LES of high-Reynolds-number Coanda flow separating from a rounded trailing edge of a circulation control airfoil

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Contents

Introduction: Circulation Control (CC) airfoil

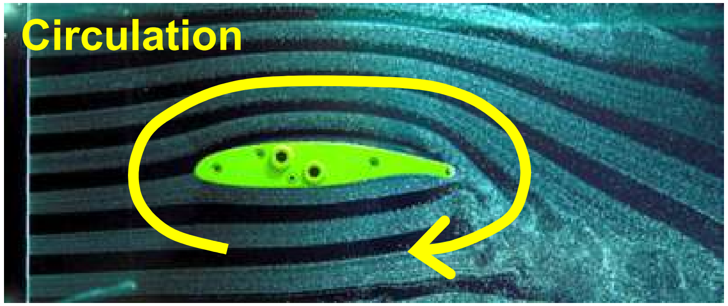
~ For the next generation of passenger aircraft ~

Circulation control by "Coanda jet"

Jet flow attaches on a rounded trailing edge of an airfoil

→ Circulation is increased

→ Lift is enhanced



Hydrogen bubble flow visualization of a CC airfoil (NASA LaRC, 2002)

CC for Aircraft applications

- Lift enhancement (by single jet-blowing)
- Maneuver support (by dual jet-blowing)

Concept image of hybrid-wing-body aircraft employing CC devices

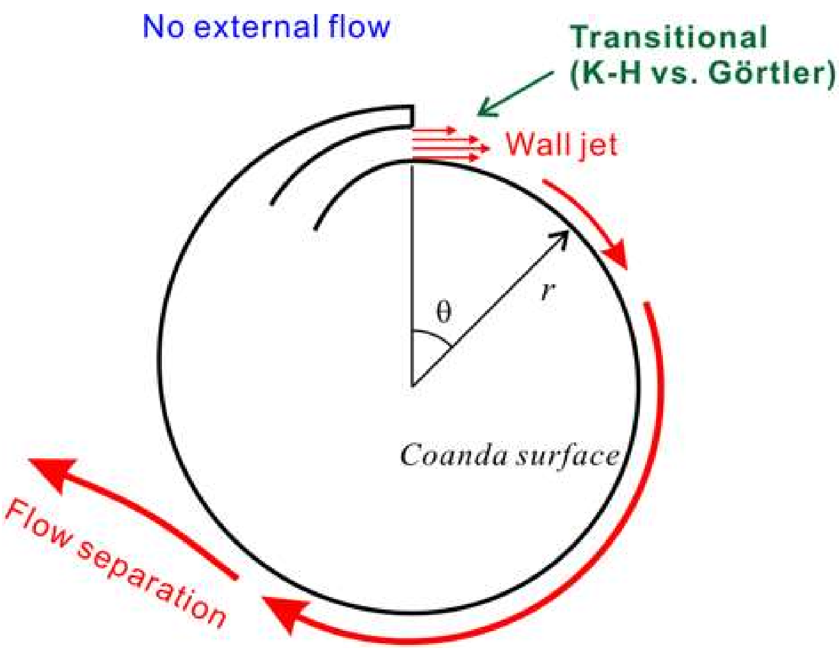
Coanda effect:

The tendency of a fluid jet to stay attached to an adjacent curved wall, named after Henri Coanda

Introduction: Separation of turbulent Coanda flow

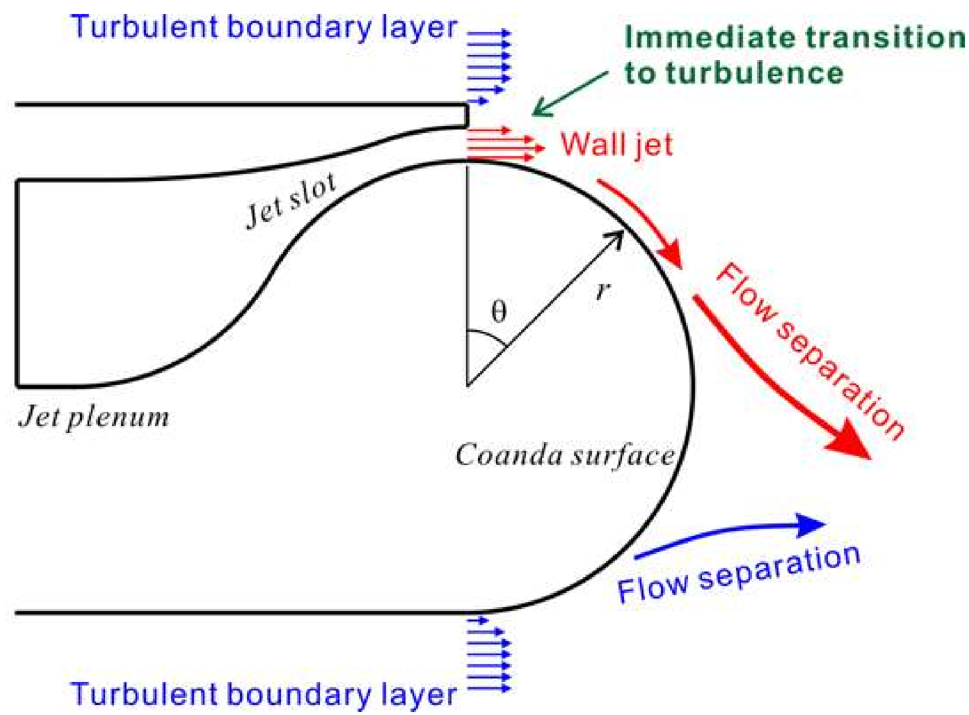
~ A major difficulty in current RANS Simulations ~

Coanda jet over a cylinder
(Exp. by Wygnanski et al.)



Jet flow characteristics are sensitive to the transition process

Coanda jet over a rounded trailing Edge of a CC airfoil



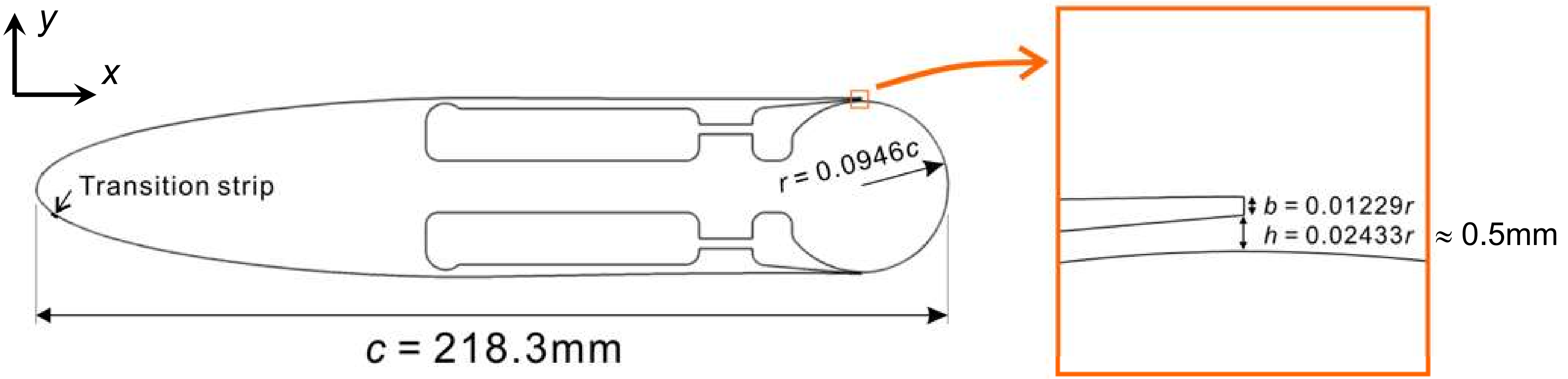
Jet flow develops to fully turbulent at the jet exit

