

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

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Sponsor:





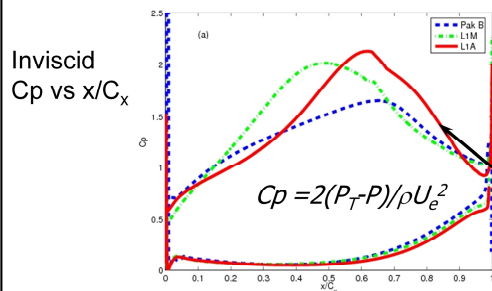
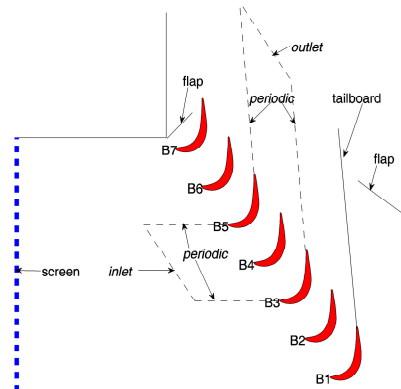
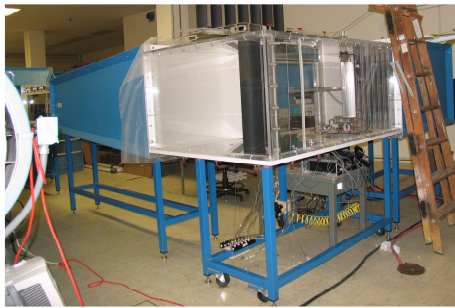
# Outline

- 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

## Facility: Low Speed Wind Tunnel with Cascade



### L1A Airfoil

- AFRL design (John Clark)
- 17% higher Zweifel than Pack B
- Aft loaded
- Strong adverse pressure gradient

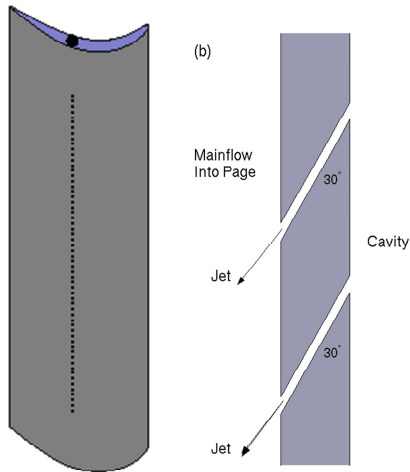
Fine screen visible at end of contraction to break up boundary layers and give clean uniform flow into cascade.

Screen replaced by grid for high FSTI cases.

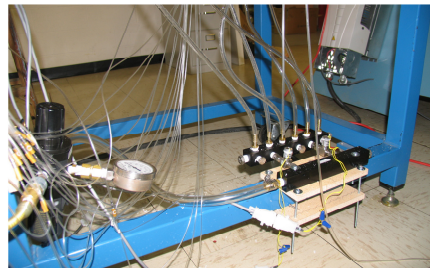
Grid is sheet metal with  $\frac{3}{4}$ " square holes spaced 1" apart for 56% open area.

Solenoid valves visible below test section for pulsed jets. Tubes connect to six of the blades.

# VGJs



- On all blades in cascade
- Located at suction peak
- 0.0059  $C_x$  diameter
- Spacing = 10.7D
- Compound Angle
  - 30° to surface
  - 90° to main flow
- Supplied from cavity in blade
- Solenoid valves for pulsing



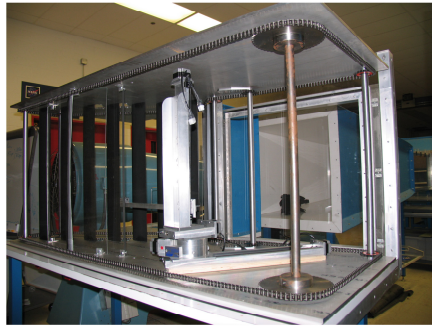
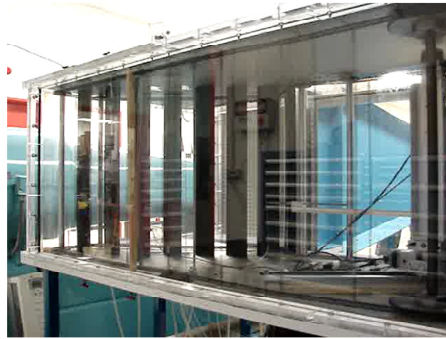
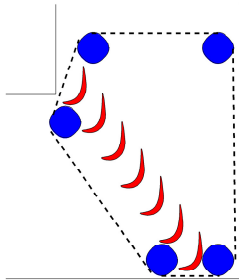
Holes 0.8 mm dia., spacing about 10 diameter apart.

