause reattachment
  - Transition-sst model provides good prediction
- VGJs control separation, pulsed better than steady
  - 20% increase in lift, 60% reduction in loss possible
  - F=0.14 generally too low
  - F=0.28 marginal, depends on Re, higher duty cycle helps
  - \( \Gamma = 0.56 \) good even with low D≤1 and 10% duty cycle
  - URANS w/ Transition-sst model not predicting jet effect
  - LES simulations generally agree with experiments
- Wakes help suppress separation as expected
  - Still room for improvement with flow control
- Upcoming work
  - More with wakes
  - Combined wakes and VG Js
  - Further attempts to predict with URANS