Objectives of the study

1. To investigate detailed physics (flow structures and statistics) of the fully turbulent Coanda jet applied to a CC airfoil, by using LES

2. To compare LES and RANS results to figure out how to improve the performance of existing RANS models for this type of flow

Airfoil configuration



- 20%-thick, non-cambered, elliptic-leading-edge CC airfoil
  (designed by Dr. Englar's research group at GTRI – currently tested at NASA Langley)
- Two independent jet plenums for the upper and lower sides
  (lower jet slot is closed in this study – may be used for "dual blowing" in future studies)
- Chord Reynolds number: 0.49 million
- Wavy transition strip attached near the leading edge

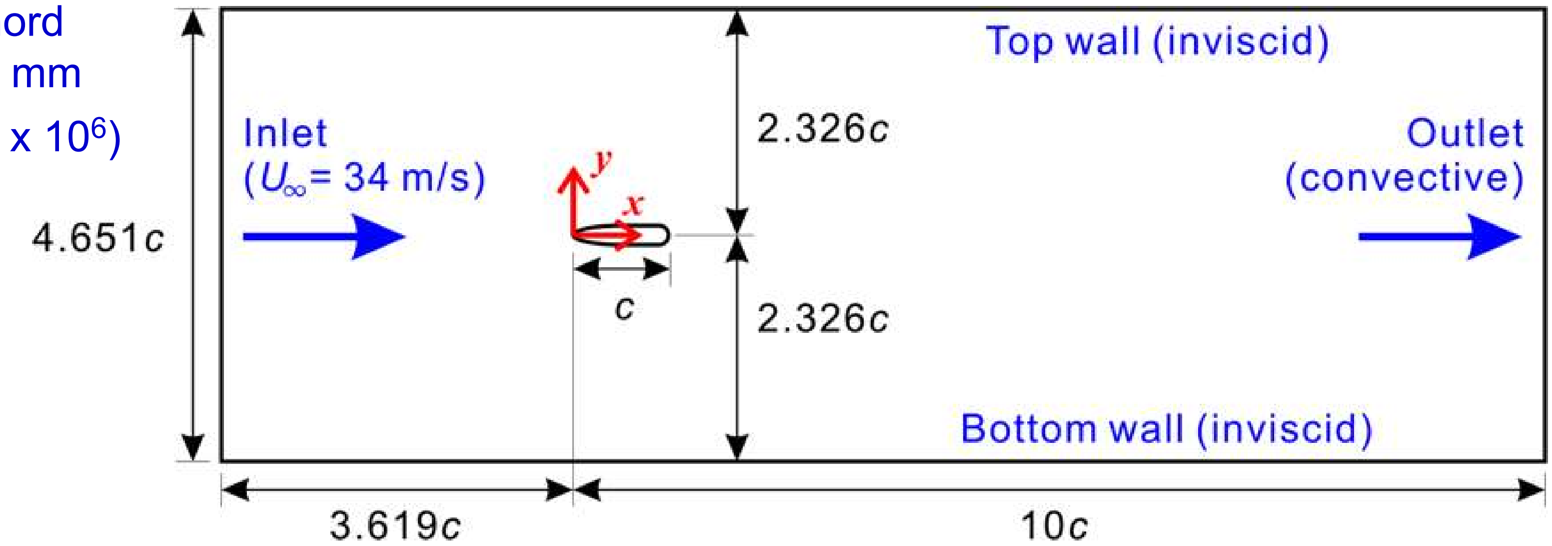
Numerical methods (LES)

Incompressible Navier-Stokes solver "CDP"
(developed at the Center for Turbulence Research, Stanford University)

- Unstructured, finite-volume solver
- Energy-conservative, 2nd-order central difference scheme
- Fully-implicit, 2nd-order time integration scheme
- Dynamic Smagorinsky model for the subgrid-scale (SGS) stresses
- Running on massively parallel supercomputers (256 CPU's used)

Computational domain & Boundary conditions

Airfoil chord
c = 218.3 mm
(Re_c = 0.49 x 10^6)



Wind tunnel geometry: NASA Langley Basic Aerodynamics Research Tunnel (BART)

Spanwise (periodic) domain size: 14 mm = 0.0641c = 27.8h

- The domain wide enough to study turbulent structures in the Coanda jet
- 3D RANS study has shown little sidewall effects at low jet-blowing case

Jet blowing conditions (at the jet exit)

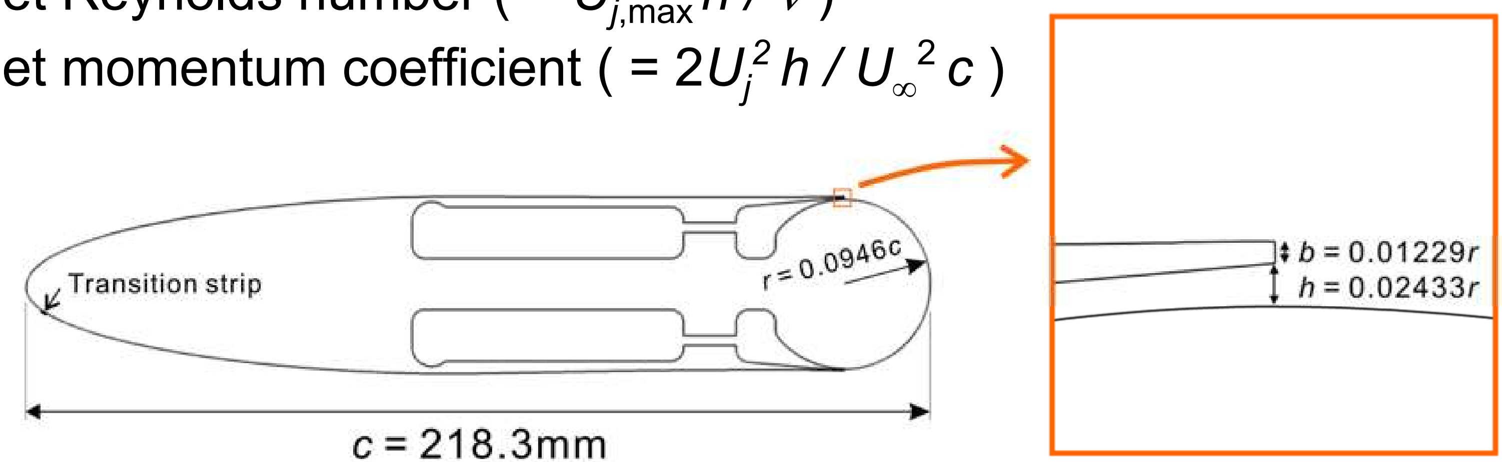
Jet-blowing rate	U_j [m/s]	$U_{j,\max}$ [m/s]	Re_j	C_μ
Low	105.3	≈ 135	≈ 4500	0.044
High	173.4	≈ 216	≈ 7200	0.120

U_j : Bulk jet velocity (mean of the time-averaged velocity profile)

$U_{j,\max}$: Maximum jet velocity (maximum of the time-averaged velocity profile)

