LES AND URANS COMPUTATIONAL INVESTIGATIONS OF LPT BLADE (L1A) SEPARATION CONTROL USING VORTEX GENERATOR JETS

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OVERVIEW

1. OBJECTIVES AND MOTIVATION
2. PROBLEM DESCRIPTION
3. COMPUTATIONAL METHOD
4. TURBULENCE MODELS
5. CASES SIMULATED
6. RESULTS
7. CONCLUSIONS

1. OBJECTIVES AND MOTIVATION (1 of 3)

Designing Highly Loaded LPT blades :

Benefits : **Reducing**

Number of blades

Production costs

Engine weight

Challenges at Low Re (high altitude cruise conditions):

- ✓ **Flow separation occurs**
- ✓ **Engine efficiency drops**
- ✓ **Fuel consumption increases**

1. OBJECTIVES AND MOTIVATION (2 of 3)

Flow Control techniques :

- PASSIVE DEVICES (boundary layer trips)
  - Simple
  - Parasitic losses at high Re numbers

- ACTIVE TECHNIQUES (Vortex Generator Jets (VGJs))
  - Harder to implement
  - Can be adjusted to operating range or turned off

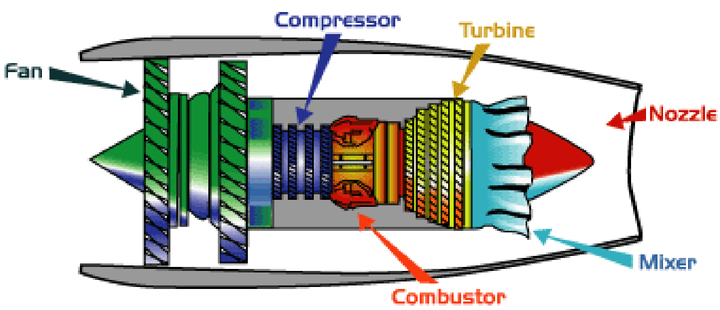
1. OBJECTIVES AND MOTIVATION (3 of 3)

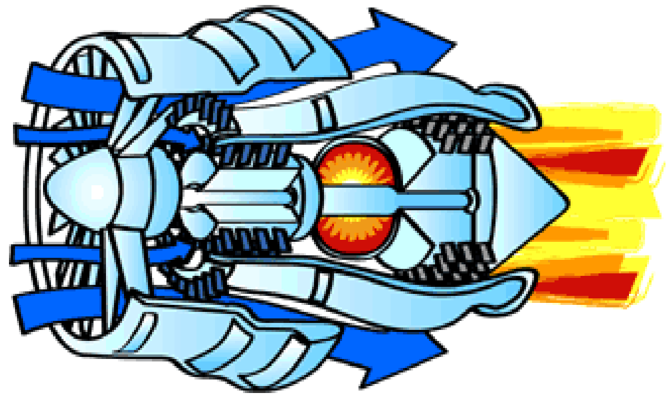
Objectives

- Experimentally and computationally investigate flow control over highly loaded LPT airfoil L1A utilizing steady VGJs
- Identify conditions where flow control is more efficient and explain flow physics behind that
- From CFD point of view: compare RANS (preferred by industry) with LES (more expensive) and with experiment, identify where those models perform well and were problems appear

LPT AIRFOIL FLOW CONTROL
OBJECTIVES AND MOTIVATION (1 of 6)

Typical jet engine operation and ways to improve efficiency:





- LPT powers Bypass flow and significantly effects fuel consumption
- Hard to increase LPT efficiency
- Reducing number of blades helps to reduce fuel consumption
- Highly loaded LPT blades result in flow separation

- Bypass flow (blue) - 80% of the thrust
- Core flow (red) - 20% of the thrust

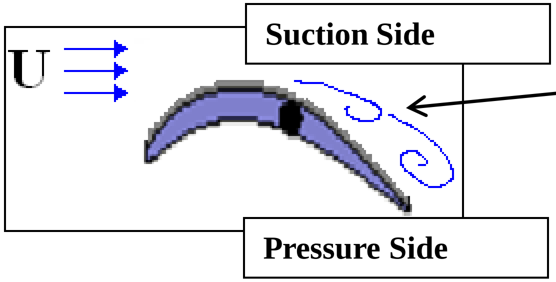
LPT AIRFOIL FLOW CONTROL
OBJECTIVES AND MOTIVATION (2 of 6)

Designing Highly Loaded LPT blades :

Benefits : Reducing

- Number of blades
- Production costs
- Engine weight

Challenges at Low Re (high altitude cruise conditions):



- Flow separation occurs
- Engine efficiency drops
- Fuel consumption increases

LPT AIRFOIL FLOW CONTROL
OBJECTIVES AND MOTIVATION (3 of 6)

Flow Control techniques :

- PASSIVE DEVICES (boundary layer trips)
  - ✓ Simple
  - ✓ Parasitic losses at high Re numbers

- ACTIVE TECHNIQUES (Vortex Generator Jets (VGJs))
  - ✓ Harder to implement
  - ✓ Can be adjusted to operating range or turned off

LPT AIRFOIL FLOW CONTROL
OBJECTIVES AND MOTIVATION (4 of 6)

Literature Review:

Experimental work:

(**Volino, 2002**): On **Pack B** airfoil **boundary layer separates** downstream of the suction peak due to the **adverse pressure gradient**. **Transition** to turbulence and flow **reattachment** might happen downstream.

Bons et al., (2008), Volino et al., (2008): The **L1A** has higher loading and **more prone to separation** than other LPT airfoils, where transition forced separated flow to reattach even at low *Re*. It is a **good airfoil for the flow control work**, combining very high loading with a need for separation control.

Bons et al., (2002), Volino (2003), McQuilling and Jacob (2004), Eldredge and Bons (2004), and Volino and Bohl (2005): used **VGJs** on the **Pack B** LPT airfoil. Separation was eliminated, even at the lowest Reynolds number considered. **Pulsed jets were more effective**. **The initial disturbance** created by each pulse caused the boundary layer to attach. **The turbulence effect** was more significant than the action of the vortices.

Volino et al., (2009): studied highly loaded **L1A** airfoil. **VGJs** were effective even at the lowest Reynolds numbers. **Pulsed jets performed better than steady jets.** A pulsing **dimensionless frequency of *F*=0.28** was marginal for good control at moderate blowing ratios. Separation **control resulted in a 20% increase in lift and up to a 70% reduction in total pressure loss**.

LPT AIRFOIL FLOW CONTROL
OBJECTIVES AND MOTIVATION (5 of 6)
Observations from previous work:

Direct Numerical Simulation (DNS)
Large Eddy Simulation (LES)
Reynolds Averaged Navier-Stokes (RANS)

CFD work:

Singh (2005): used **LES** for LPT cascade predictions at **low Re** numbers, where the **flow separated** and never reattached.

Gross and Fasel (2008): used **DNS, LES and RANS** models to predict **Pack B** airfoil flows. **Agreement** with experimental data was achieved in some instances, but **significant differences** were observed in others. This was attributed to possible **differences between the inlet flow conditions** in the experiment and computations.

Flow control is **challenging for CFD** because of its **transitional** nature in combination with **highly three dimensional** flow around the jets.

Garg (2002): used **RANS** to predict **Pack B** flow **with and without VGJs**. **Predicted correct separation location in the baseline case** (without VGJs) as well as showed that **separation vanishes in the flow control case** as in experiment. However, the **separated region and the wake were not well predicted**, which is common for RANS

Rizzetta and Visbal (2005): used **LES** to investigate the flow control with **pulsed VGJs** in the **Pack B** cascade. **For inlet Re = 25,000 and B=2 flow control helped to keep flow attached for an additional 15% of the chord**. Although **CFD flow field**, in their work, **considerably differed from experimental**, numerical and experimental **time-mean velocity profiles were in a reasonable agreement**

LPT AIRFOIL FLOW CONTROL
OBJECTIVES AND MOTIVATION (6 of 6)

Objectives

- Study the **flow over** highly loaded LPT airfoil **L1A** at different Re to identify **flow regimes where flow control is needed**
- Study effect of **freestream turbulence** on separation
- Computationally investigate **flow control** over **L1A** airfoil utilizing **steady and pulsed VGJs** and compare results with Experimental data
- Identify under which **conditions (B, f, DC) flow control is more effective** and explain **flow physics** behind that
- Compare **RANS** (preferred by industry) and **LES** (more expensive) approaches to turbulence modeling with experiment, to test which approach is **appropriate for the flow control** type of problems

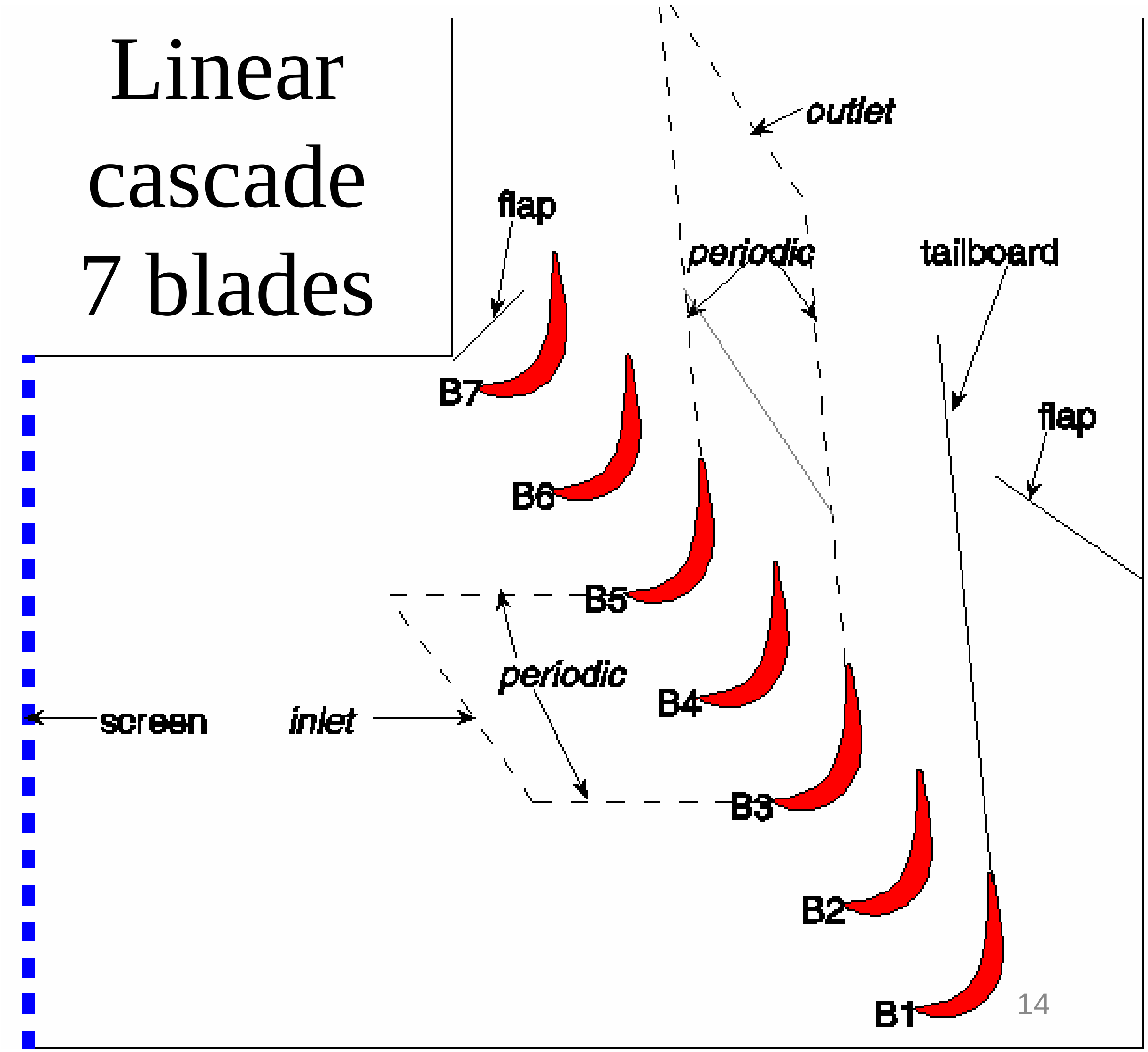
LPT AIRFOIL FLOW CONTROL
CASES SIMULATED (1 of 1)

