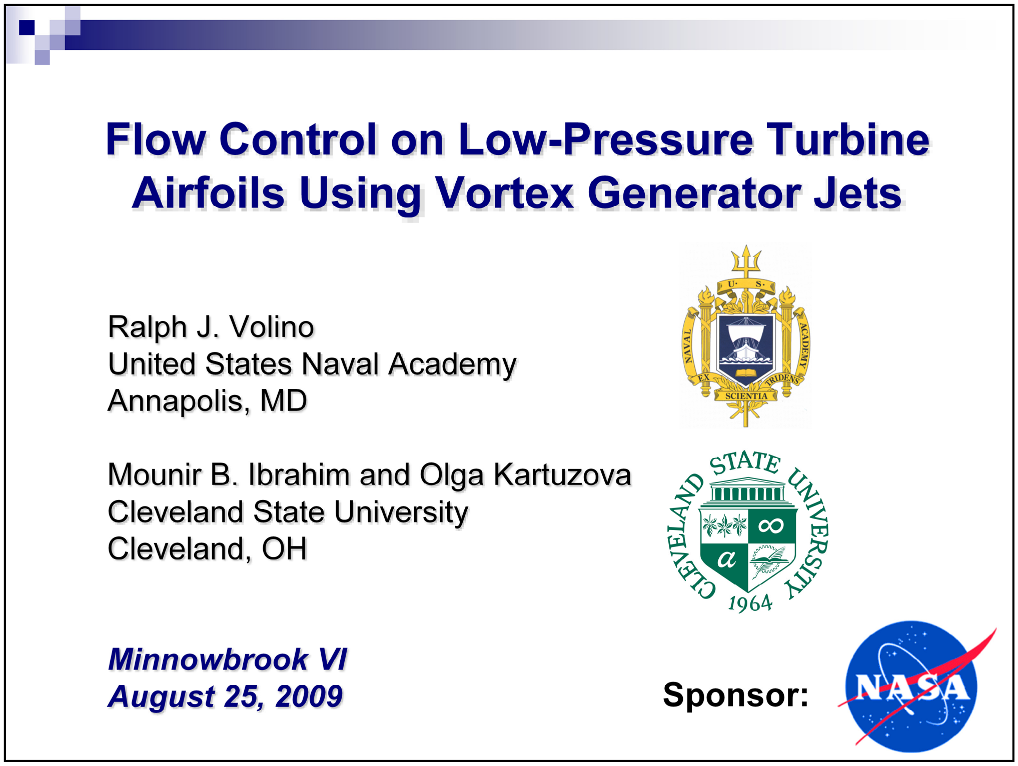

Flow Control on Low-Pressure Turbine Airfoils Using Vortex Generator Jets

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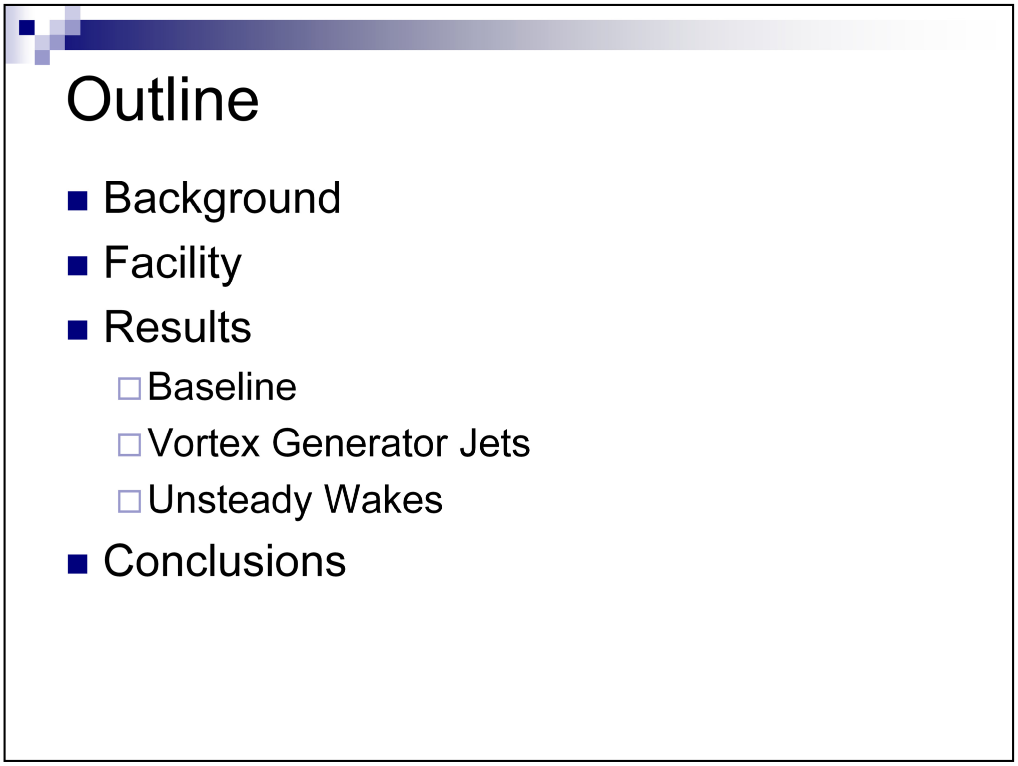
Minnowbrook VI
August 25, 2009

Sponsor:



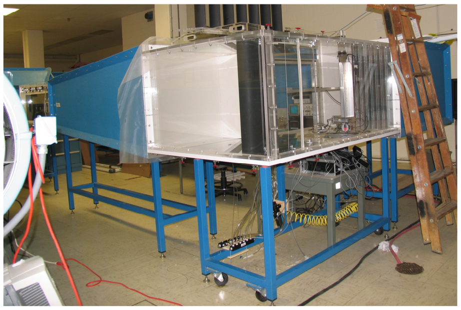
Outline

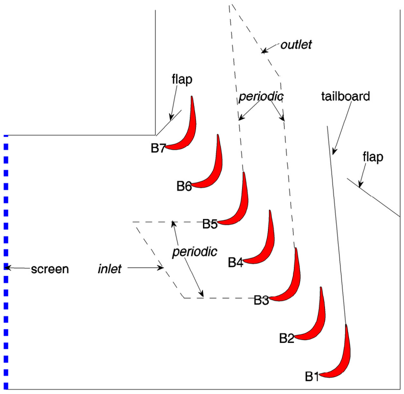
- Background
- Facility
- Results
  - ☐ Baseline
  - ☐ Vortex Generator Jets
  - ☐ Unsteady Wakes
- Conclusions

Background

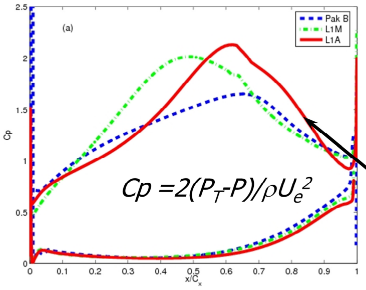
- Motivation – Higher loading on Low-Pressure Turbine (LPT) airfoils
  - Reduce airfoil count, weight, cost
  - Increase efficiency
  - Limited by suction side separation
- Growing understanding of transition, separation, wake effects
  - Improved models (e.g. Transition-sst, Menter et al., 2006)
  - 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





Inviscid
Cp vs x/C_x



$Cp = 2(P_T - P)/\rho U_e^2$

L1A Airfoil

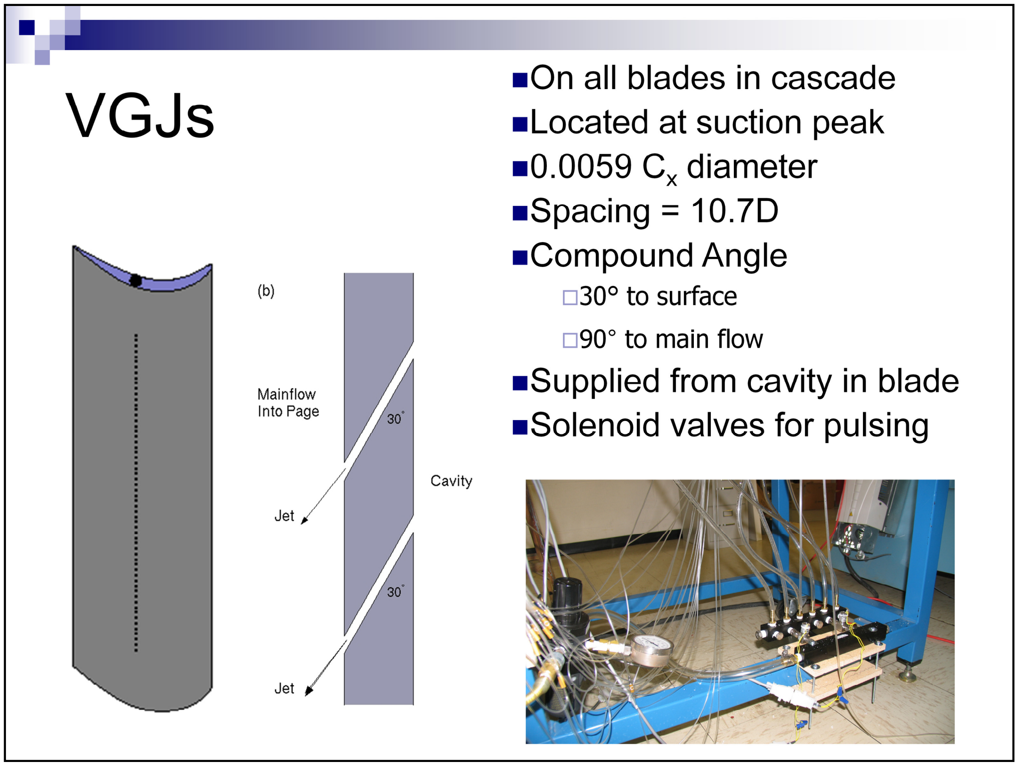
- AFRL design (John Clark)
- 17% higher Zweifel than Pack B
- Aft loaded
- Strong adverse pressure gradient

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 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.