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](#)

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[Click to play animation](#)

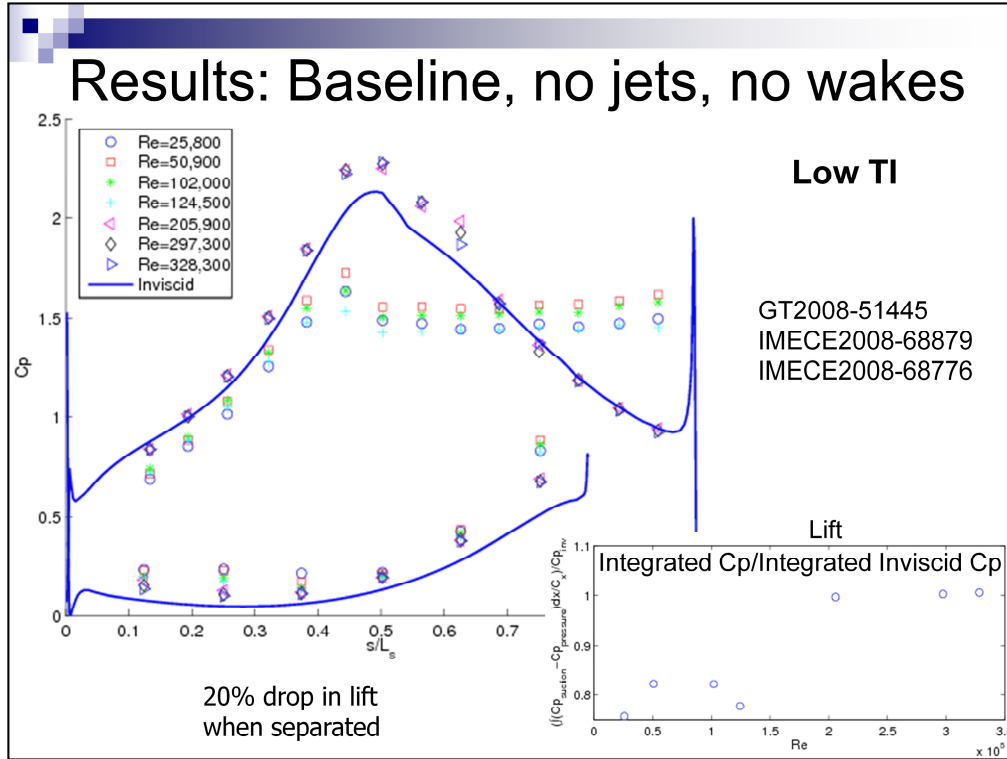
[Click to play animation](#)

filename: 04MOV00474.mpg and 04MOV00475.mpg

# Conditions

- Freestream turbulence  
TI=0.5%, 4% (integral scale  $\sim 0.1C_x$ )
- VGJ blowing ratio  
B=0.25 – 3.0
- Pulsing frequency  
f=0, 3, 6, 12, 24, 48 Hz  
 $F=fL_{j-te}/U_{ave}=0 - 1.12$
- Jet duty cycle  
D=10%, 50%

$Re=U_e L_s/\nu$ Exit velocity Suction surface length	$Re=U_i C_x/\nu$ Inlet velocity Axial chord
25,000	10,070
50,000	20,150
100,000	40,290
150,000	60,440
200,000	80,580
300,000	120,880