$\text{Re} = U_e L_s / \nu$ - exit Re number based on nominal exit velocity from the cascade and suction surface length

Geometry	Linear cascade of 7 airfoils	Baseline *(No Jets)*	Flow control *(row of VGJs on the airfoil's suction surface)*
Re and Blowing ratio	Re=25,000, B=0; Re=50,000, B=0; Re=100,000, B=0; Re=300,000, B=0;	**Re=25,000, B=0; Re=100,000, B=0; Re=300,000, B=0;**	Re = 25,000: B=1 and B = 3 **Re = 50,000: B=0.5 and B = 2** Re = 100,000: B=0.25 and B = 1
Turbulence model	Inviscid	**SKW-sst, V2F, Transition-sst**	**LES**, **Transition-sst**
Frequency	N/A	N/A	**3, 12 and 24 Hz**
Duty Cycle	N/A	N/A	**0%, 10%** and **50%**

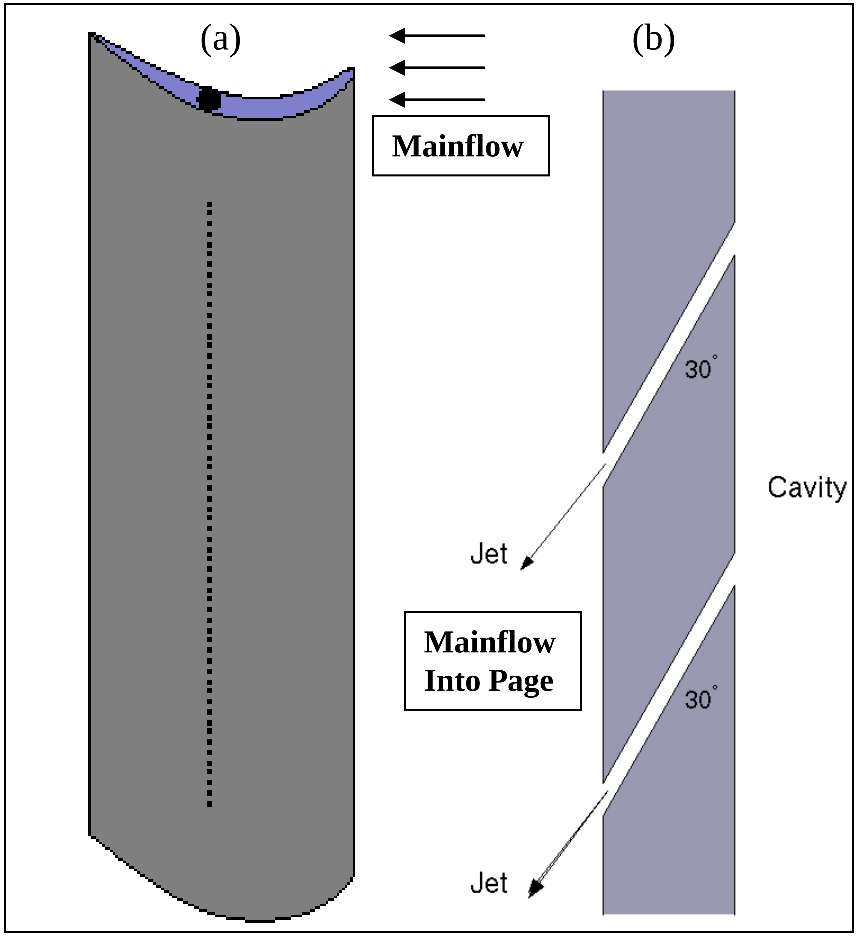
LPT AIRFOIL FLOW CONTROL
GEOMETRY AND BOUNDARY CONDITIONS (1 of 2)

- **Highly loaded** LPT airfoil designed at the Air Force Research Laboratory (AFRL) and designated **L1A**
- **Transitional** flow with **separation** at **low Reynolds numbers**
- **Steady** and **Pulsed VGJs** to **eliminate** flow **separation** and **reduce losses**

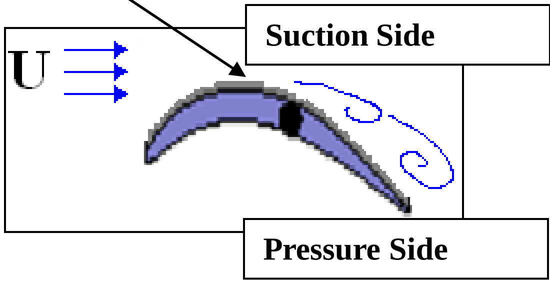


LPT AIRFOIL FLOW CONTROL
GEOMETRY AND BOUNDARY CONDITIONS (2 of 2)

Vortex Generator Jets



- On all blades in cascade (CFD: one blade with periodicity)
- Located at suction peak
- D = 0.8 mm
- Spacing = 10.7D
- Compound Angle
  - 30° to surface
  - 90° to main flow
- Supplied from cavity in blade (CFD: jet tube included in calculations)



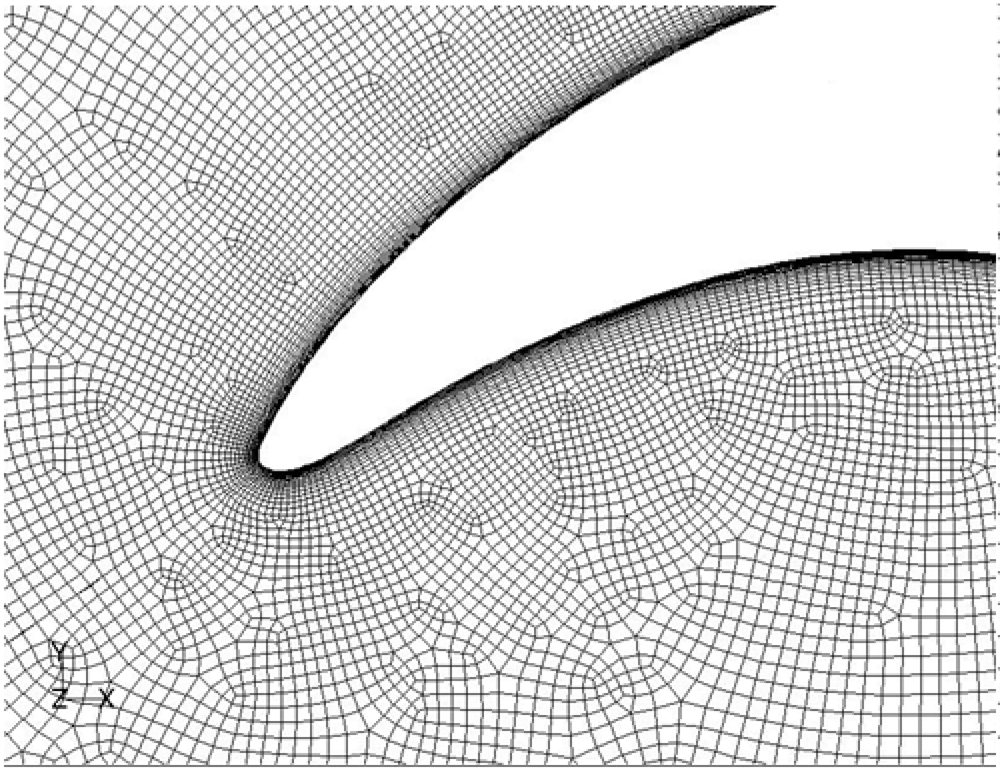
LPT AIRFOIL FLOW CONTROL
NUMERICAL METHODS (1 of 3)

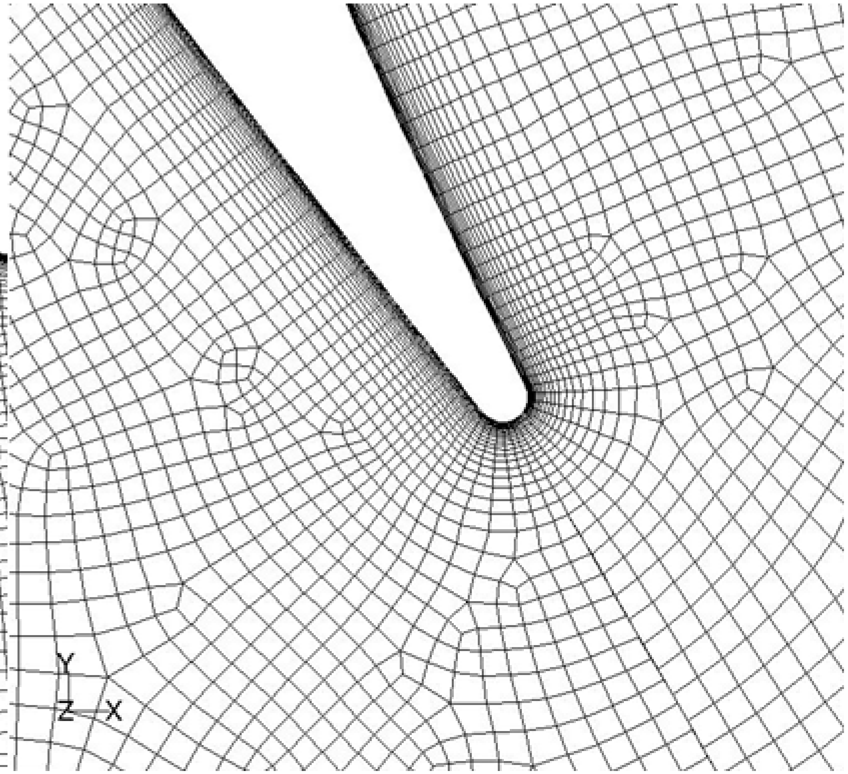
- FLUENT commercial code with Finite-Volume Method
- URANS were used for the baseline study (no jets), **Large Eddy Simulation (LES) was compared with URANS (Transition-sst model) for the flow control cases**
- **Dynamic Kinetic Energy Subgrid-Scale Model was used with LES**
- Incompressible flow (Ma < 0.1)
- Third order discretization for Momentum and Turbulence equations, except for LES, where Bounded Central Differencing was used for the Momentum equations

LPT AIRFOIL FLOW CONTROL
NUMERICAL METHODS (2 of 3)
Computational grid- URANS (Baseline)