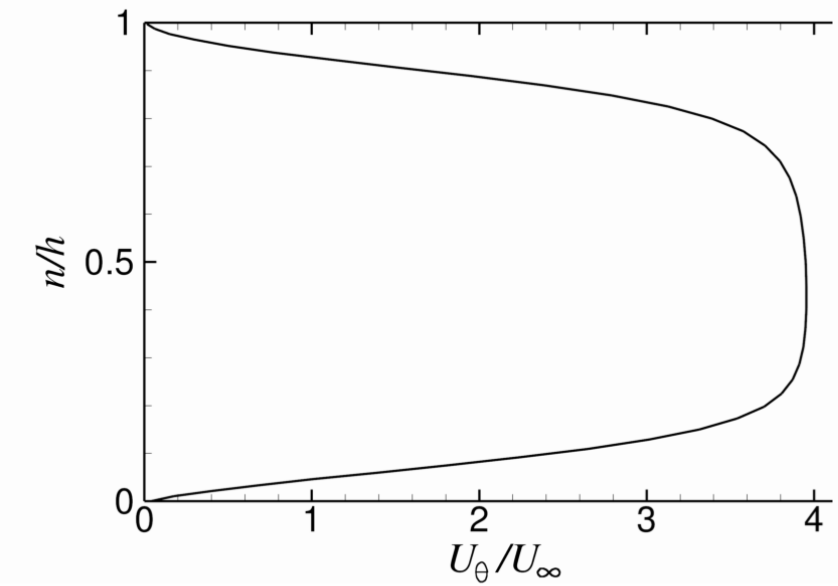
Re_j : Jet Reynolds number ($= U_{j,\max} h / \nu$)

C_μ : Jet momentum coefficient ($= 2U_j^2 h / U_\infty^2 c$)

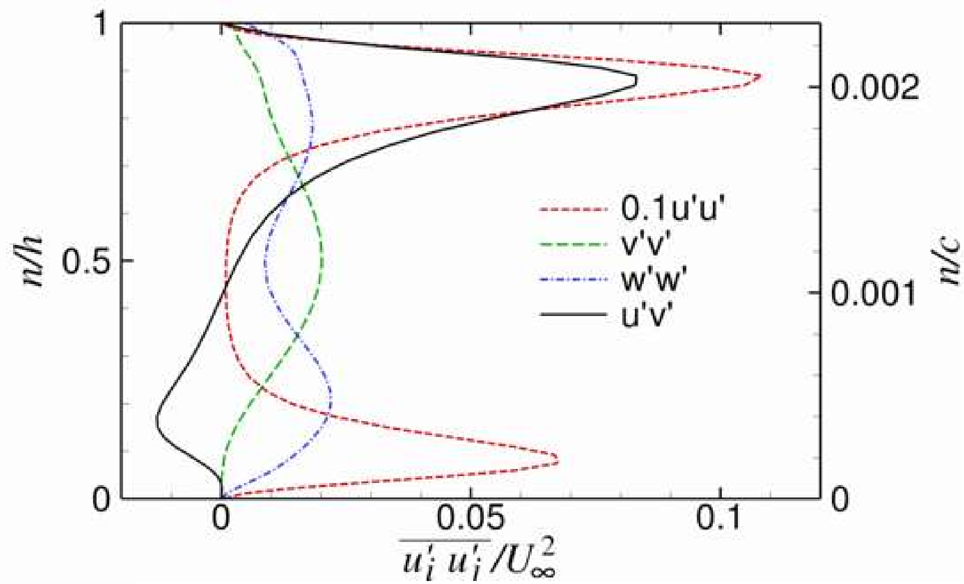


Mean flow profiles (at the jet exit)

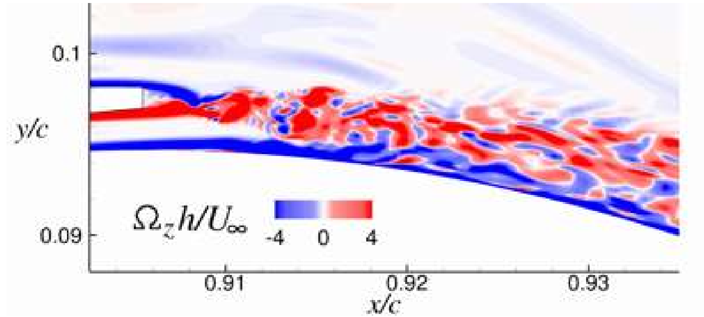
Streamwise velocity



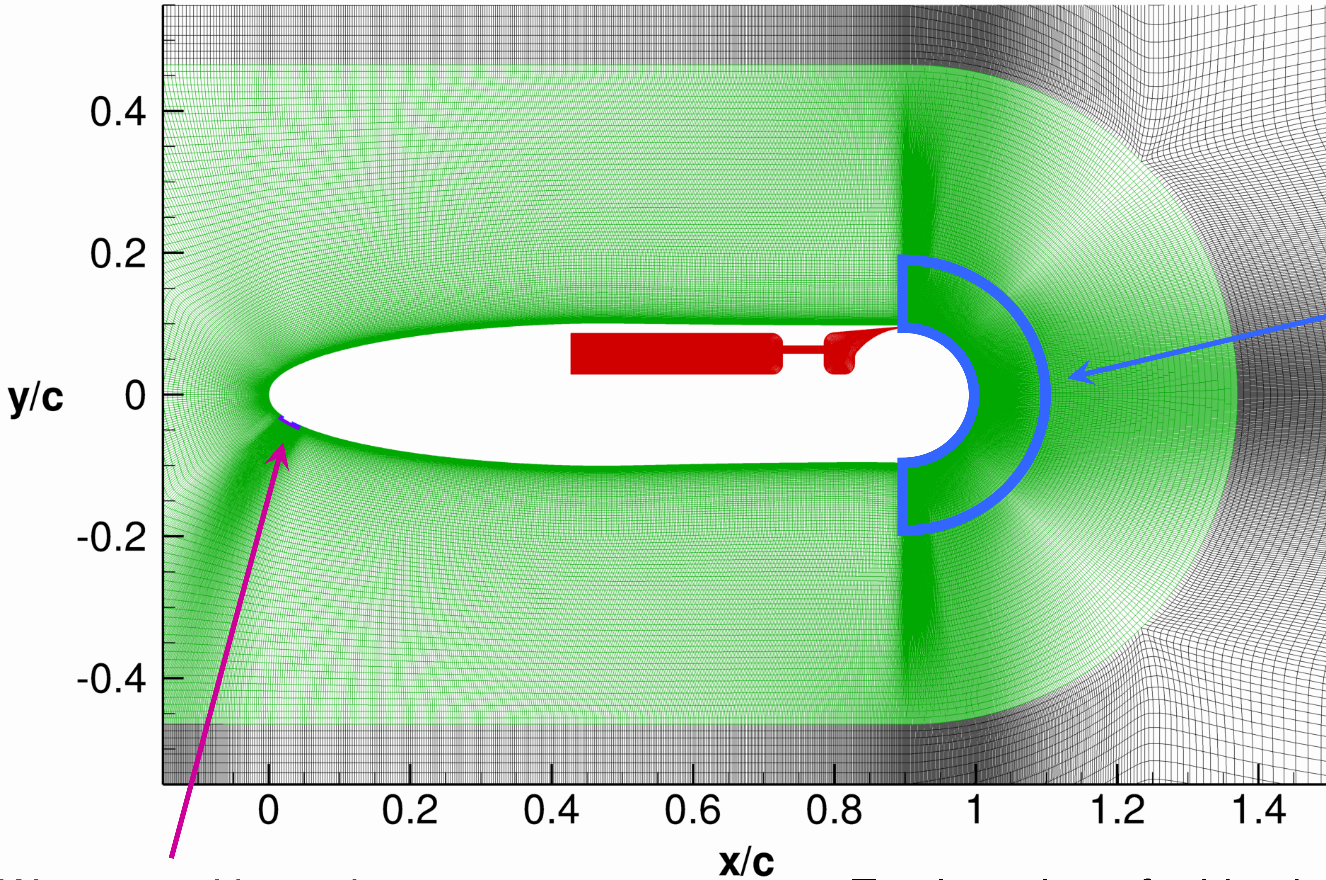
Reynolds stresses



Jet oscillating due to alternating (von Kármán type) vortex shedding behind the thin jet blade