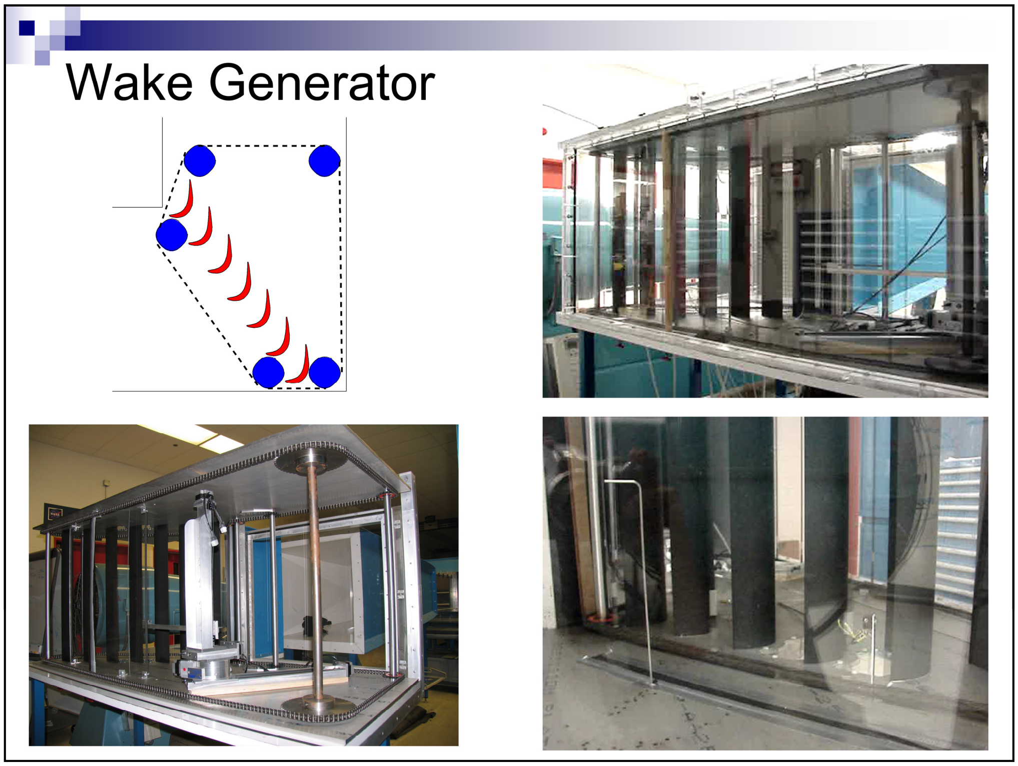


VGJs

- 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

filename: 04MOV00477.mpg

Click to play animation

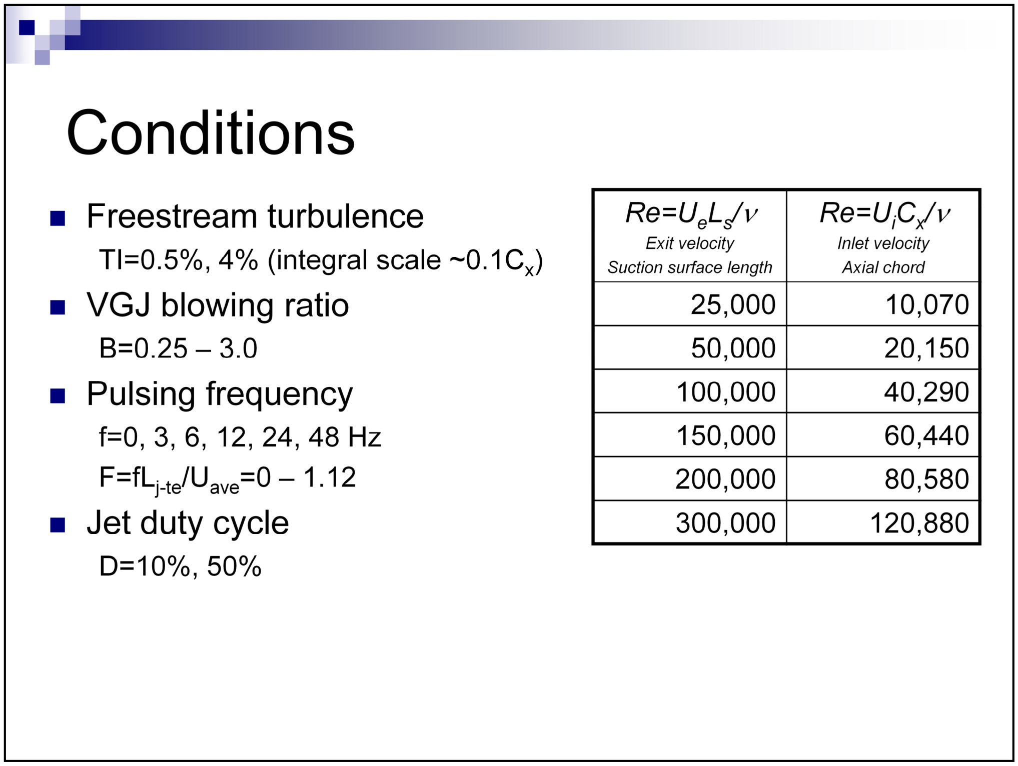
Click to play animation

filename: 04MOV00473.mpg and 04MOV00476.mpg

Click to play animation

Click to play animation

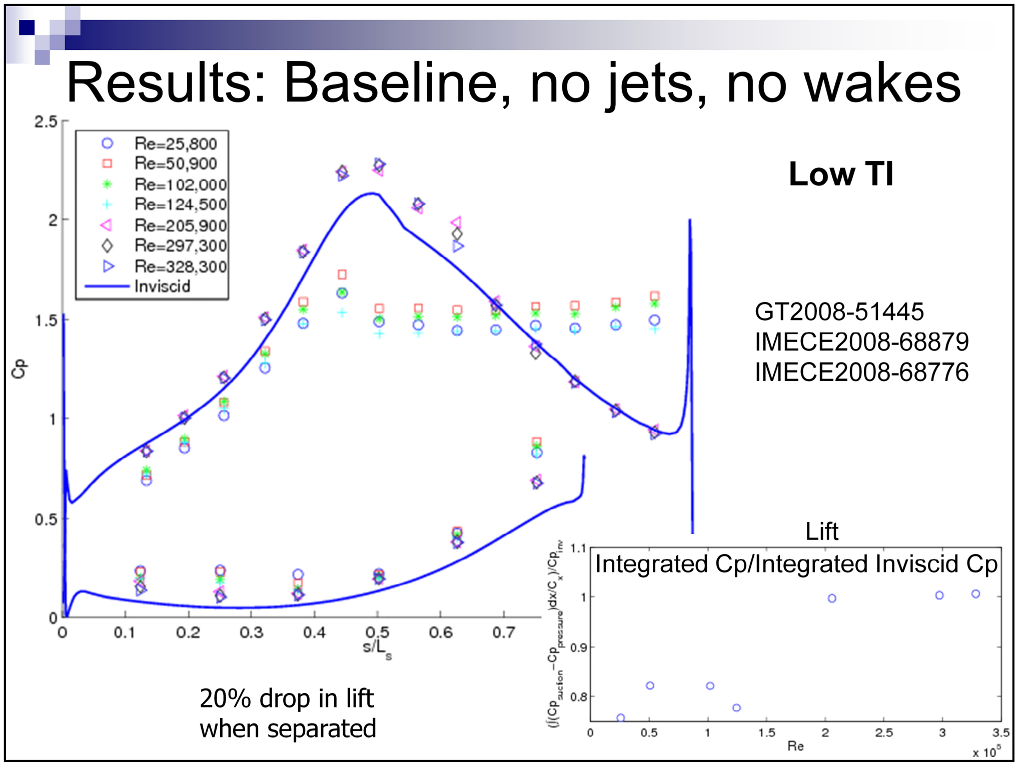
filename: 04MOV00474.mpg and 04MOV00475.mpg