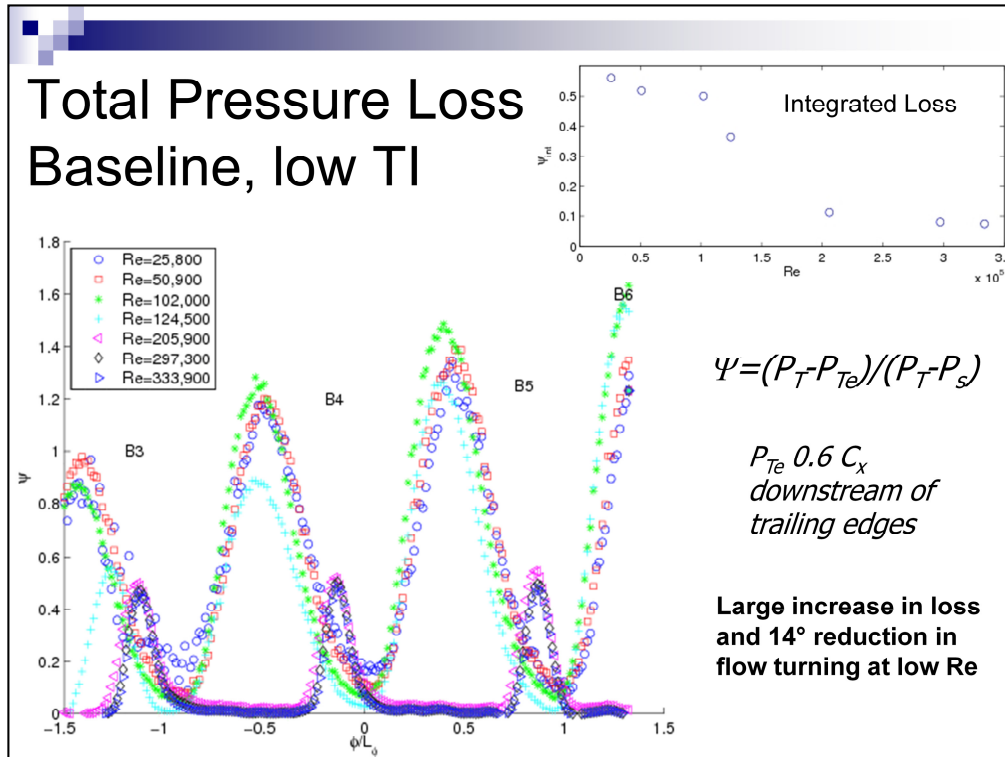
Separation clear at lower Re.

High Re cases show only small separation bubble at  $s/L_s=0.6$ , 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  $0.6 C_x$  downstream of trailing edges.

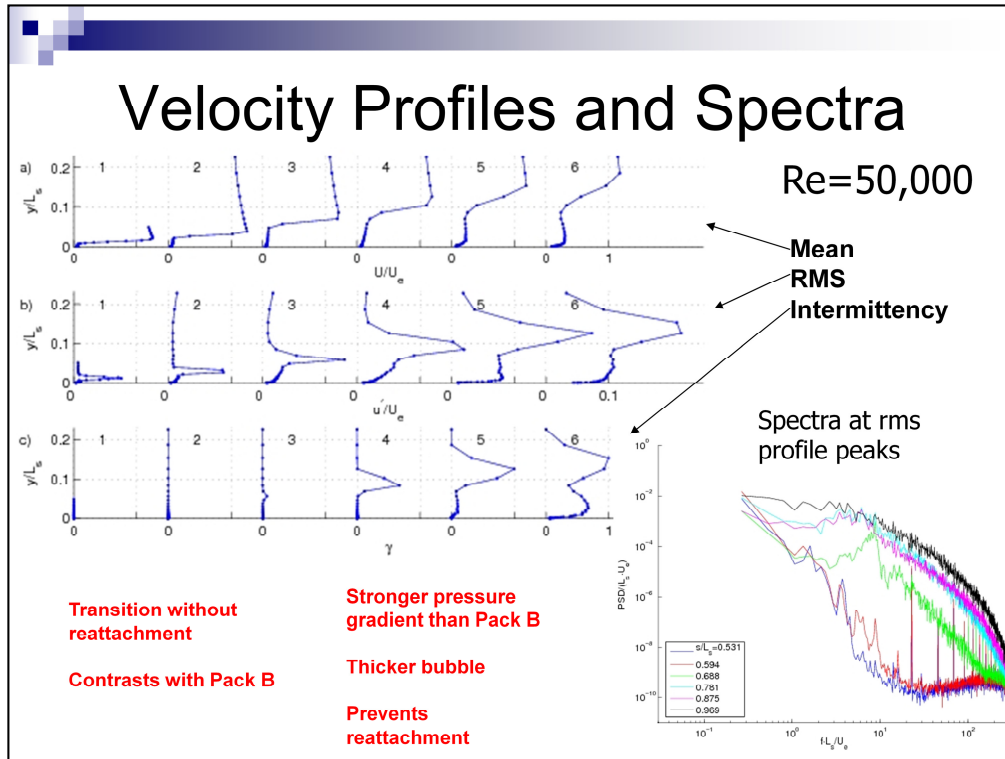
Three highest Re cases show low total pressure loss with almost zero loss between wakes.