Computational grids



Wavy transition strip

Multi-block structured grids for the whole domain

3 levels of grids for the Coanda region (Nθ x Nr x Nz)

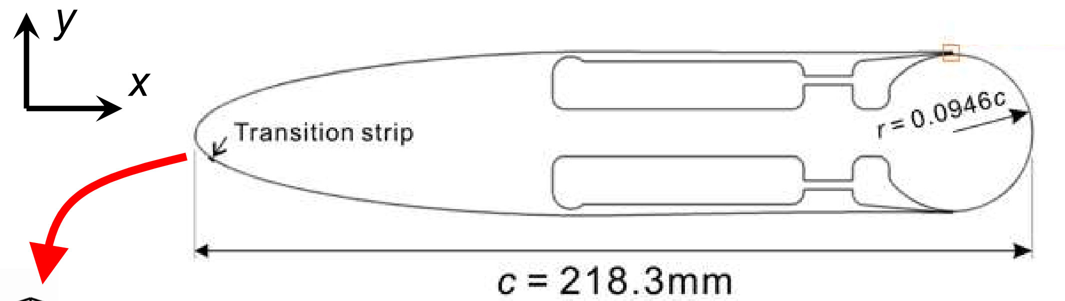
Coarse
400 x 160 x 128

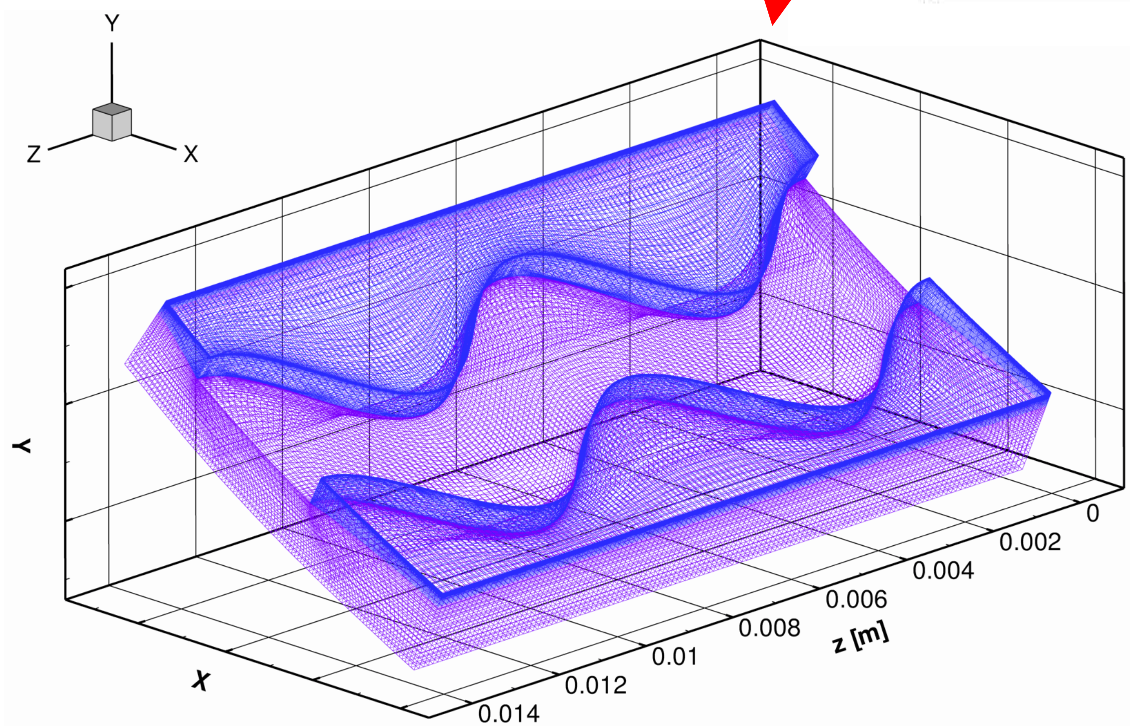
Medium
800 x 160 x 128

Fine
800 x 160 x 256

Total number of grid points: 116 million (Fine grid)

Wavy transition strip





Wavy strip directly meshed using multi-block structured grids

Strip height:	0.56 mm
Strip width:	3.0 mm
Wavelength:	7.0 mm
Amplitude:	2.0 mm

Grid resolution (Fine grid)

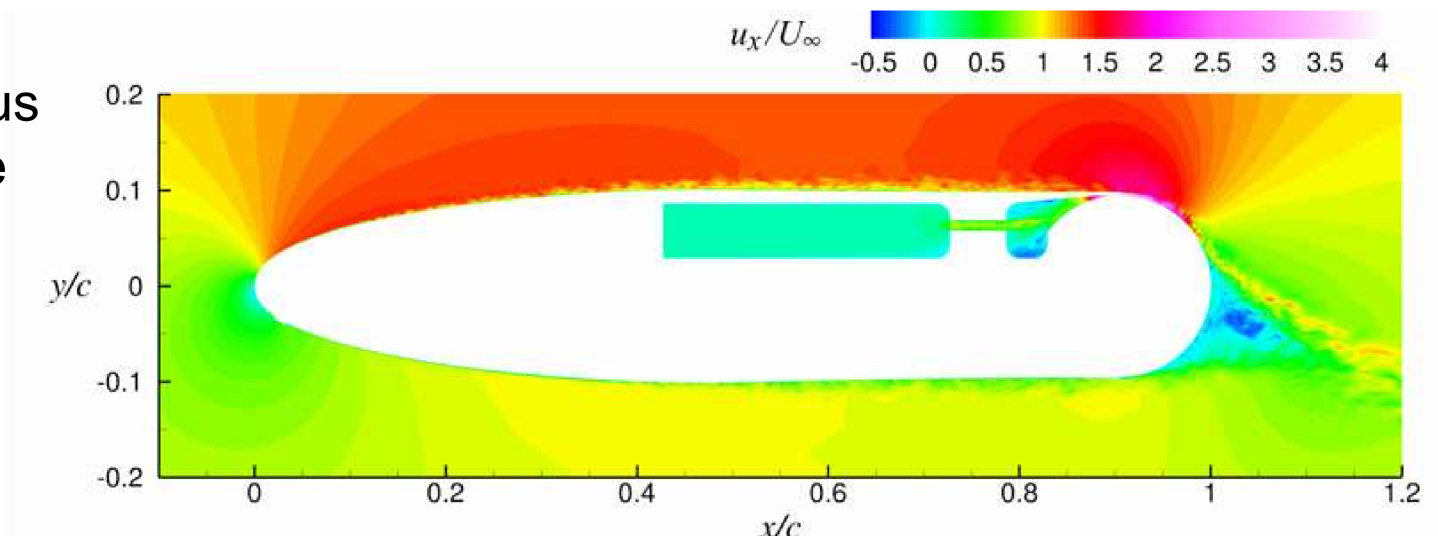
Coanda surface	Resolution [mm]	Resolution in wall units		
	$(\theta = 10^\circ \sim 170^\circ)$	$(\theta = 15^\circ)$	$(\theta = 30^\circ)$	$(\theta = 45^\circ)$
Chordwise	0.0902	≈ 95	≈ 65	≈ 30
Wall-normal	0.00127	≈ 1.4	≈ 1.0	≈ 0.5
Spanwise	0.0547	≈ 55	≈ 40	≈ 18

Airfoil surface	Resolution [mm]	Resolution in wall units	
	$(x/c = 0.5)$	(upper, $x/c = 0.5$)	(lower, $x/c = 0.5$)
Chordwise	0.4906	≈ 70	≈ 45
Wall-normal	0.00254	≈ 0.4	≈ 0.25
Spanwise	0.0547	≈ 7.5	≈ 5.0