Conditions

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

$Re=U_eL_s/\nu$ *Exit velocity* *Suction surface length*	$Re=U_iC_x/\nu$ *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



Results: Baseline, no jets, no wakes

Low TI

GT2008-51445
IMECE2008-68879
IMECE2008-68776

Lift

Integrated Cp/Integrated Inviscid Cp

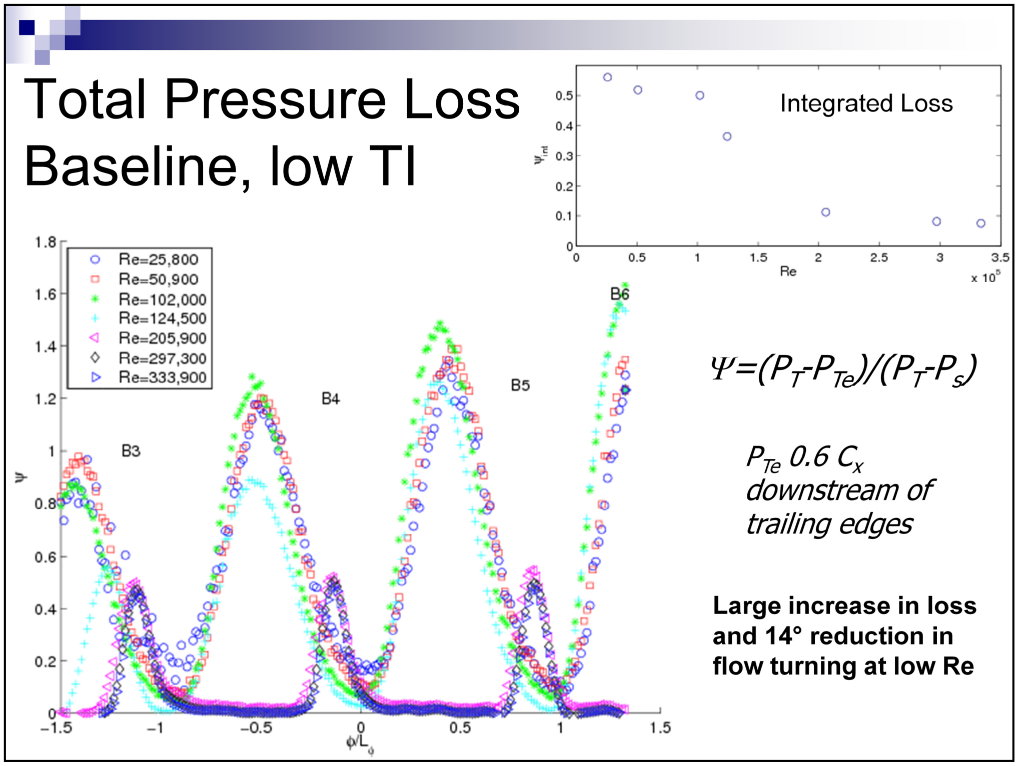
20% drop in lift
when separated

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.



Total Pressure Loss Baseline, low TI

$\Psi=(P_T-P_{Te})/(P_T-P_s)$

P_{Te} 0.6 C_x downstream of trailing edges

Large increase in loss and 14° reduction in flow turning at low Re

Measured with Kiel probe traversed at midspan 0.6 Cx downstream of trailing edges.

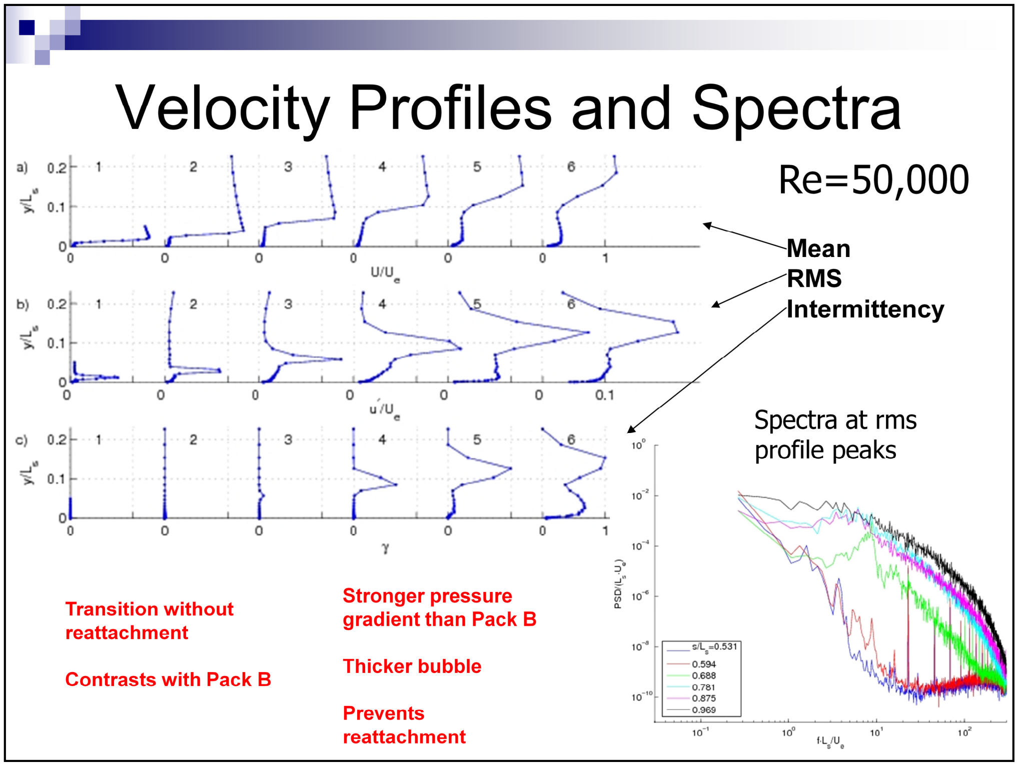
Three highest Re cases show low total pressure loss with almost zero loss between wakes.