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.

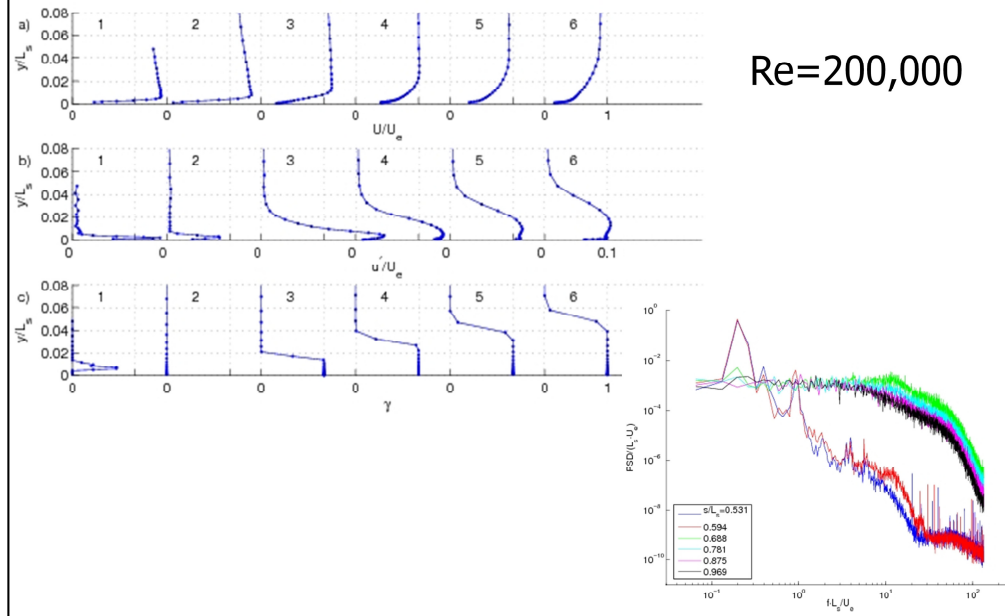


Similar behavior at Re=50,000, but transition moves somewhat upstream and is clearer in the intermittency profiles.

Still does not reattach.

Peak in spectra at station 3 is clear.

# Velocity Profiles and Spectra

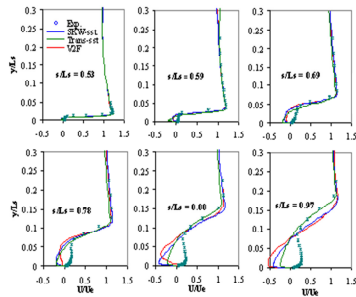


Small separation, but clearly reattached downstream.

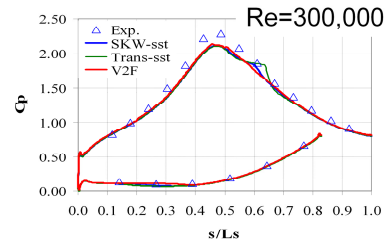
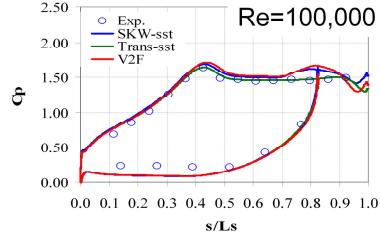
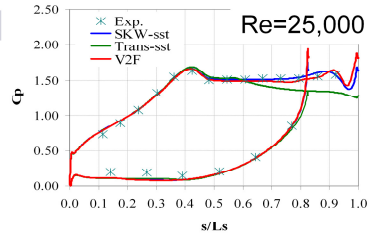
Rms  $u'$  peak close to wall.