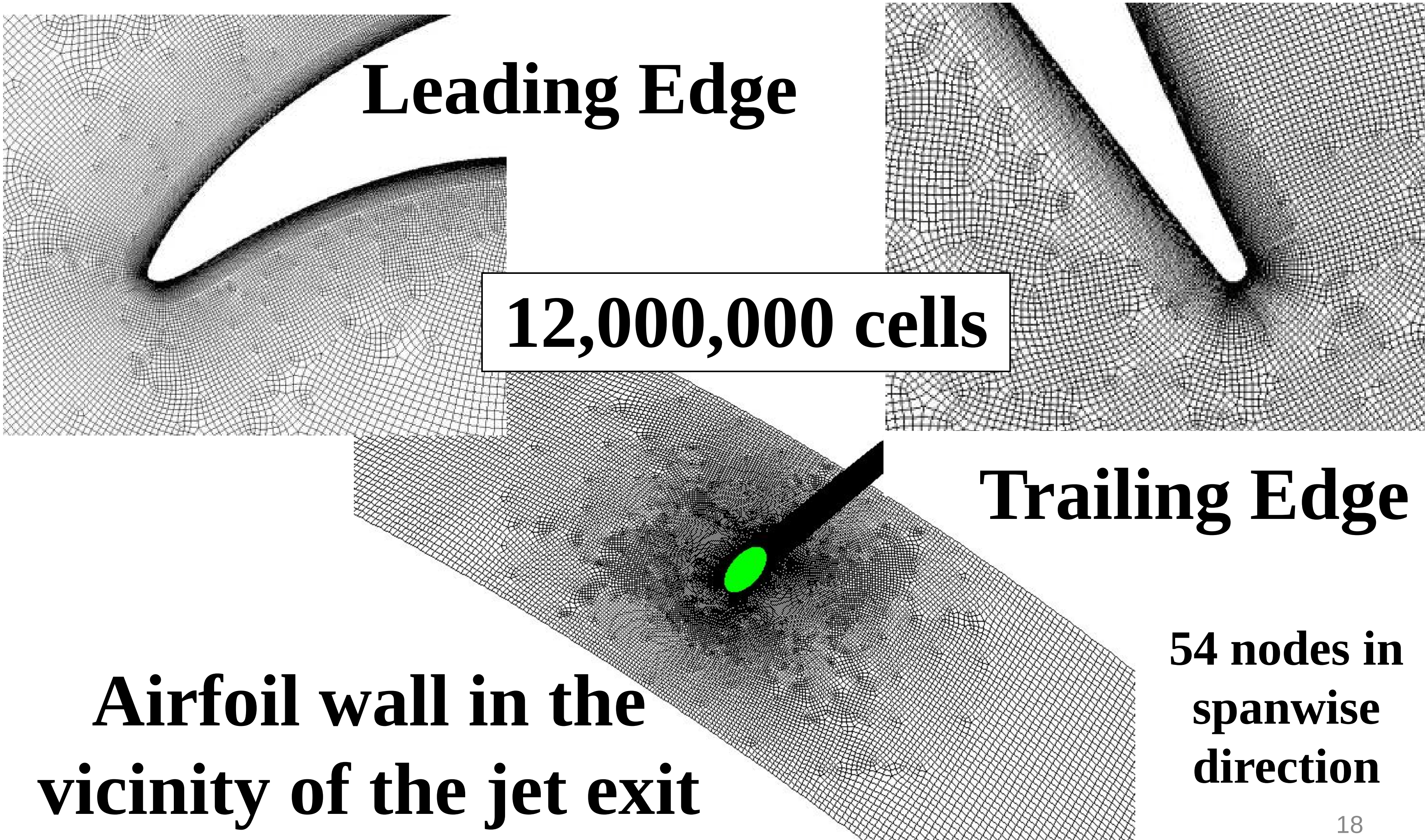
1,500,000 cells

Leading Edge **Trailing Edge**





LPT AIRFOIL FLOW CONTROL
NUMERICAL METHODS (3 of 3)
Computational grid- LES and URANS (Flow Control)



Definitions:

Re $U_e L_s / \nu$, exit Reynolds number

L_s suction surface length

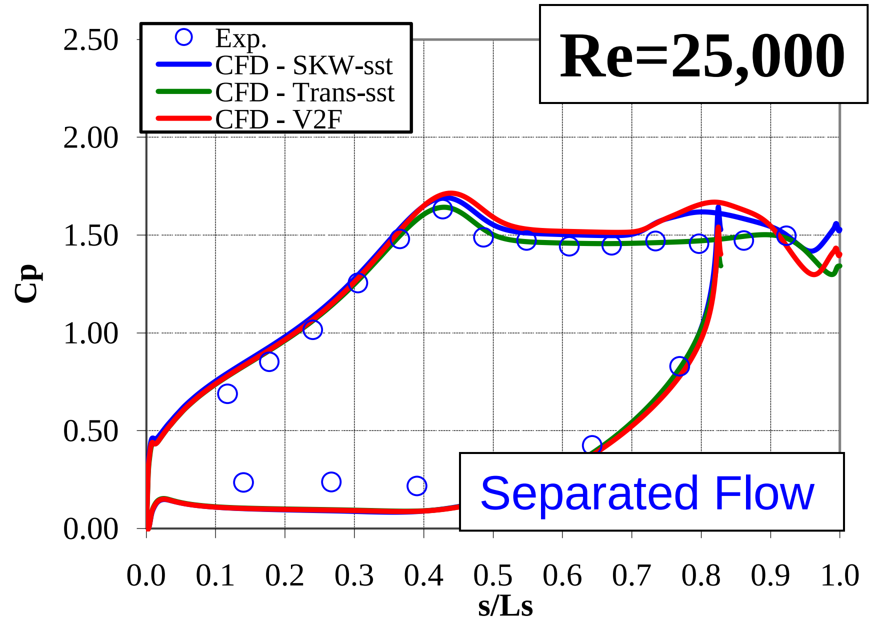
U_e nominal exit freestream velocity, based on inviscid solution

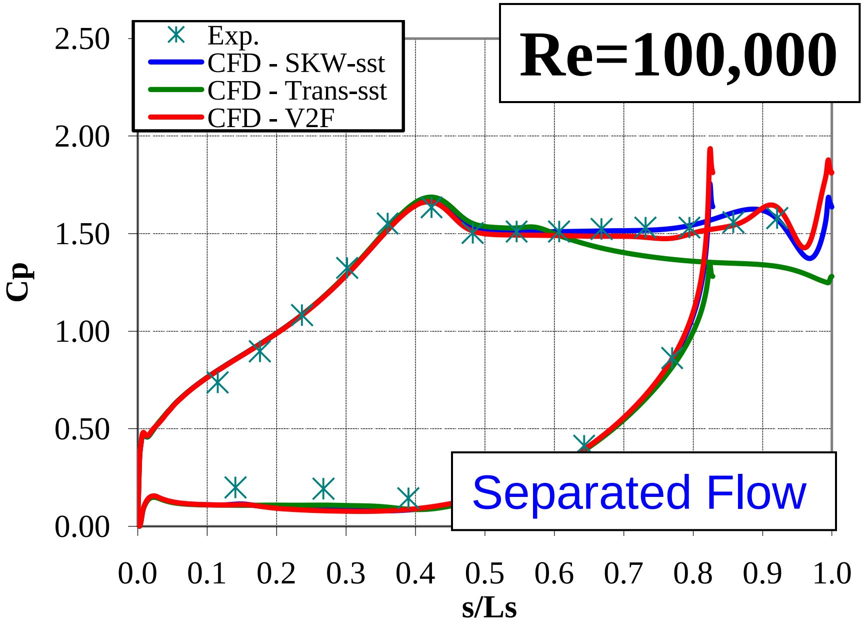
LPT AIRFOIL FLOW CONTROL
RESULTS (1 of 14)

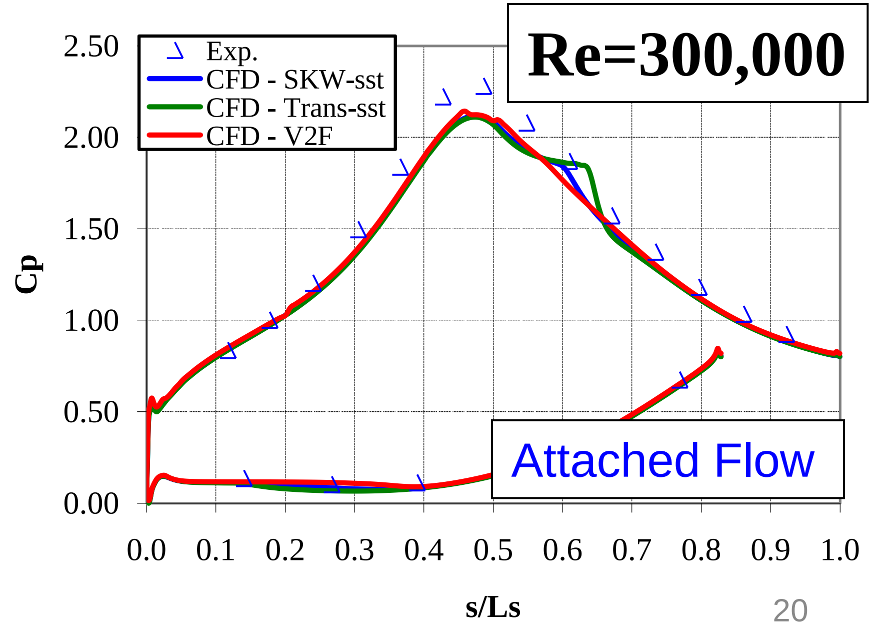
Baseline (no jets)