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.



Velocity Profiles and Spectra

Re=50,000

Mean
RMS
Intermittency

Spectra at rms profile peaks

Transition without reattachment

Contrasts with Pack B

Stronger pressure gradient than Pack B

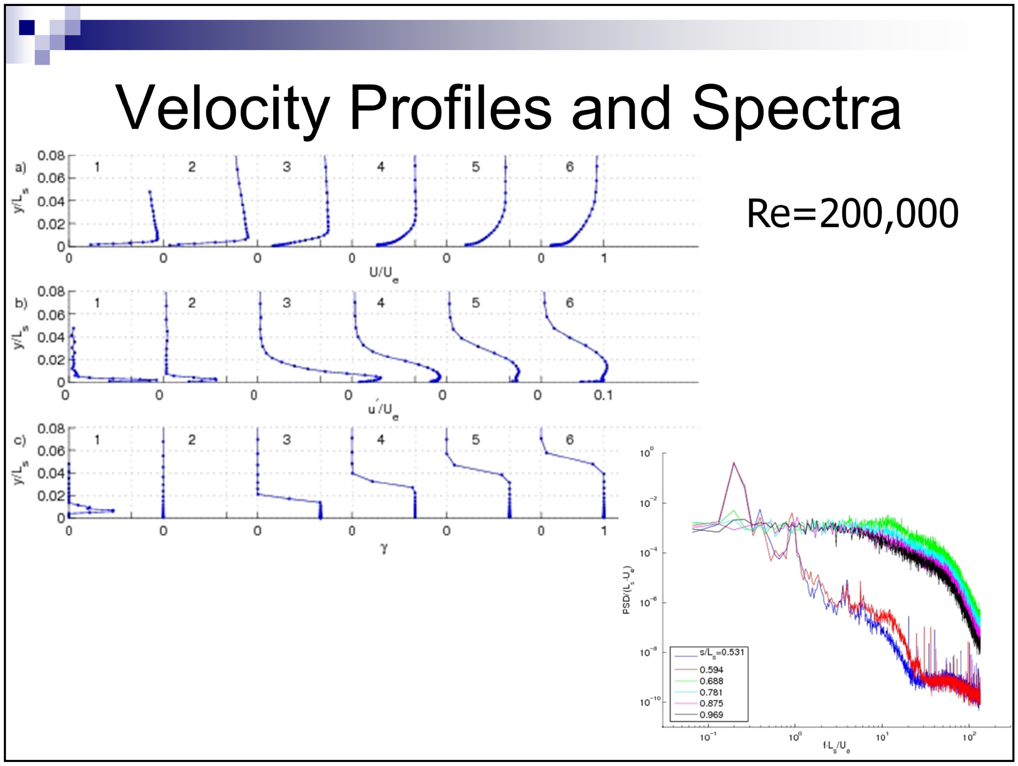
Thicker bubble

Prevents reattachment

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

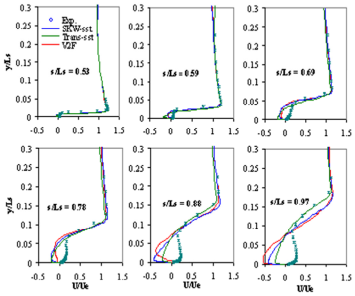
Re=200,000

Small separation, but clearly reattached downstream.

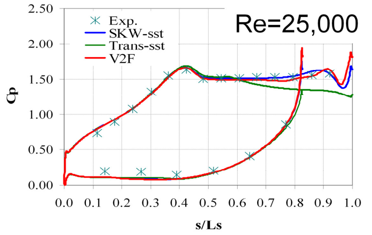
Rms u' peak close to wall.

CFD Predictions

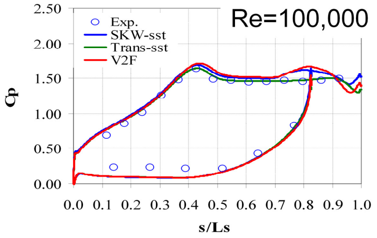
- Most models fail to predict separation
  - ☐ Standard k-ε, realizable k-ε, etc.
- A few more successful
  - ☐ k-ω sst (Menter, 1994)
  - ☐ v2-f (Durbin, 1995)
  - ☐ Transition-sst (Menter et al., 2006)
- Transition-sst best
  - ☐ Predicts Cp, ψ, velocity, turbulence, transition correctly