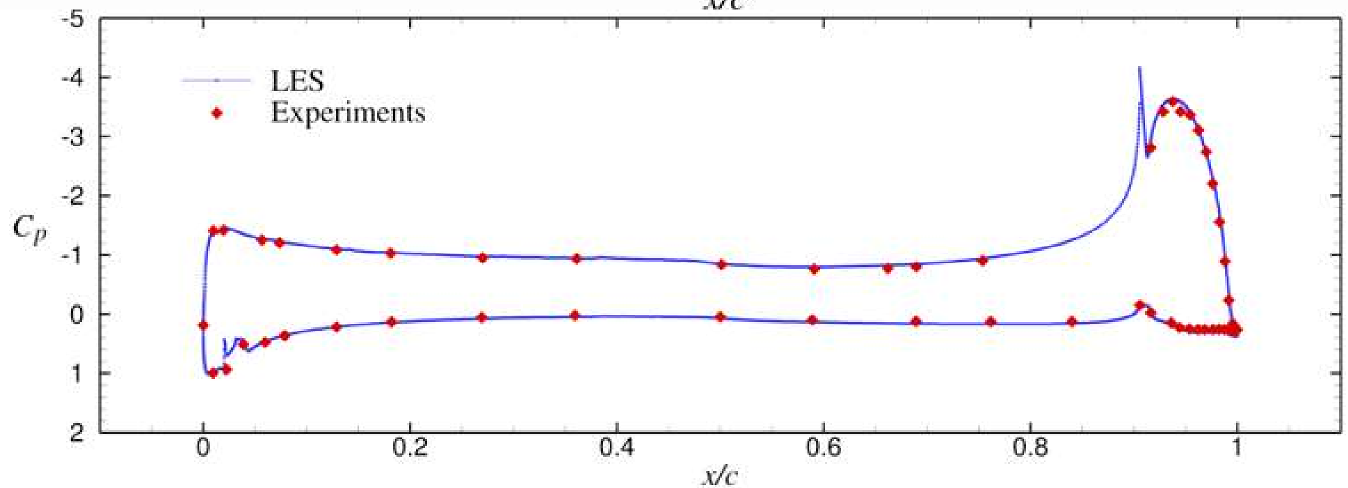
SGS eddy viscosity: Up to about 5 times larger than the molecular viscosity μ (just downstream of the jet exit, where RANS eddy viscosity is about 40 to 50 μ)