Cp profiles

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



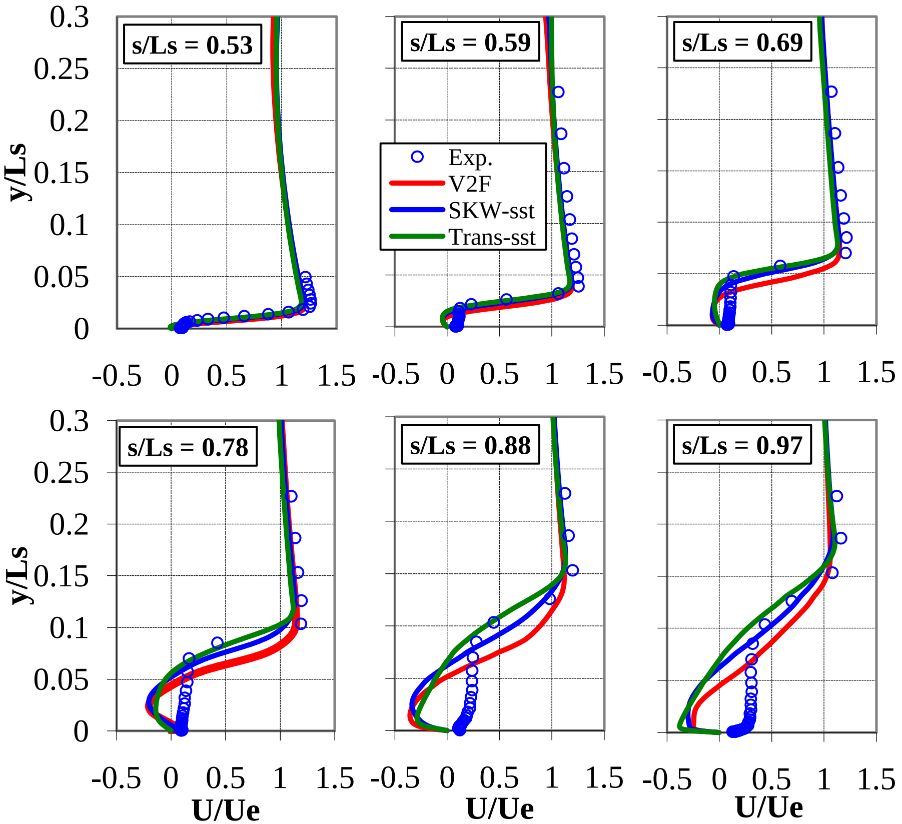




LPT AIRFOIL FLOW CONTROL

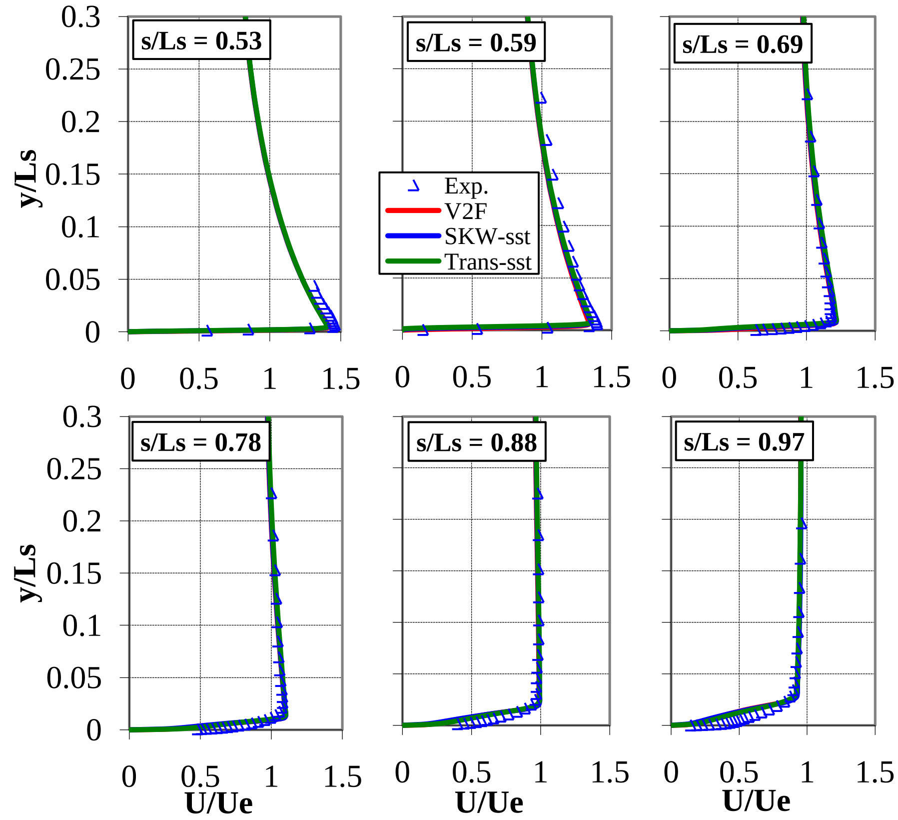
RESULTS (2 of 14) Baseline (no jets)

Velocity profiles



Re=25,000

Separated flow



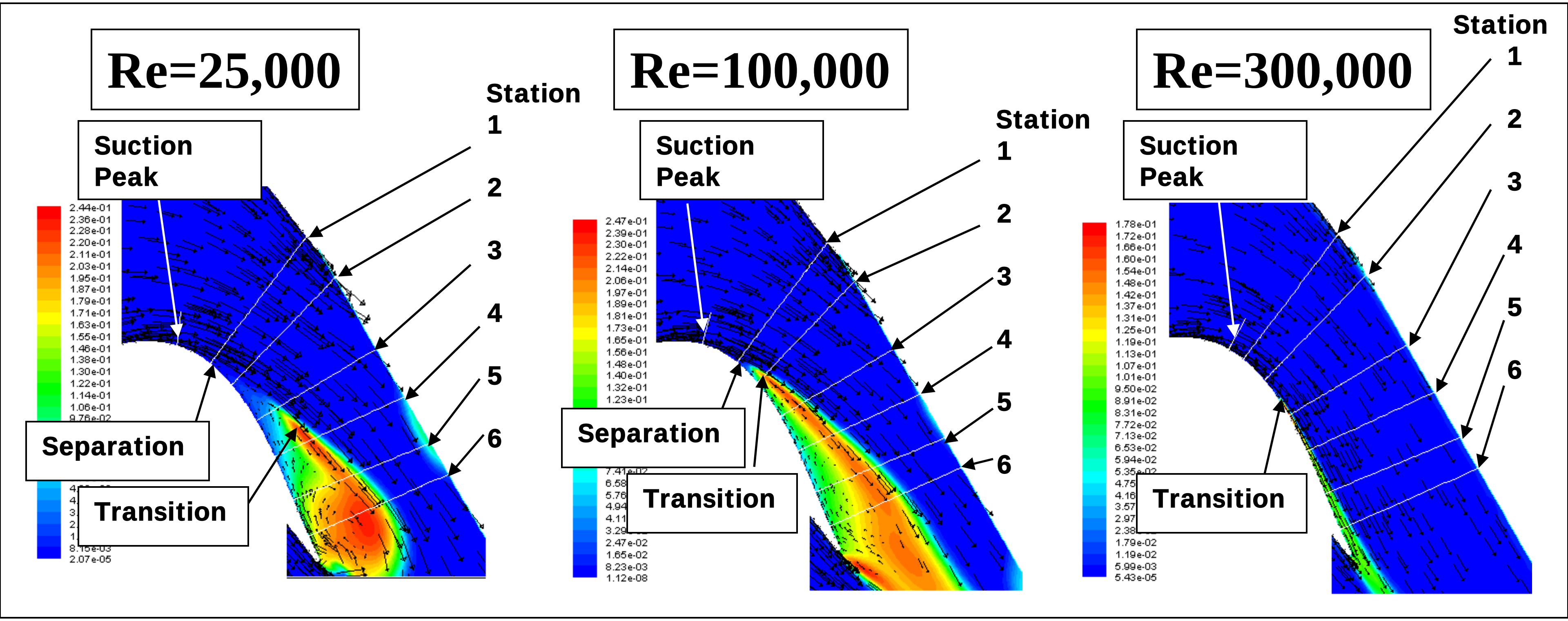
Re=300,000

Attached Flow

LPT AIRFOIL FLOW CONTROL
RESULTS (3 of 14)

Baseline (no jets)

Prediction of transition



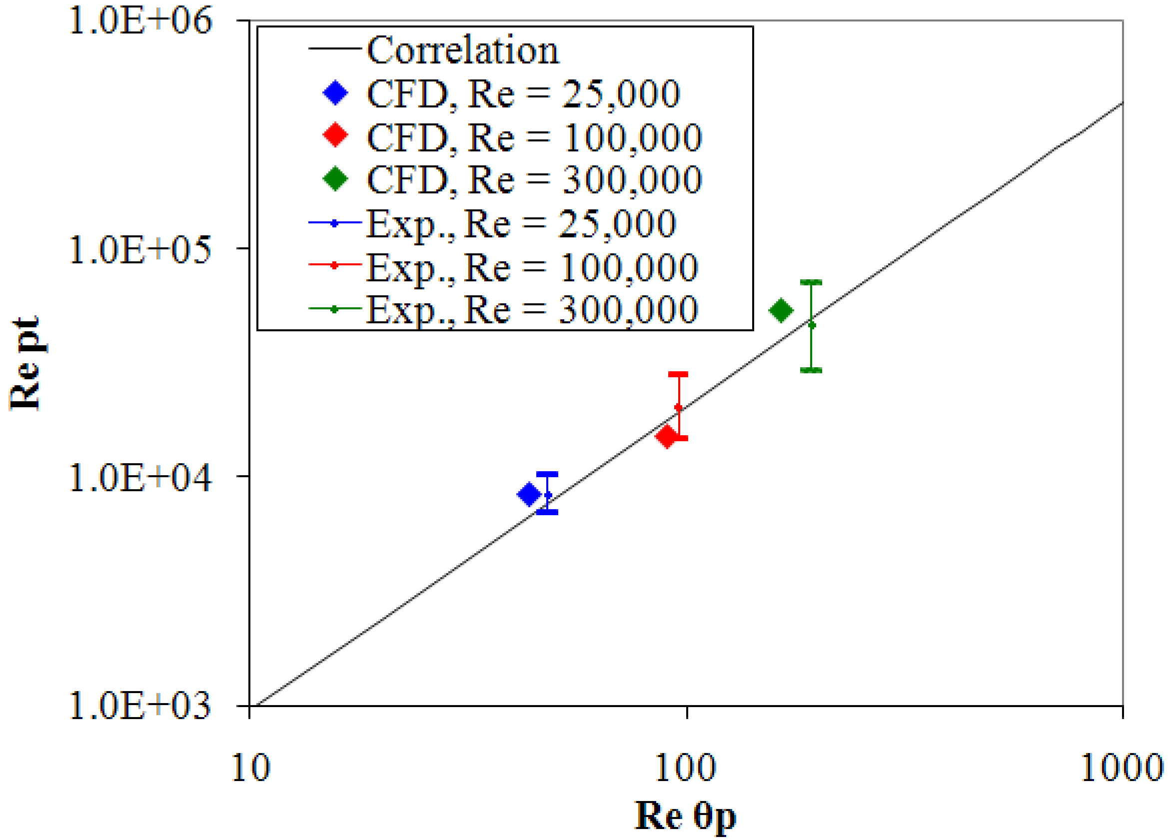
Contours of u'/U_e, and velocity vectors (from Trans-sst model)

LPT AIRFOIL FLOW CONTROL

RESULTS (4 of 14)

Baseline (no jets)

Prediction of transition



Re θp - momentum thickness Re number at the pressure minimum location

Re pt - the Reynolds number based on the freestream velocity at the suction peak and the streamwise distance from the suction peak to transition

Comparison between CFD data (Trans-sst Model) and correlation for the start of transition

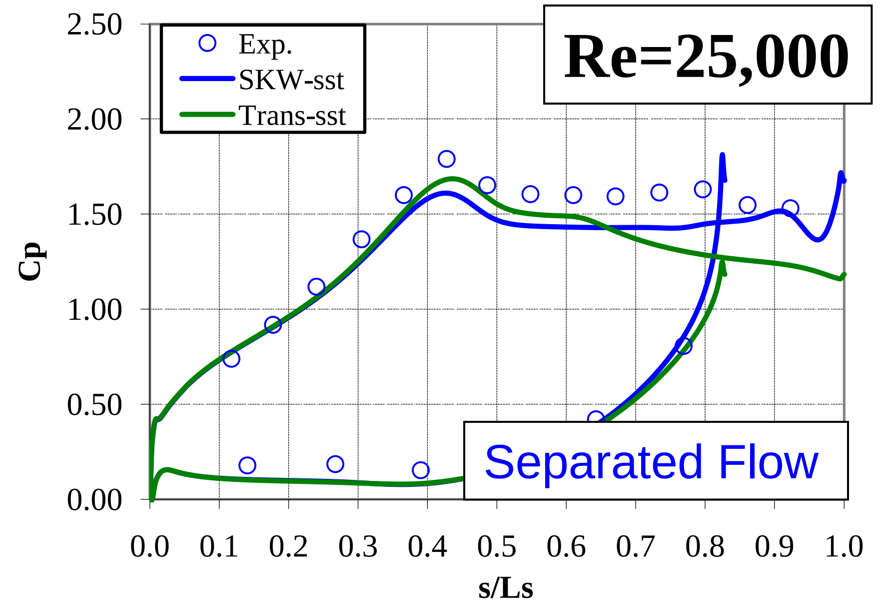
LPT AIRFOIL FLOW CONTROL
RESULTS (5 of 14)