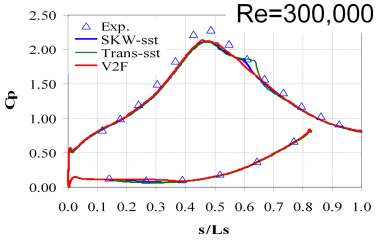
Re=100,000



Re=25,000

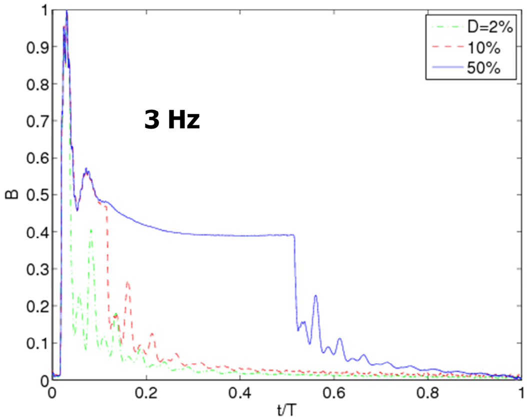


Re=100,000



Re=300,000

VGJ results



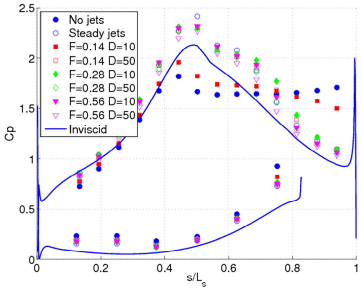
Jet Velocity

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

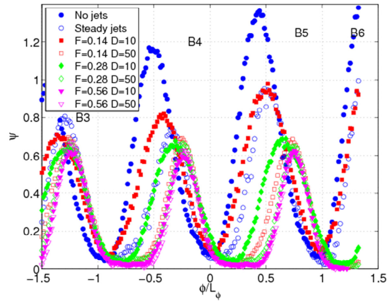
GT2009-59983

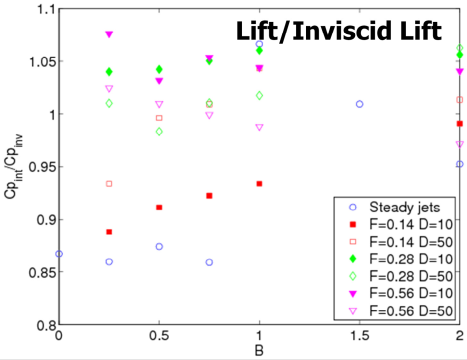
With B=1 and steady jets,
jet volume flow is 0.04% of main flow