# CFD Predictions

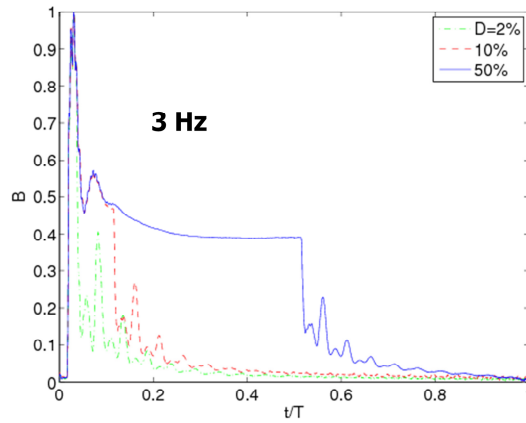
- Most models fail to predict separation
  - Standard k- $\epsilon$ , realizable k- $\epsilon$ , etc.
- A few more successful
  - k- $\omega$  sst (Menter, 1994)
  - v2-f (Durbin, 1995)
  - Transition-sst (Menter et al., 2006)
- Transition-sst best
  - Predicts  $C_p$ ,  $\psi$ , velocity, turbulence, transition correctly



Re=100,000



# VGJ results



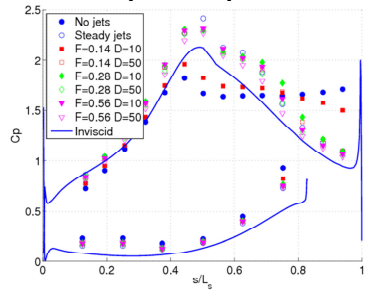
## Jet Velocity

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

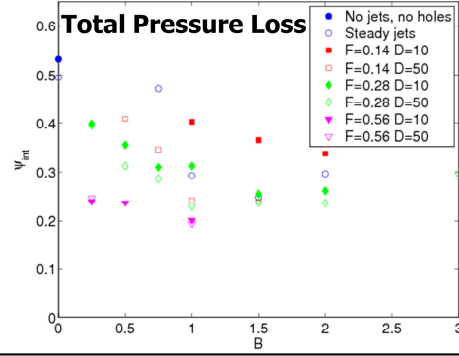
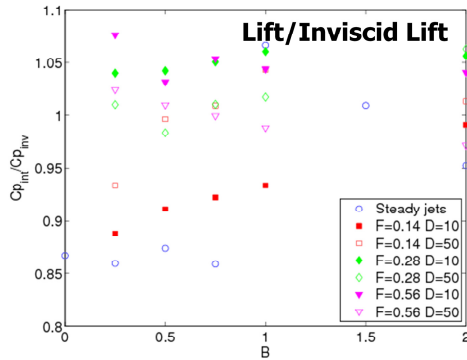
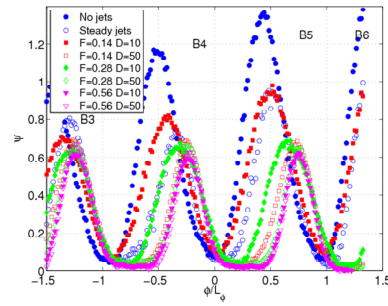
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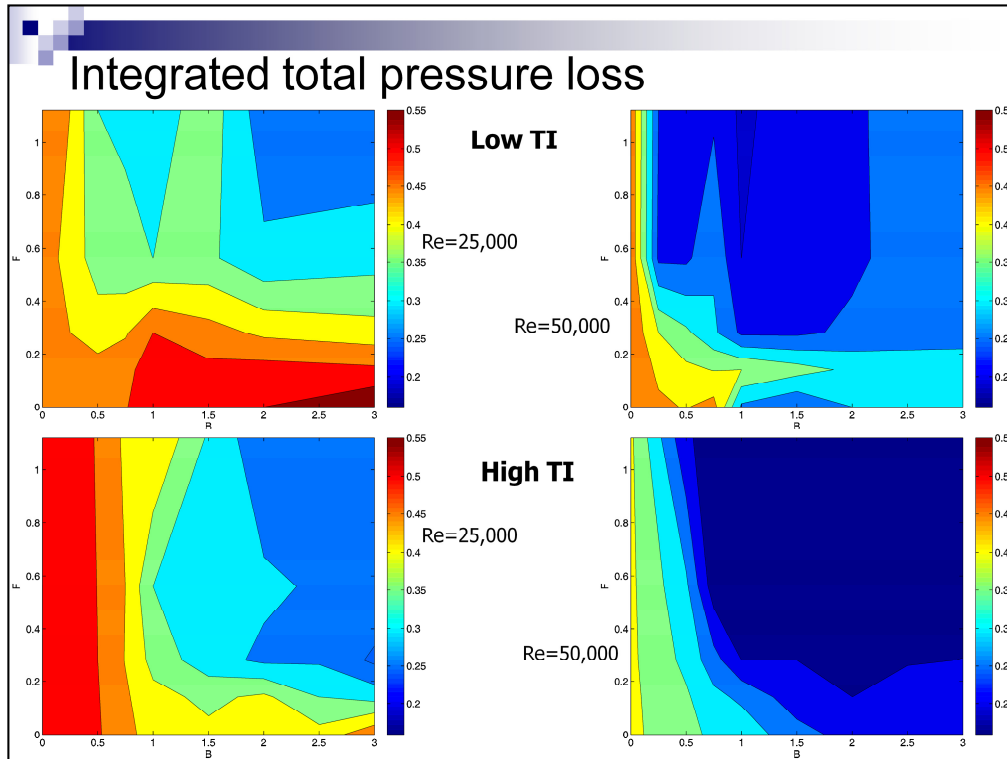
**With  $B=1$  and steady jets,  
jet volume flow is 0.04% of main flow**