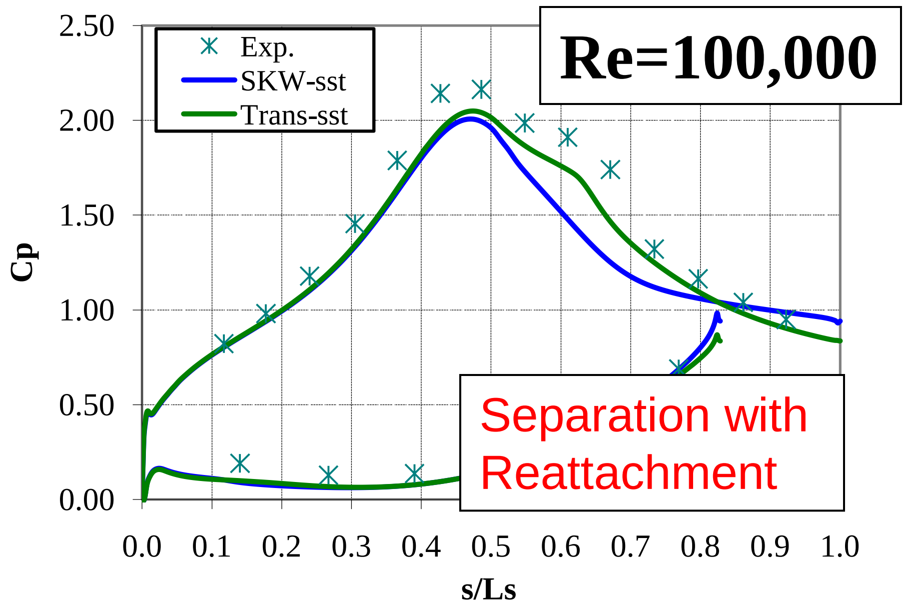
Baseline (no jets):

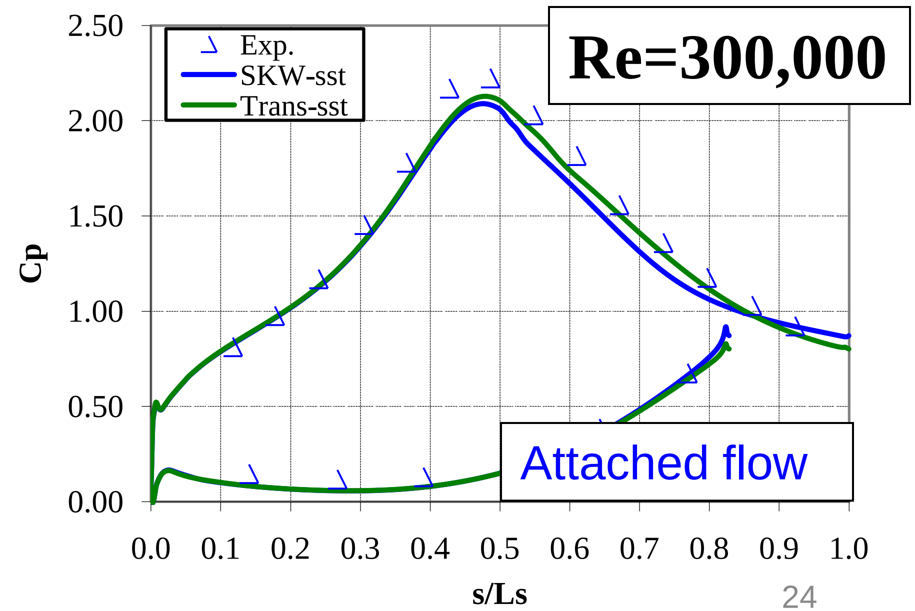
High Free Stream Turbulence

Cp profiles

$$C_p = 2(P_T - P)/\rho\, U_e$$





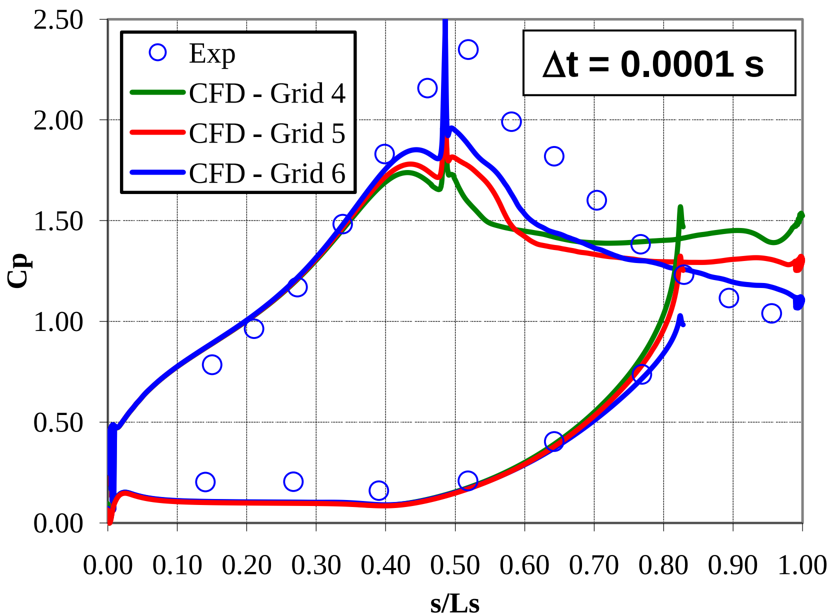


LPT AIRFOIL FLOW CONTROL

RESULTS (6 of 14) Flow Control: Model Validation

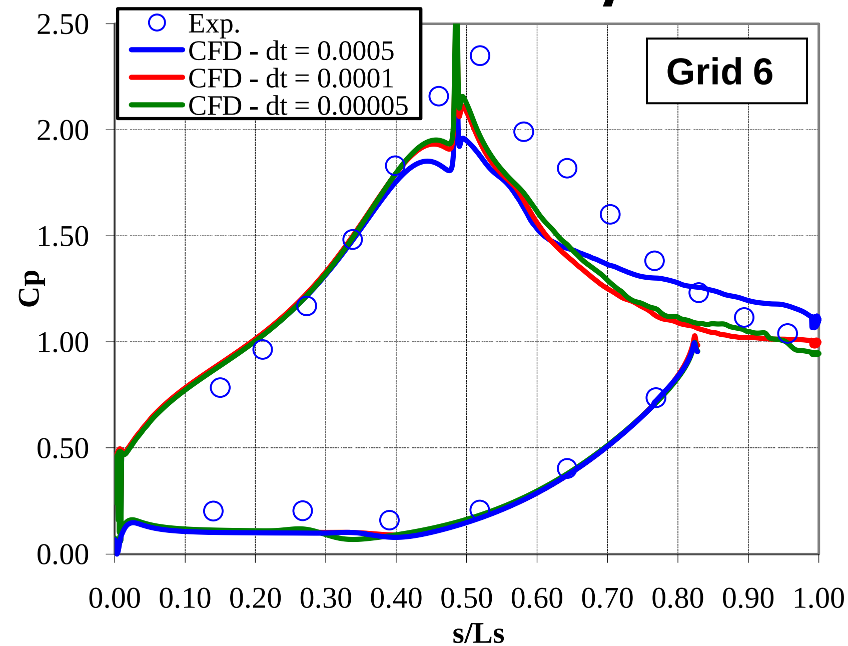
Grid independence study

Grid #	Size (cells)	Number of grids in z direction	y+	Δz+	Δx+
4	1,500,000	15	<1	12.6	1 - 100
5	5,900,000	30	<1	6.3	0.4 - 52
6	**11,900,000**	**54**	**<1**	**0.4 - 3.5**	**0.4 - 52**



(Recommended values for LES are:
$y^+ \sim 2$; $\Delta x^+ \sim 50\text{-}150$; $\Delta z^+ \sim 15\text{-}40$
(Piomelli and Chasnov))

Δt effect study



Some general recommendations:
Δt should be small enough to resolve the time-scale of the smallest resolved eddies, such as:
$U \Delta t / \Delta x \sim 2.5$ or less (Fluent)

In this case: (based on freestream velocity and Δx in the separated region)
U 0.0005 / Δx ~ 9.30
U 0.0001 / Δx ~ 1.86
U 0.00005 / Δx ~ 0.93