LES results: Flow around the airfoil

Instantaneous streamwise velocity

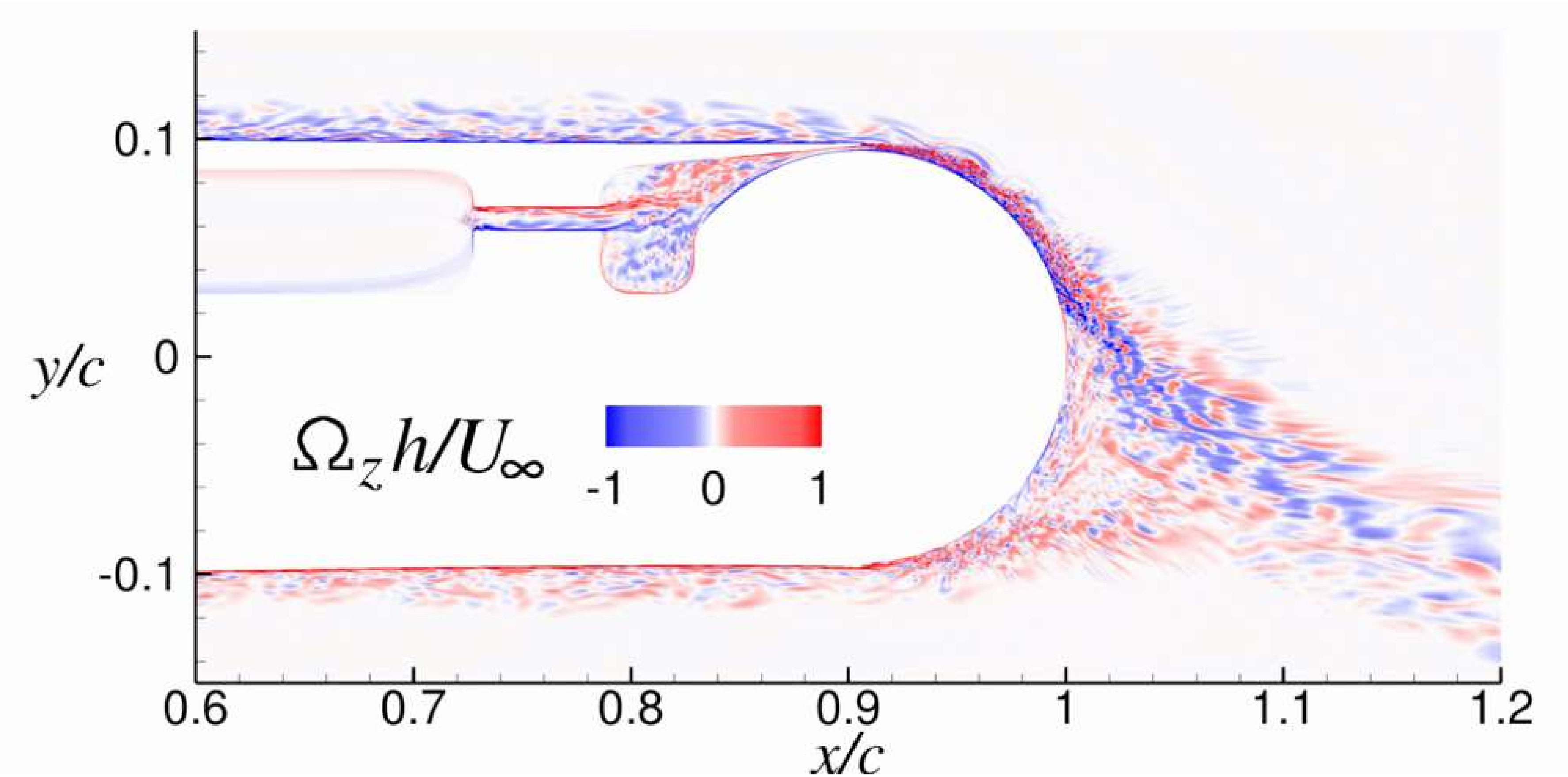


Time-averaged pressure coefficient

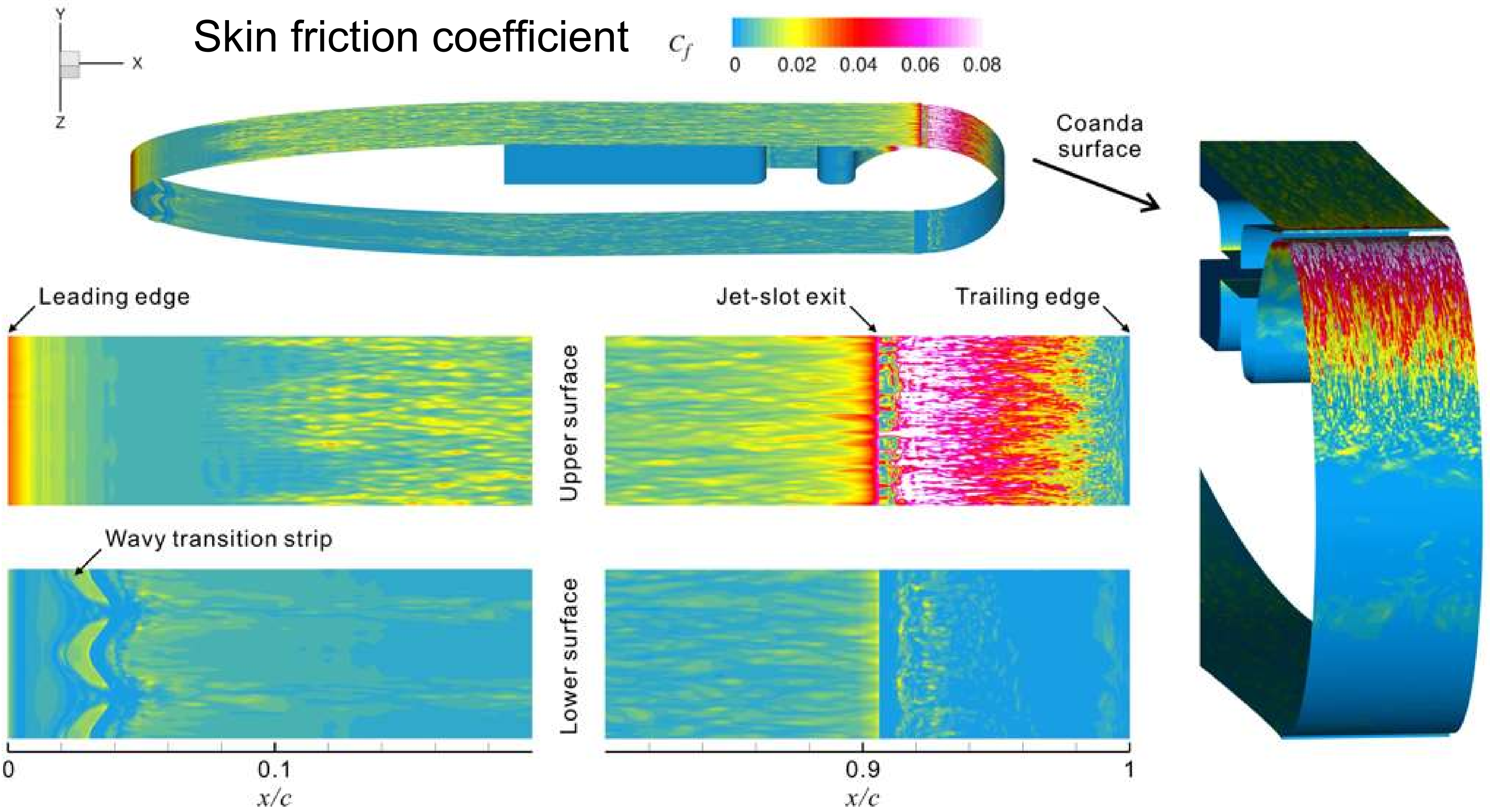


LES results: Flow around the airfoil

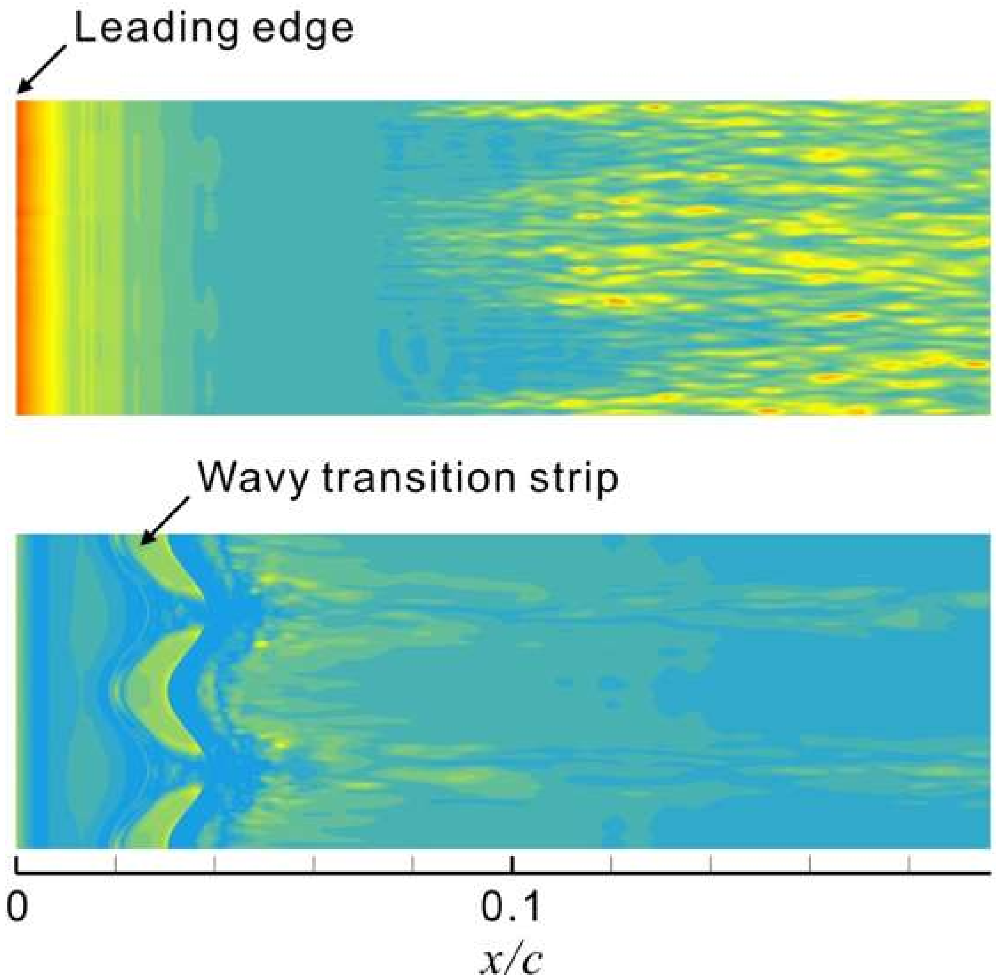
Instantaneous spanwise vorticity



LES results: Flow around the airfoil



LES results: Self-sustained transition



Turbulence was sustained with no “inlet disturbances” given in the present LES (disturbances were given to the whole domain only at the initial stage)