# Re=50,000, Low TI



B=1



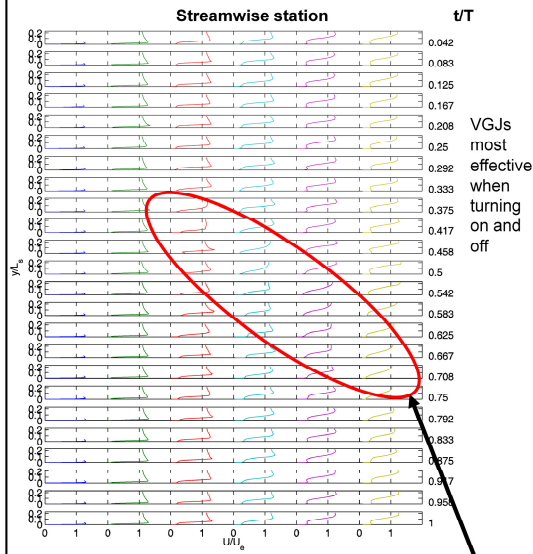


[Click to play animation](#)

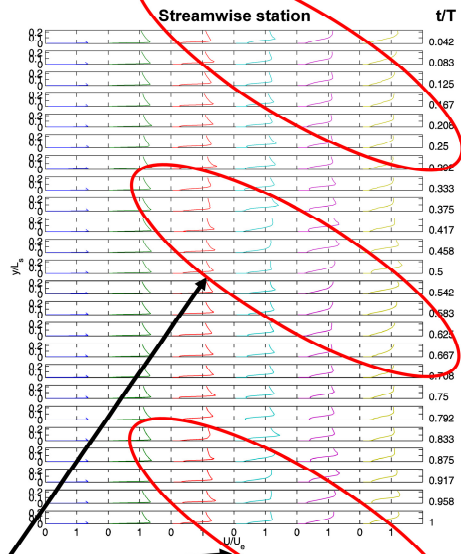
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Phase Averaged Velocity,  $Re=25,000$ ,  $F=0.28$ ,  $B=1.0$

10% Duty Cycle

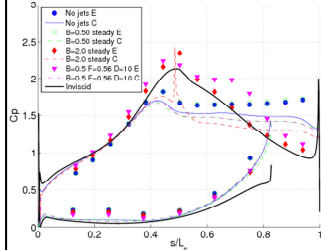


50% Duty Cycle

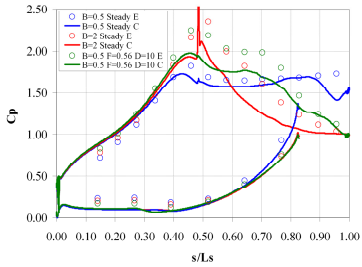




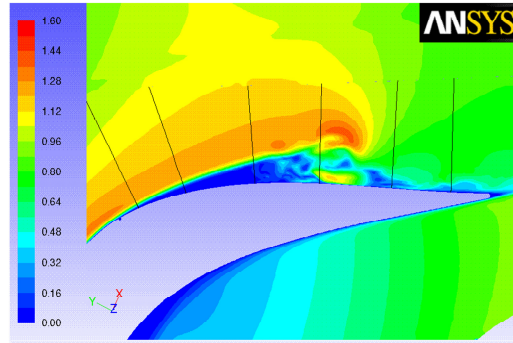
# CFD Predictions



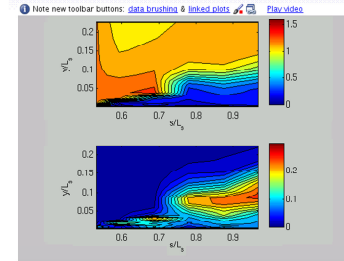
URANS with Transition-sst model fails to capture VGJ effect