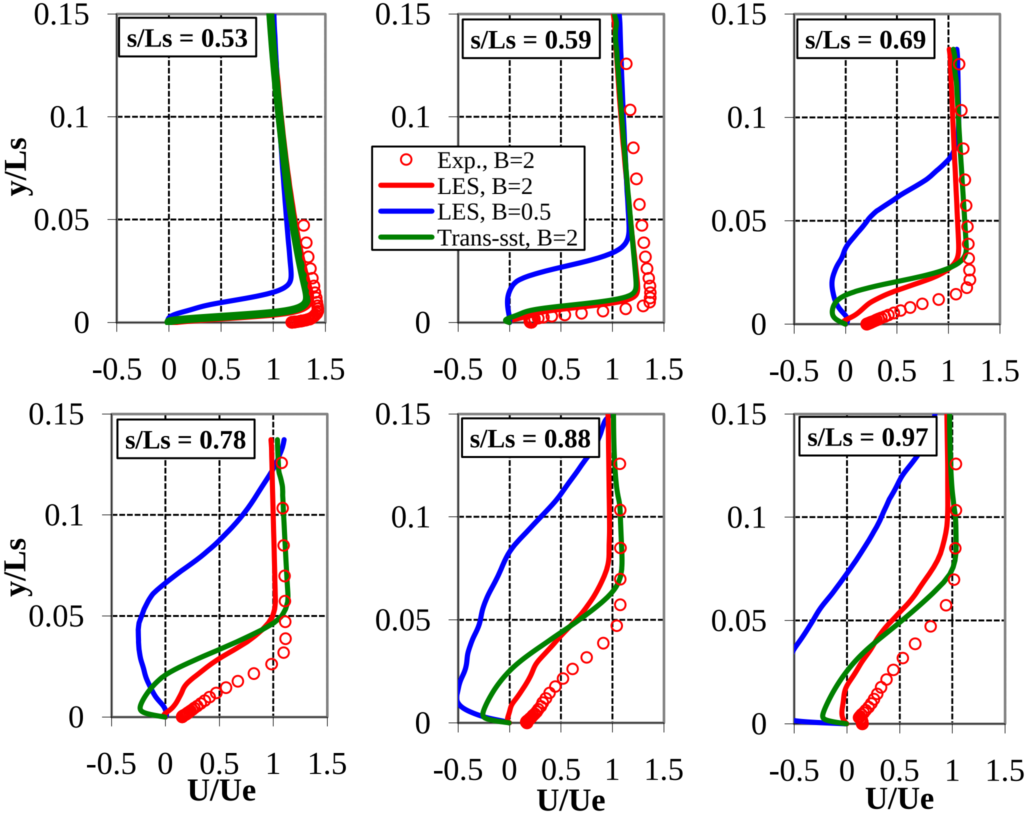
LPT AIRFOIL FLOW CONTROL

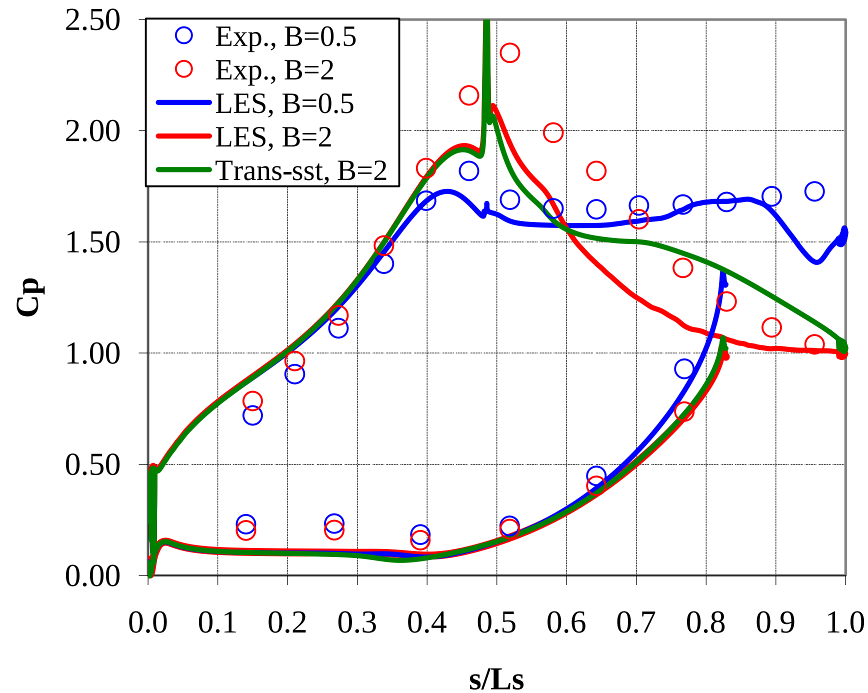
RESULTS (7 of 14) Flow Control

Re=50,000

Steady blowing VGJs

Velocity profiles





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

Massively Separated flow at **low B**
Reduction in separation at **high B**

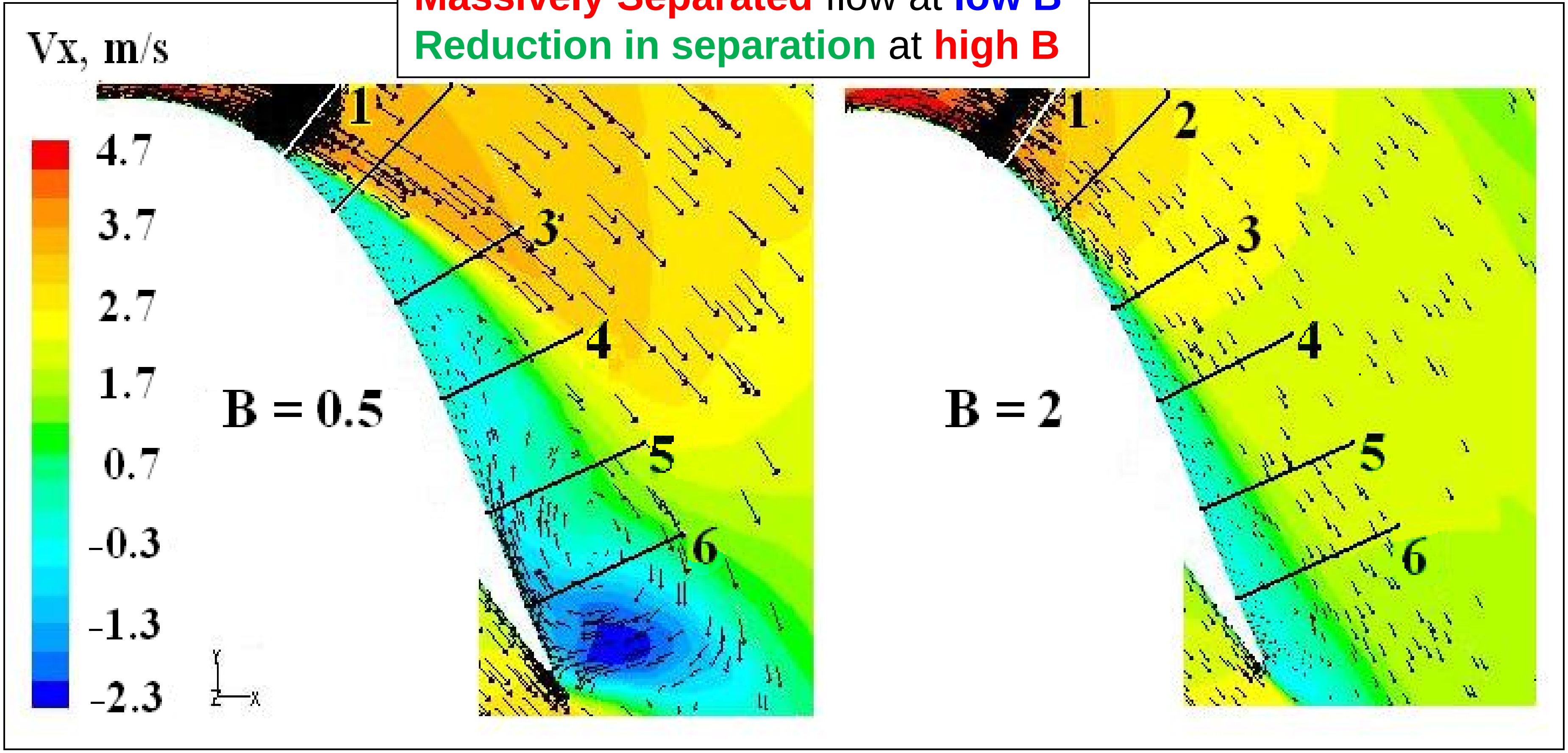
LES in a **better agreement** with Exp.

LPT AIRFOIL FLOW CONTROL

RESULTS (8 of 14) Flow Control

Steady blowing VGJs, Re=50,000

Massively Separated flow at **low B**
Reduction in separation at **high B**



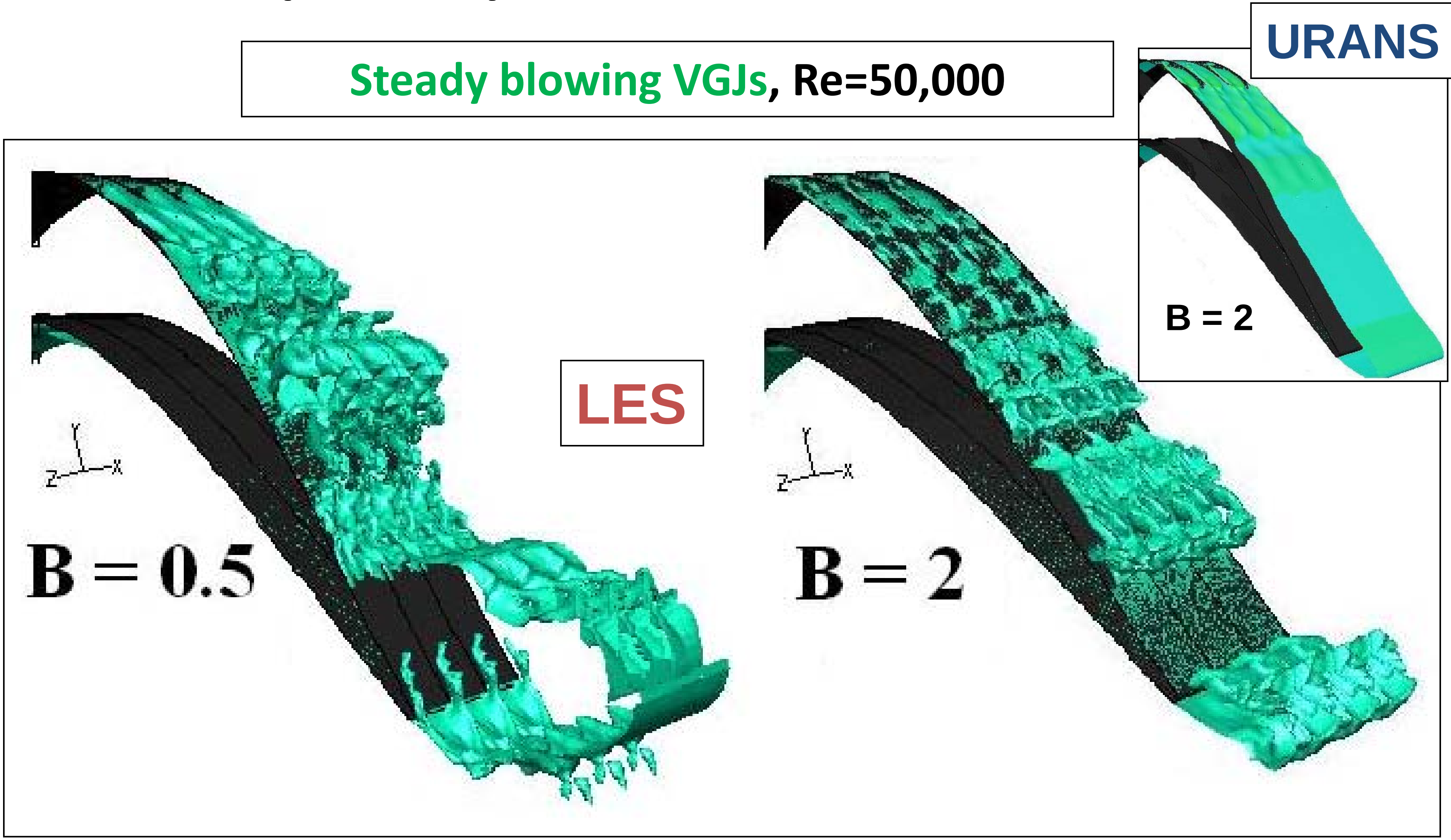
Mean X-velocity contours and velocity vectors (LES)

LPT AIRFOIL FLOW CONTROL

RESULTS (9 of 14) **Flow Control**

RANS: larger separation bubble, do not show **turbulence structures** responsible for **reattachment**

Steady blowing VGJs, Re=50,000



Instantaneous isosurfaces of Vx=0.01 m/s (LES)

Q-criterion(Second Invariant of Velocity Gradient Tensor)

$$\mathbf{Q} = -\frac{1}{2}\left(\overline{S_{ij}}\,\overline{S_{ij}} - \overline{\Omega_{ij}}\,\overline{\Omega_{ij}}\right)$$

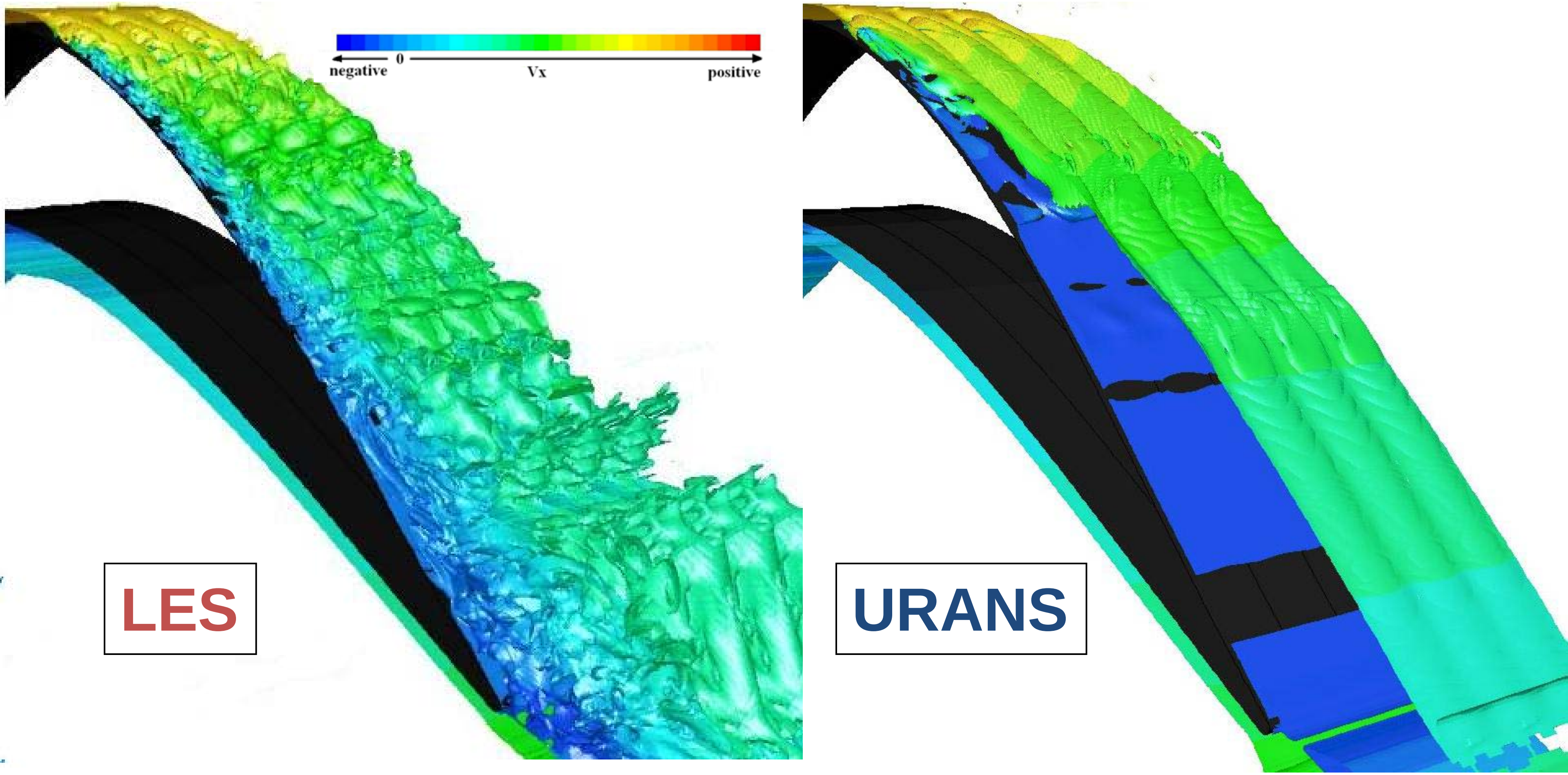
$$\overline{\mathbf{S}}_{\mathbf{ij}} = \frac{1}{2}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)$$