Upper side

Spanwise modulation

↓

Transition to turbulence sustained around x/c = 0.1

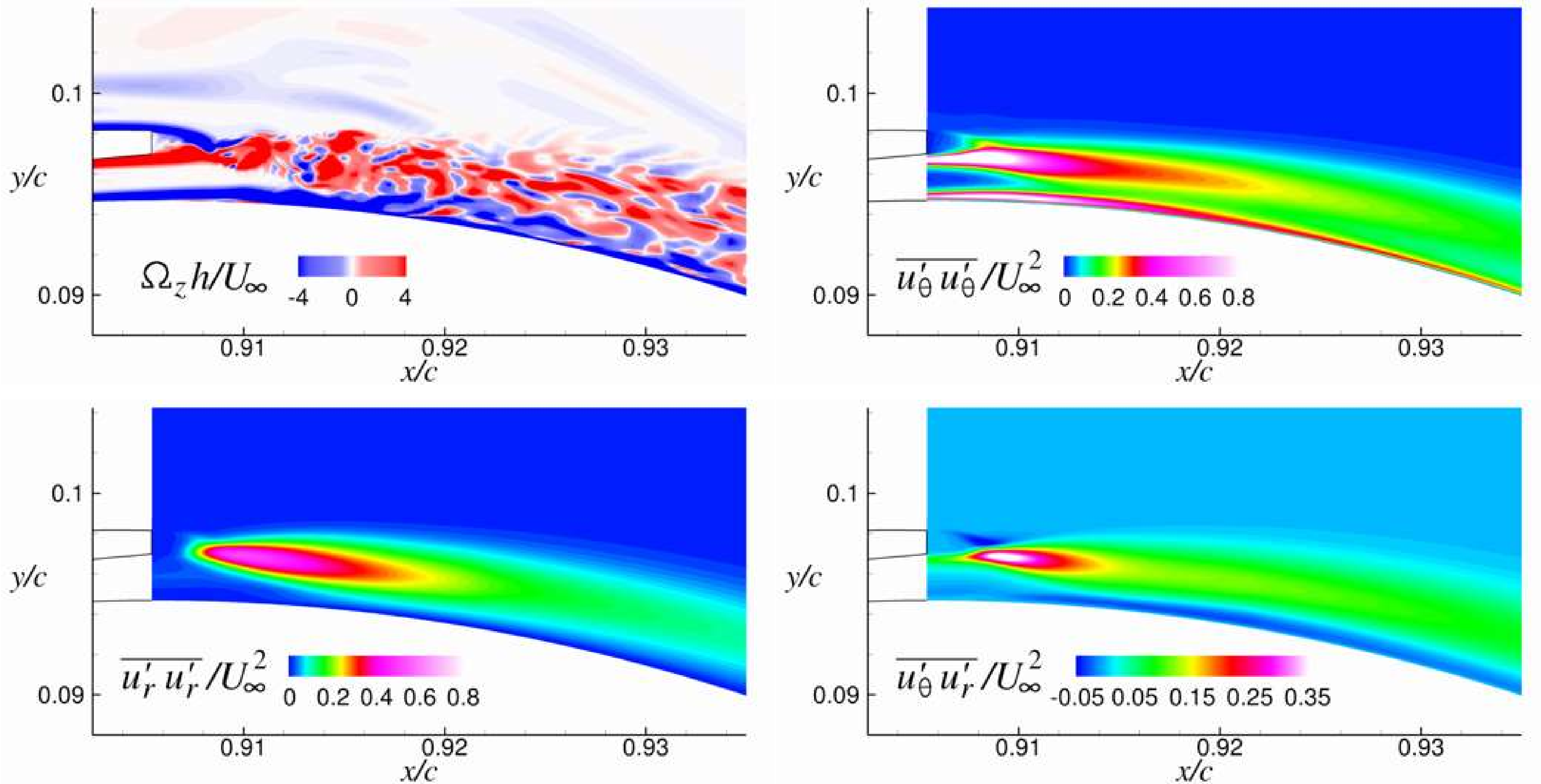
Lower side

3D separation behind the strip

↓

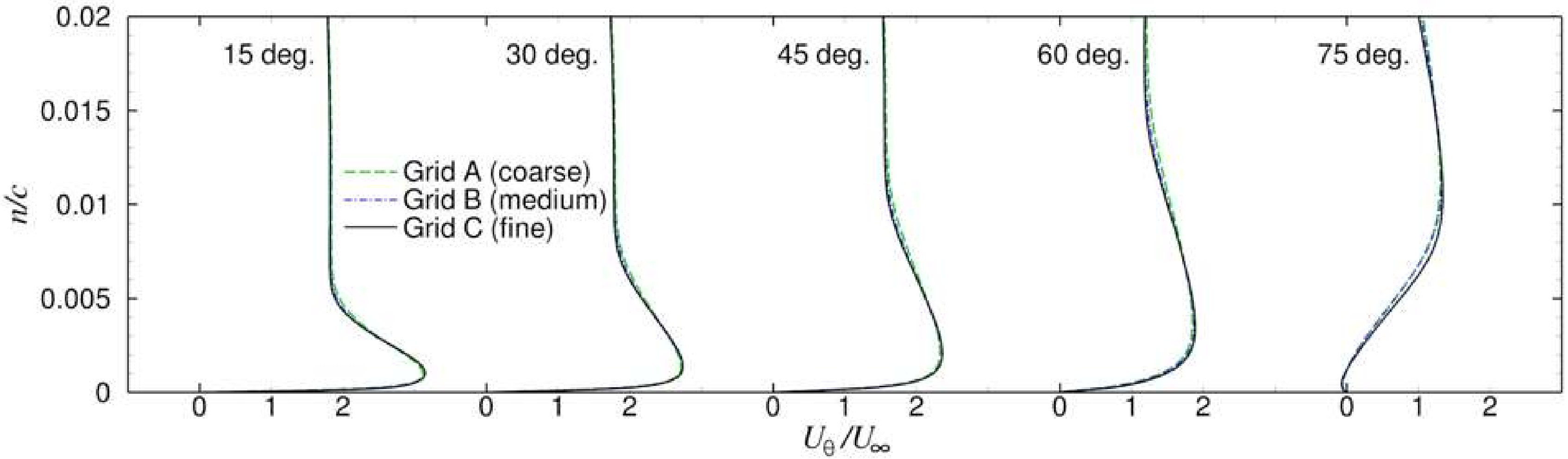
Transition to turbulence sustained around x/c = 0.4