LES produces better results but at higher cost



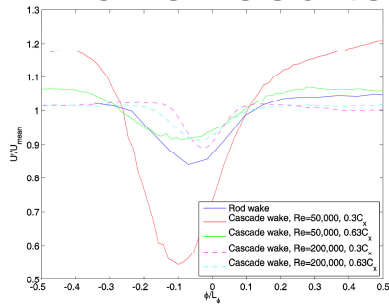
Contours of u-over-ue (Time=2.4131e+00) Apr 30, 2009



**F=0.56**  
**D=10%**  
**B=0.5**

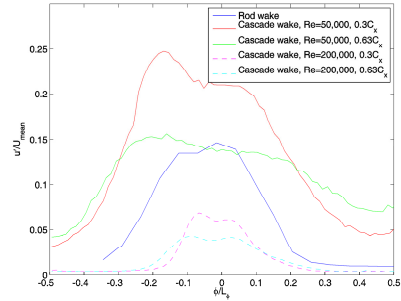
Comparison of experimental (E) and CFD (C) Cp profiles for Re=50,000 cases

# Wake results

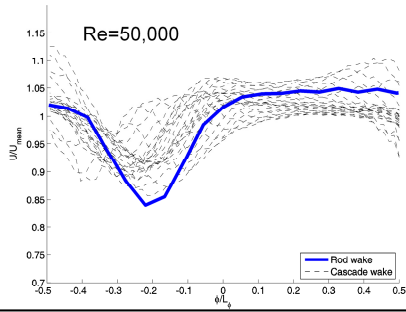


Mean Velocity

Rod wake at cascade inlet and airfoil wakes downstream of cascade w/o VGJs

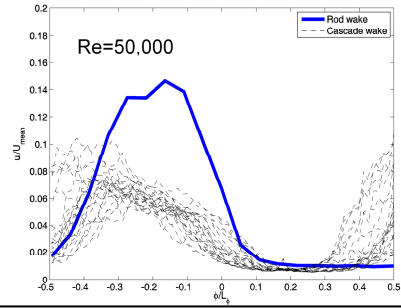


RMS streamwise velocity



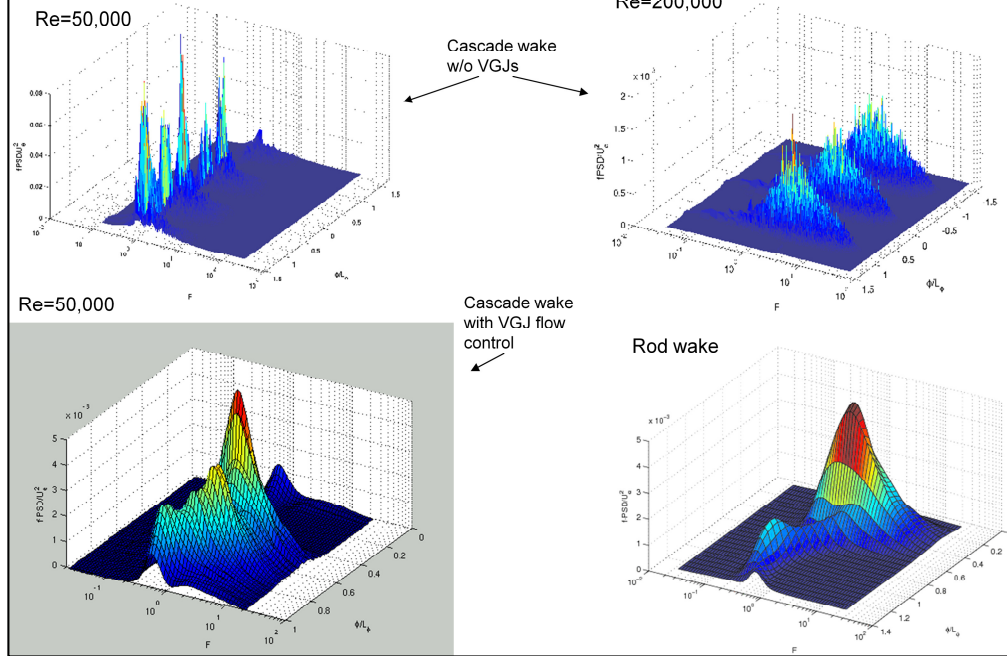