$$\overline{\boldsymbol{\Omega}}_{\mathbf{ij}} = \frac{1}{2}\left(\frac{\partial \overline{u_i}}{\partial x_j} - \frac{\partial \overline{u_j}}{\partial x_i}\right)$$

LPT AIRFOIL FLOW CONTROL
RESULTS (10 of 14) Flow Control

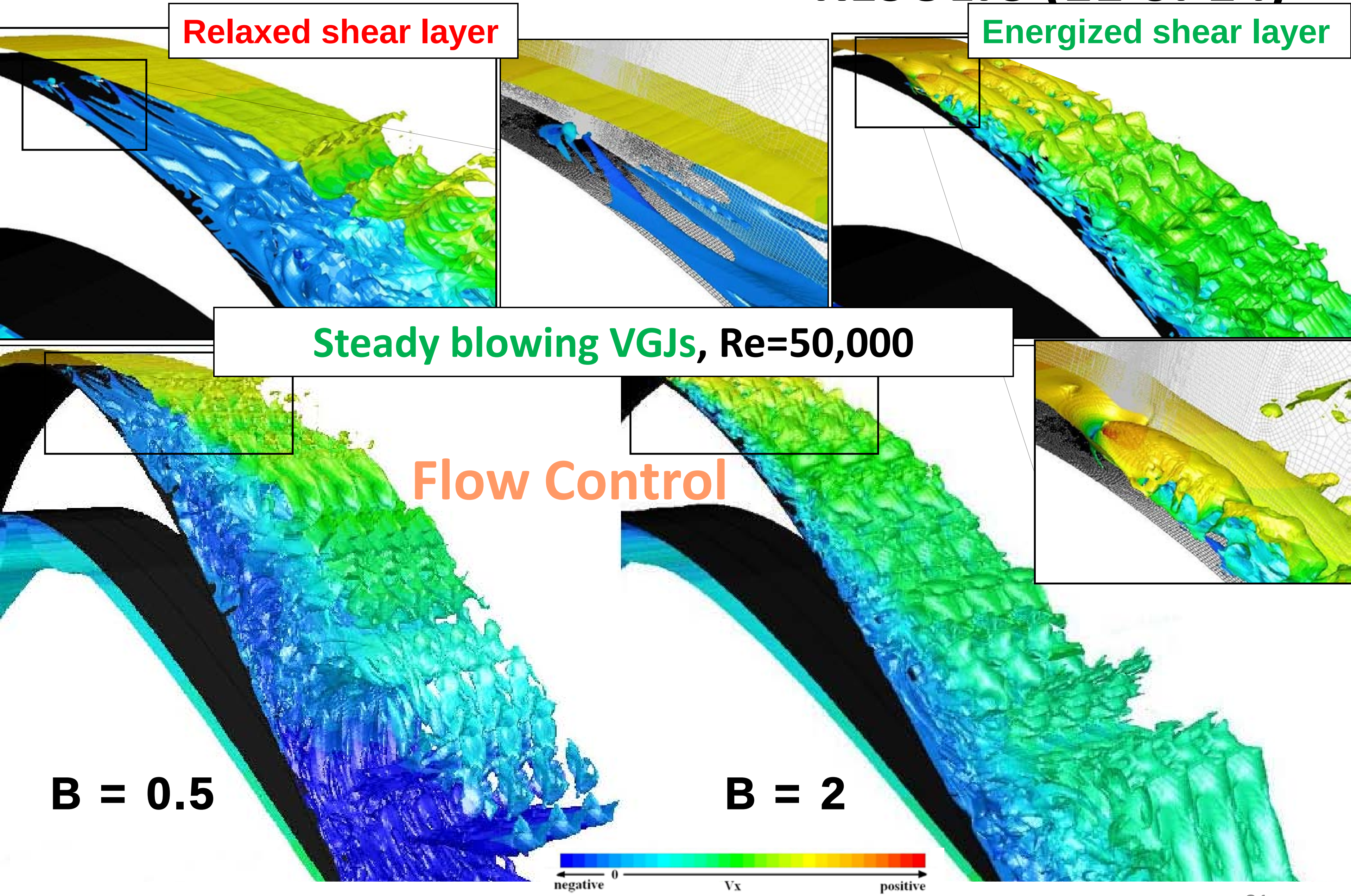
$$Q = -\frac{1}{2}\frac{\partial \bar{u}_i}{\partial x_j}\frac{\partial \bar{u}_j}{\partial x_i} = -\frac{1}{2}\left(\bar{S}_{ij}\bar{S}_{ij} - \bar{\Omega}_{ij}\bar{\Omega}_{ij}\right)$$

Steady blowing VGJs, Re=50,000



Instantaneous isosurfaces of Q-criterion colored by Vx

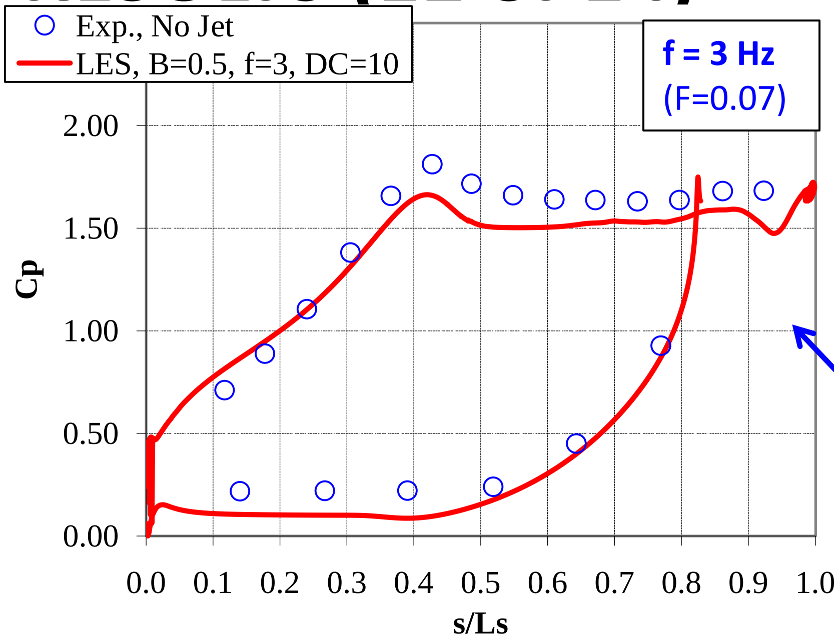
LPT AIRFOIL FLOW CONTROL RESULTS (11 of 14)

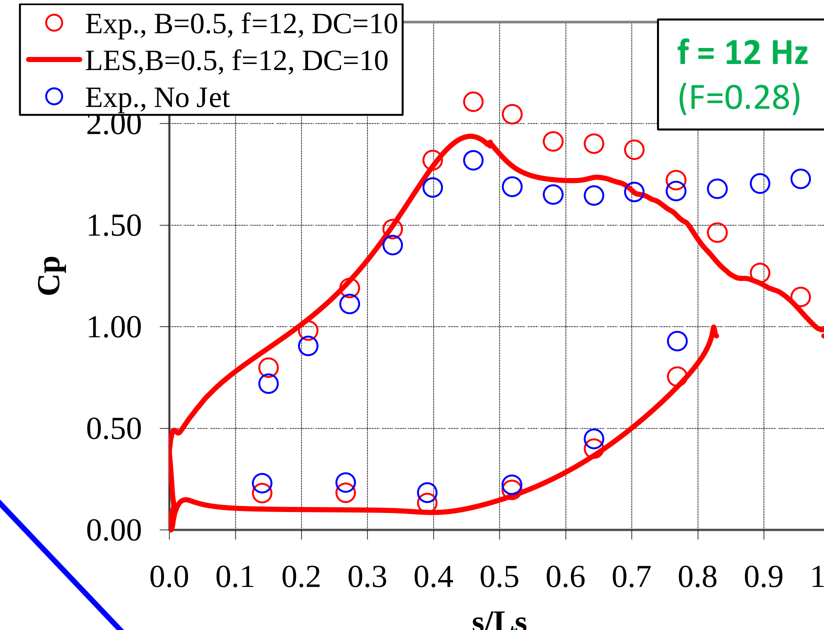


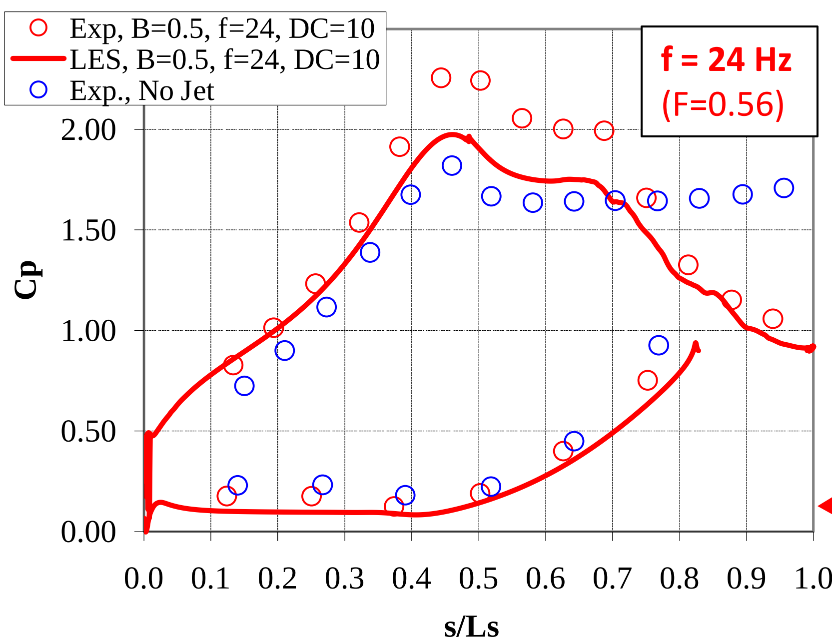
Instantaneous isosurfaces of Q-criterion (LES)