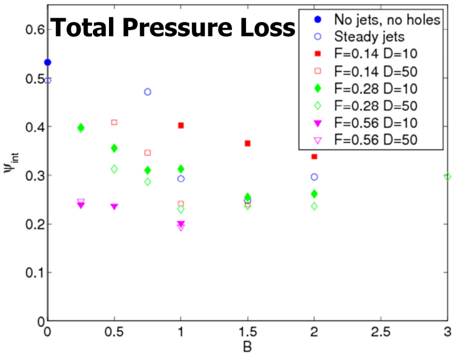
Re=50,000, Low TI

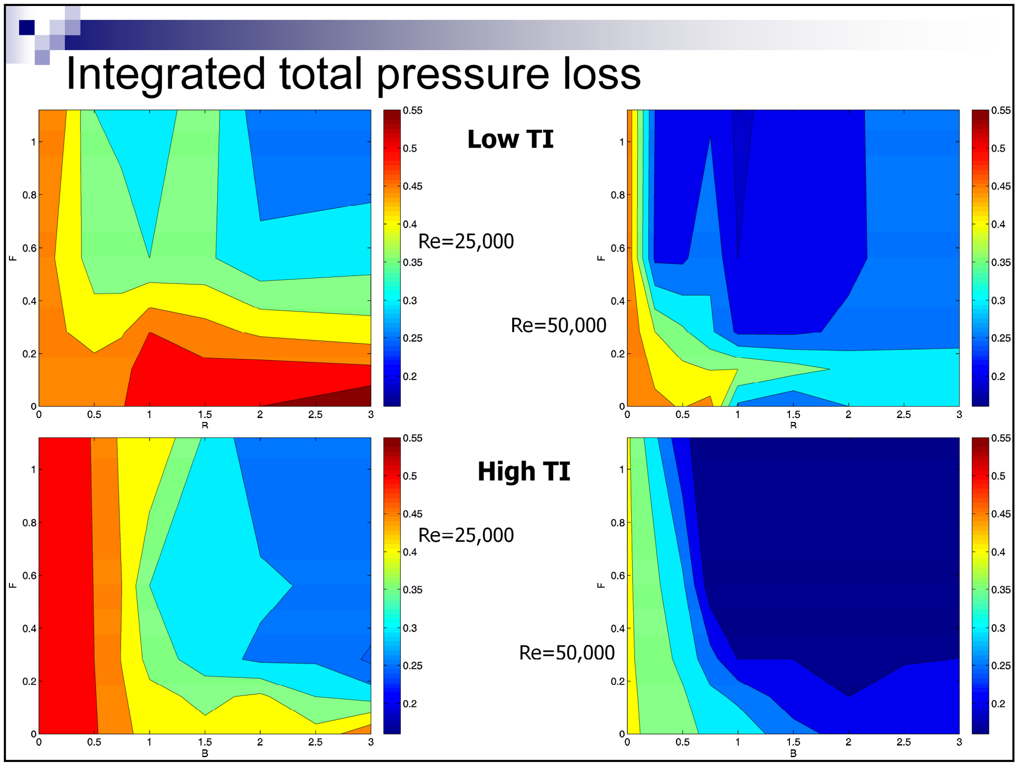


B=1









Integrated total pressure loss

Low TI

Re=25,000

Re=50,000

High TI

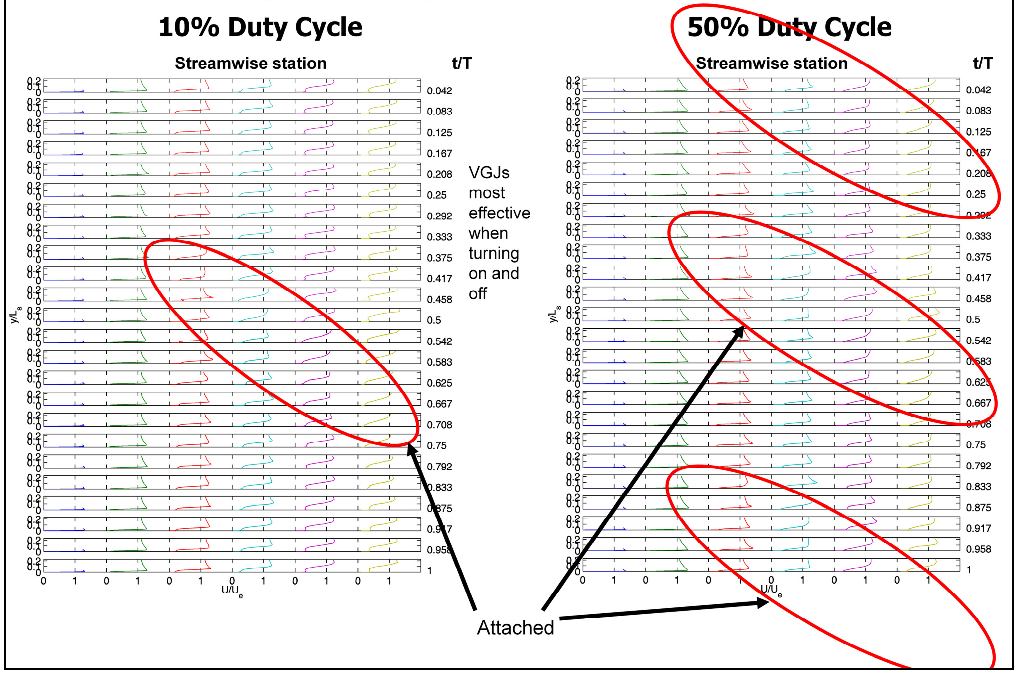
Re=25,000

Re=50,000

Click to play animation

filename: 04bc50f24d10b050.avi

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



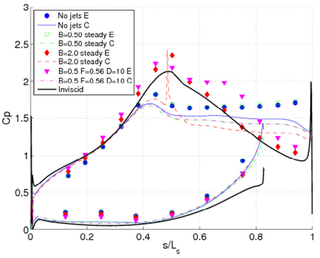
10% Duty Cycle

50% Duty Cycle

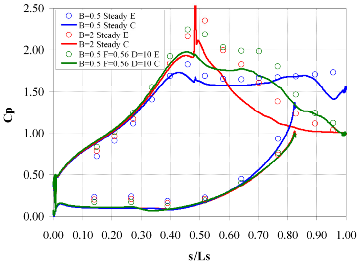
VGJs most effective when turning on and off

Attached

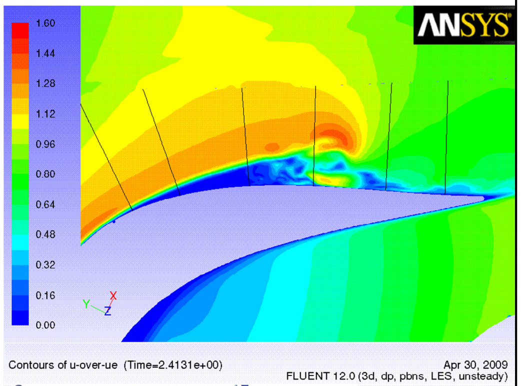
CFD Predictions



URANS with Transition-sst model fails to capture VGJ effect



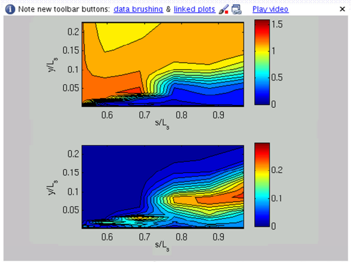
LES produces better results but at higher cost



Contours of u-over-ue (Time=2.4131e+00)

Apr 30, 2009

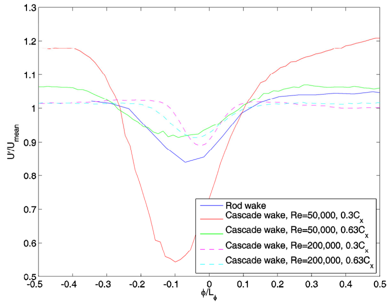
FLUENT 12.0 (3d, dp, pbns, LES, unsteady)