Re=50,000

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



Re=50,000

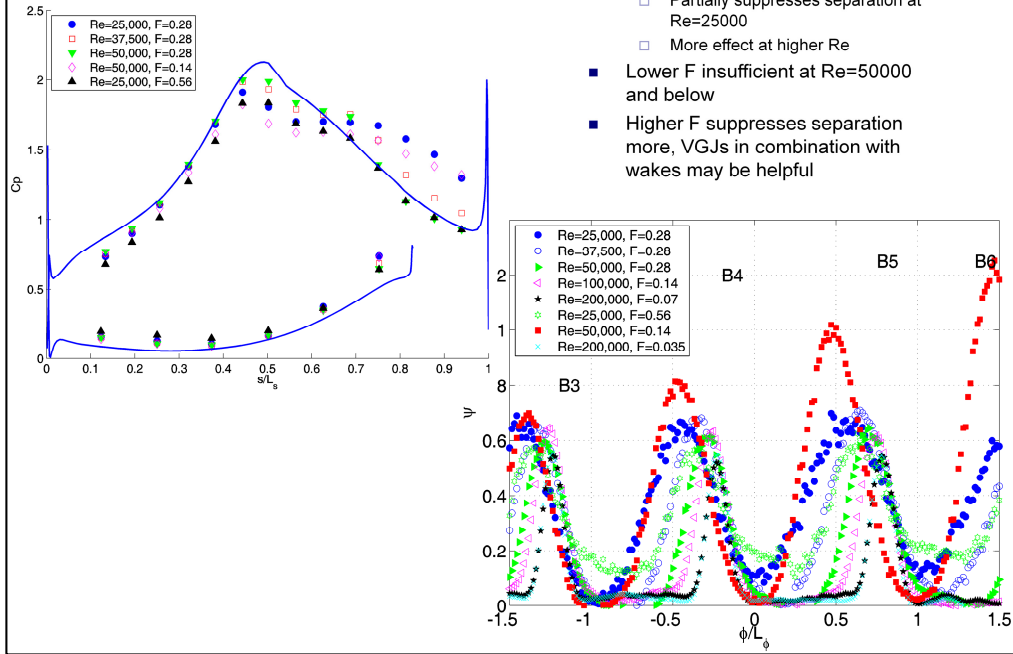
# Wake spectra



[Click to play animation](#)

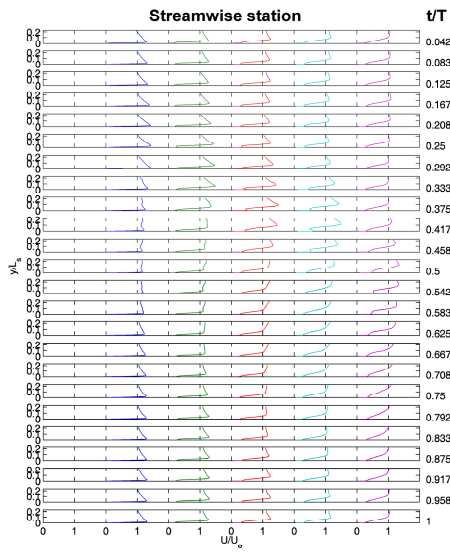
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# Pressure results

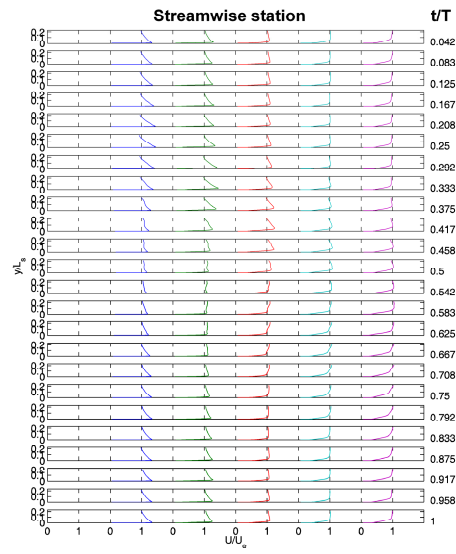


# Phase Averaged Velocity, $F=0.28$

## 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
  - $F=0.56$  good even with low  $B \leq 1$  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 VGJs
  - Further attempts to predict with URANS