LPT AIRFOIL FLOW CONTROL RESULTS (12 of 14) Flow Control

Pulsed VGJs, Re=50,000, effect of frequency







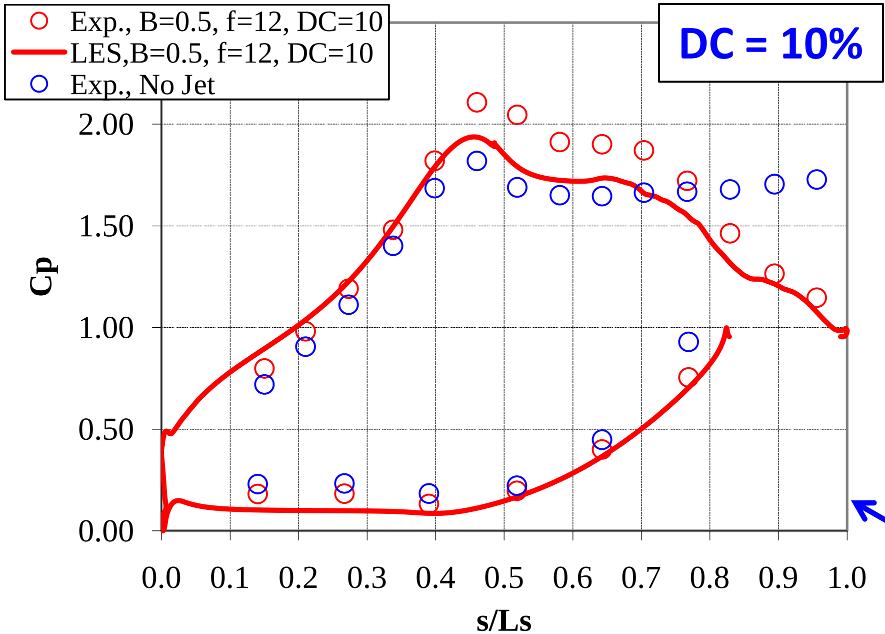
Summary of all Pulsed Cases Examined. (NA = Not Available)

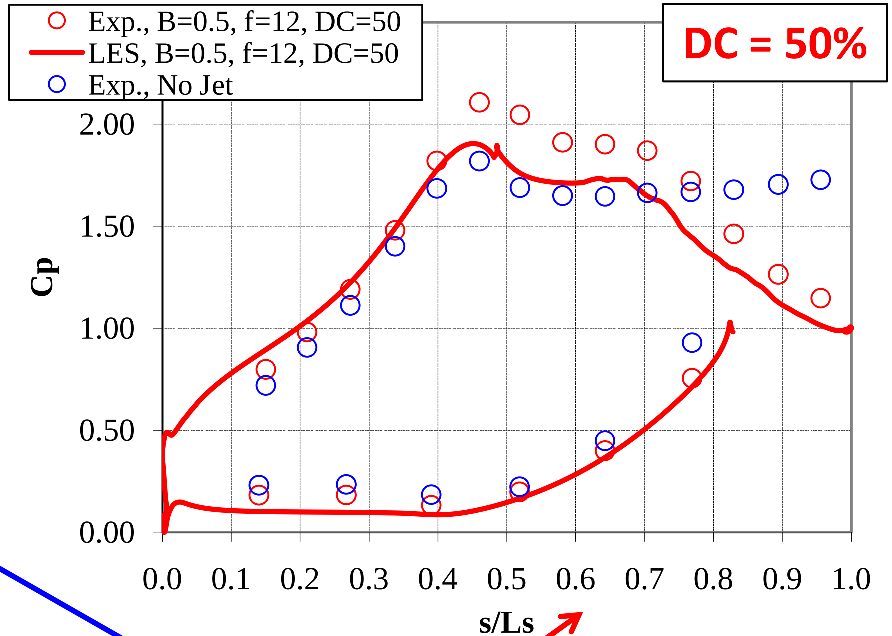
Case	1	2	3	4	5	6	7
Re/1000	25	50	100	25	50	50	50
B	1.0	0.5	0.25	1.0	0.5	0.5	0.5
DC %	10	10	10	10	10	10	50
f, Hz	3	3	3	12	12	24	12
U_{aver}, m/s	2.17	4.35	8.7	2.17	4.35	4.35	4.35
F	0.14	0.07	0.035	0.56	0.28	0.56	0.28
ψ_{int}, CFD	0.923	1.026	0.825	0.515	0.372	0.246	0.384
ψ_{int} Exp	NA	NA	NA	0.346	0.356	0.237	0.313

ψ_{int} total pressure loss integrated over the blade spacing

LPT AIRFOIL FLOW CONTROL RESULTS (13 of 14)Flow Control

Pulsed VGJs, Re=50,000, effect of Duty Cycle





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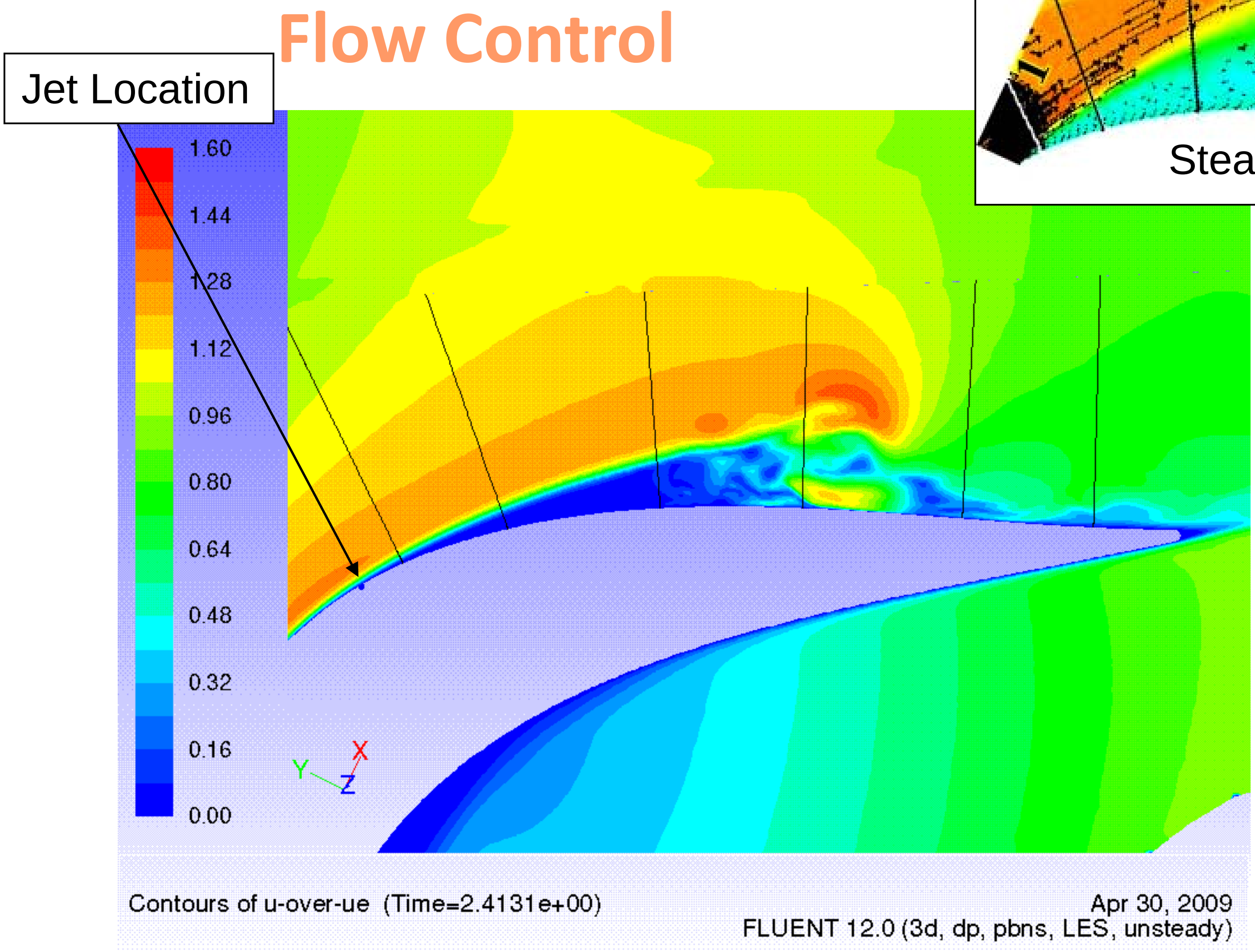
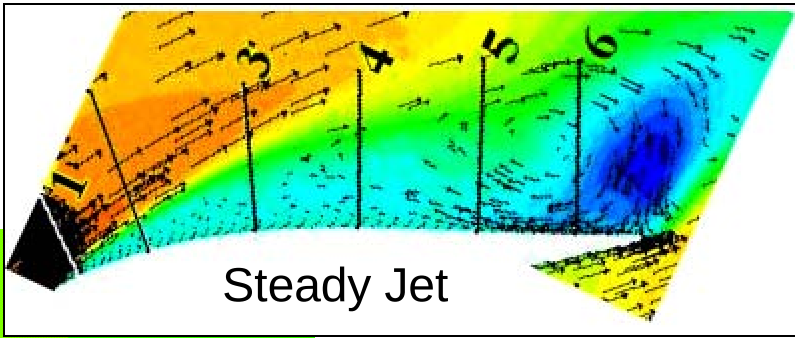
Case	1	2	3	4	5	6	7
Re/1000	25	50	100	25	50	50	50
B	1.0	0.5	0.25	1.0	0.5	0.5	0.5
DC %	10	10	10	10	10	10	50
f, Hz	3	3	3	12	12	24	12
U_{aver}, m/s	2.17	4.35	8.7	2.17	4.35	4.35	4.35
F	0.14	0.07	0.035	0.56	0.28	0.56	0.28
ψ_{int}, *CFD*	0.923	1.026	0.825	0.515	0.372	0.246	0.384
ψ_{int} *Exp*	NA	NA	NA	0.346	0.356	0.237	0.313

ψ_{int} *total pressure loss integrated over the blade spacing*

LPT AIRFOIL FLOW CONTROL RESULTS (14 of 14)

Pulsed VGJs, Re=50,000





Dimensionless streamwise velocity contours, Re = 50,000, B = 0.5, f=12 Hz, DC=10 %

LPT AIRFOIL FLOW CONTROL
Conclusions (1 of 2)

- **Separation** on the **L1A** airfoil occurs at **low Re** (≤100,000) with no reattachment
- At **elevated freestream turbulence** levels **reattachment** occurs at Re = 100,000
- Active **flow control** with **steady VGJs** helps to significantly **reduce separation** for all Re **at high B** and is **not effective at low B**
- **URANS** are capable of accurately predicting **flow over an airfoil** at different Re
- **LES** is needed in order to **capture VGJs effect** where URANS (Transition-sst model) have difficulties

LPT AIRFOIL FLOW CONTROL
Conclusions (2 of 2)

- **Pulsing VGJs** with **low B** helps to **reduce or eliminate separation**, when **steady blowing** with the same B is **not effective**
- **Dimensionless frequencies of 0.28** and above result in significant **reduction or elimination of separation** even at **low B**
- **Increasing** pulsation **frequency** is more **effective** than increasing **DC**

Future Work

- Study effect of the wake of the upcoming airfoil on the separation
- Develop an algorithm where jet B, f, and DC will be adjusted with flow regime and wake passing frequency
- Develop RANS model capable of capturing VGJs effect
- Conduct DNS study of the L1A airfoil flow control problem

QUESTIONS