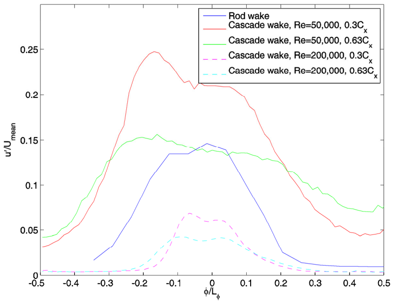
F=0.56
D=10%
B=0.5

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

Wake results

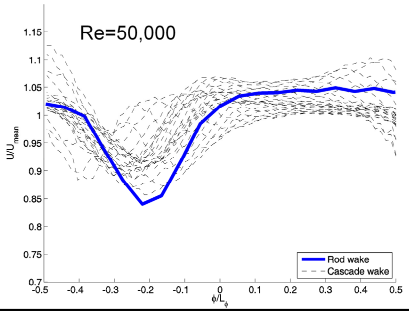


Rod wake at cascade inlet and airfoil wakes downstream of cascade w/o VGJs

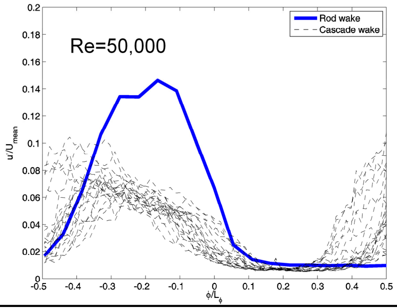


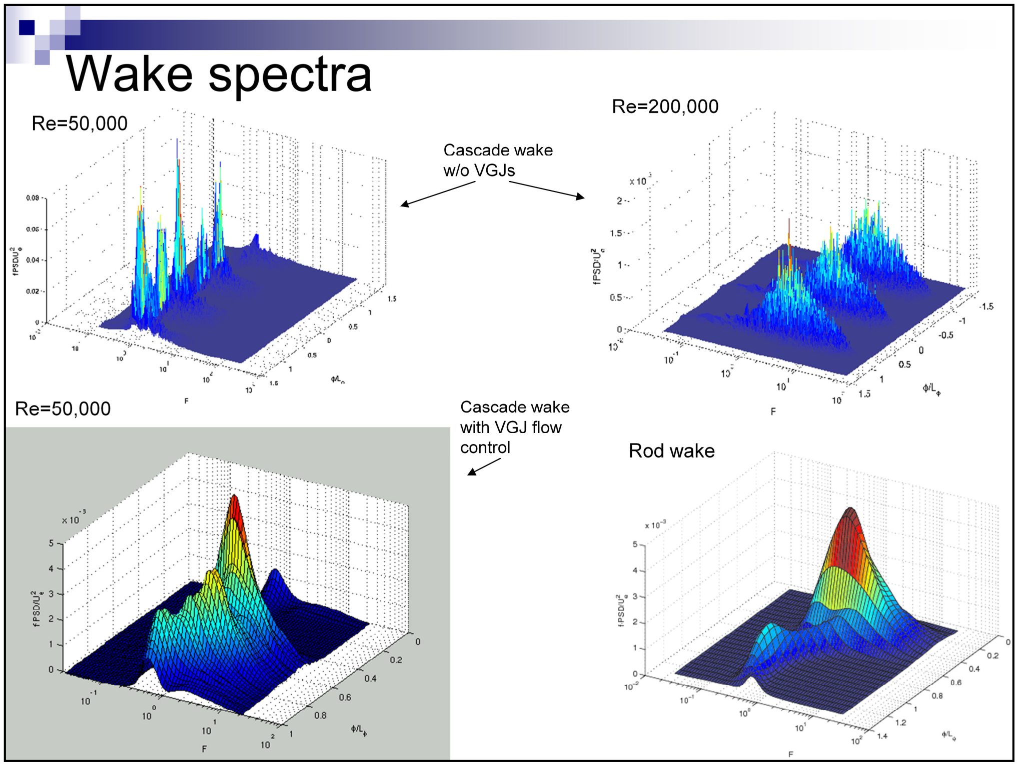
Mean Velocity

RMS streamwise velocity



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





Wake spectra

Re=50,000

Cascade wake w/o VGJs

Re=200,000

Re=50,000

Cascade wake with VGJ flow control

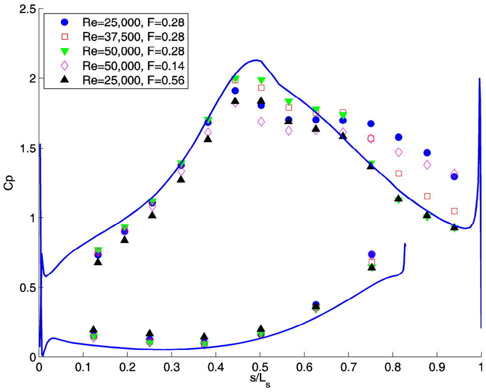
Rod wake

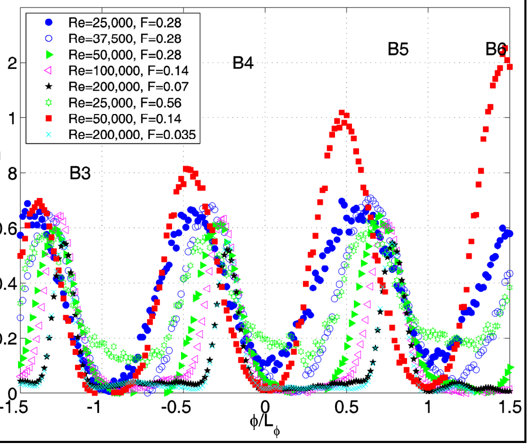
Click to play animation

filename: 04ws50f24d10b100.avi

Pressure results

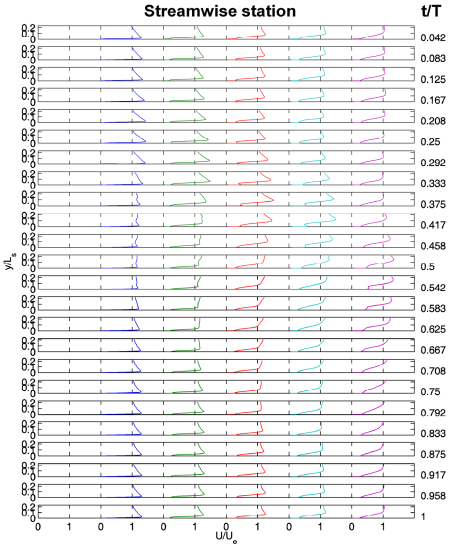
- Expected wake F=0.28
  - Partially suppresses separation at Re=25000
  - More effect at higher Re
- Lower F insufficient at Re=50000 and below
- Higher F suppresses separation more, VGJs in combination with wakes may be helpful



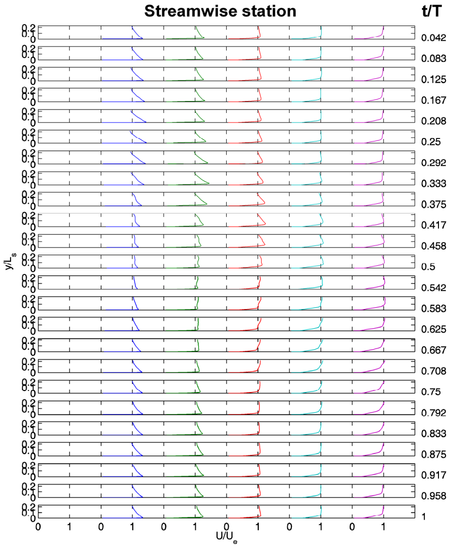


Phase Averaged Velocity, F=0.28

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
  - F=0.56 good even with low B≤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