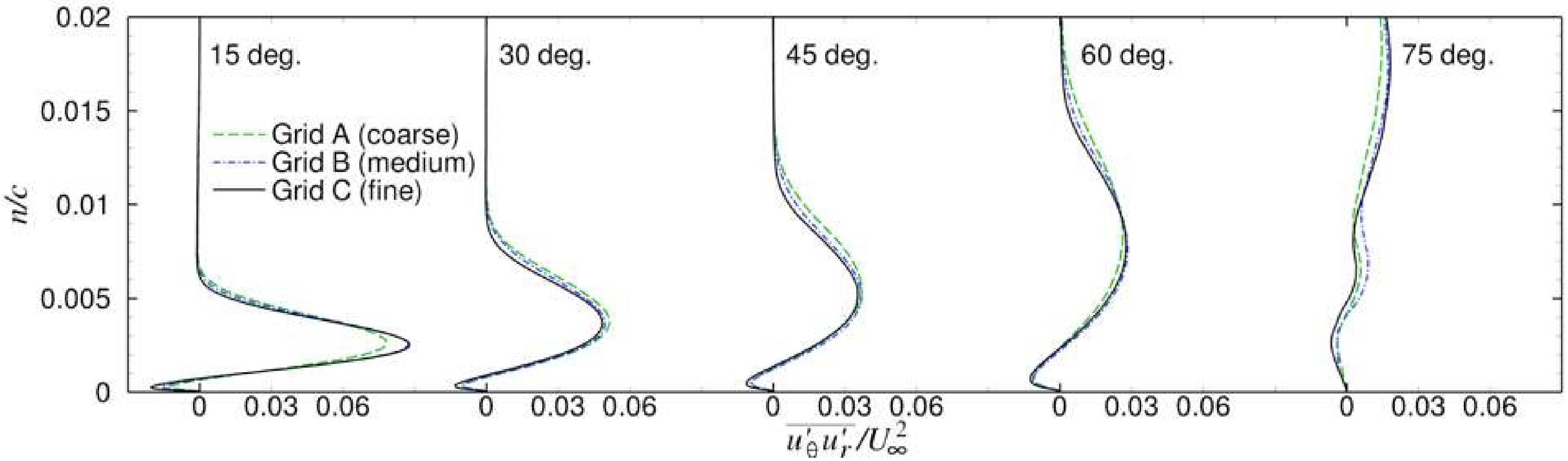
LES results: Flow around the jet exit



LES results: Coanda jet profiles

Top: Streamwise velocity
Bottom: Reynolds shear stress





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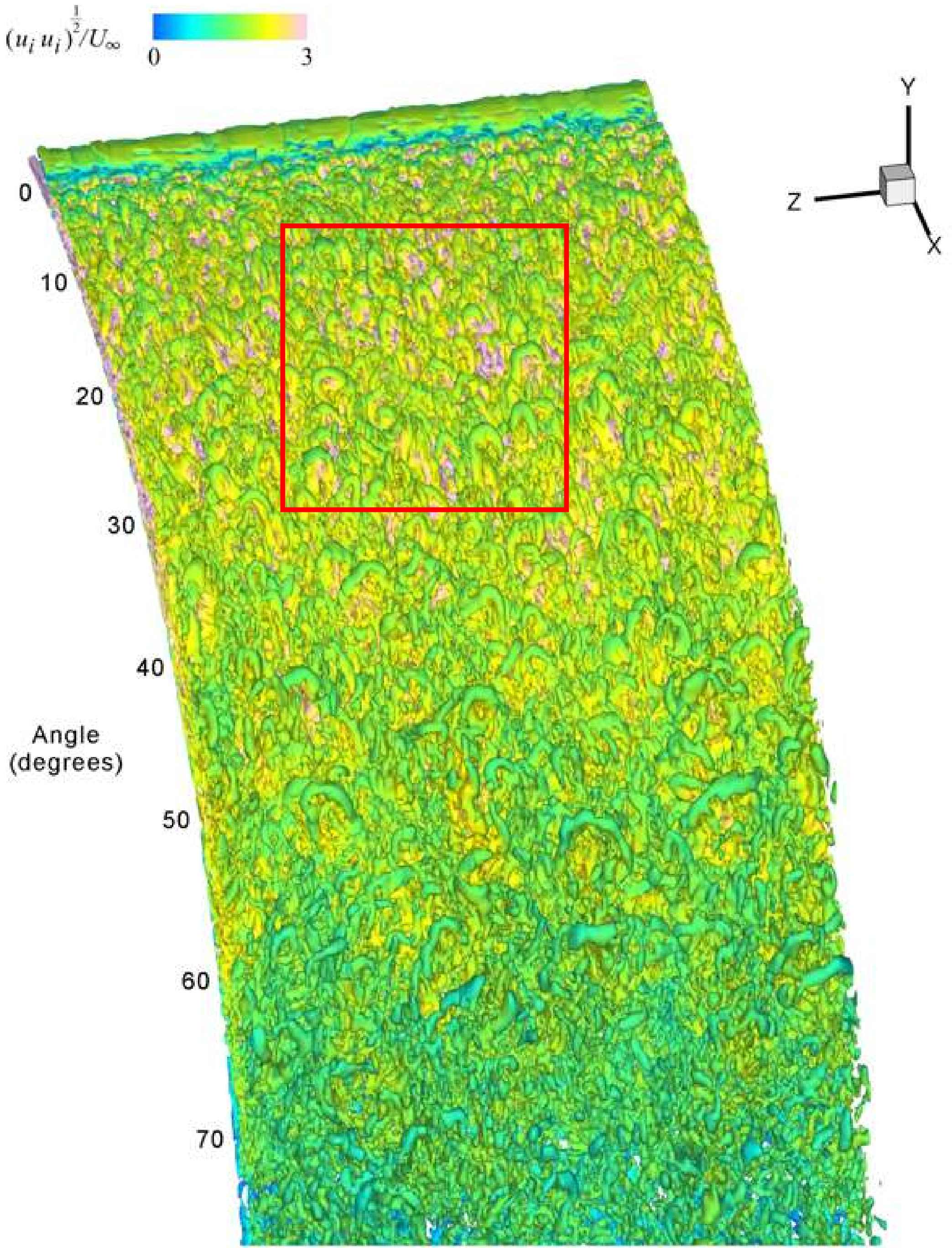
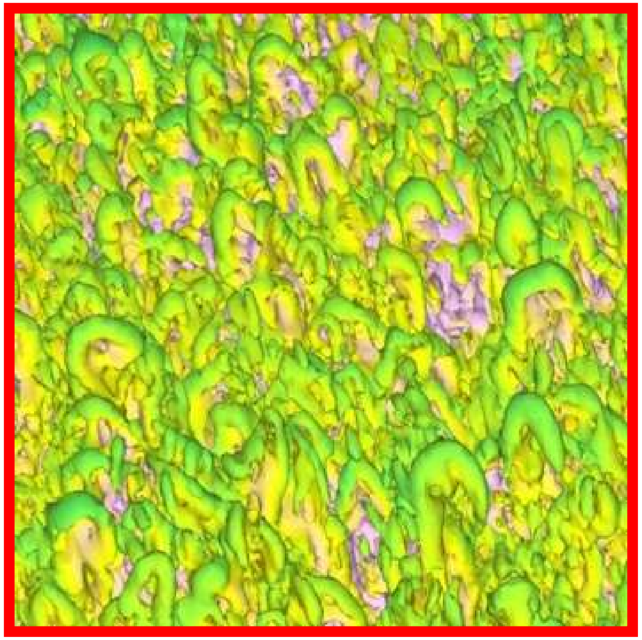
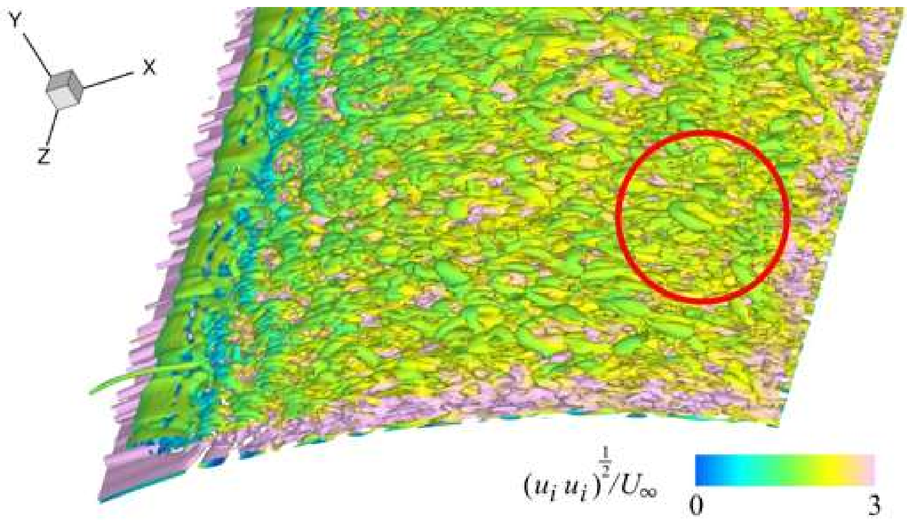
LES results: Vortical flow structures in the Coanda jet

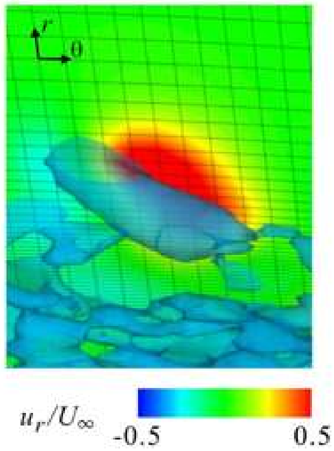
Isosurfaces of Q
(2nd Invariant of velocity gradient tensor)
colored based on velocity magnitude



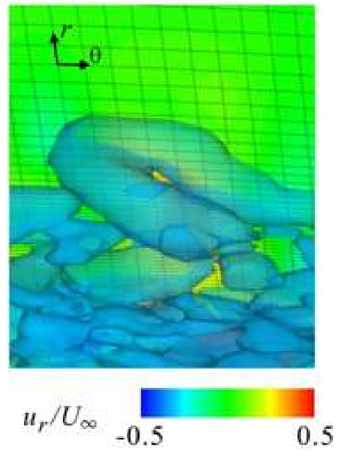


LES results: Backward-tilted hairpin vortices





Radial (r) velocity between the legs



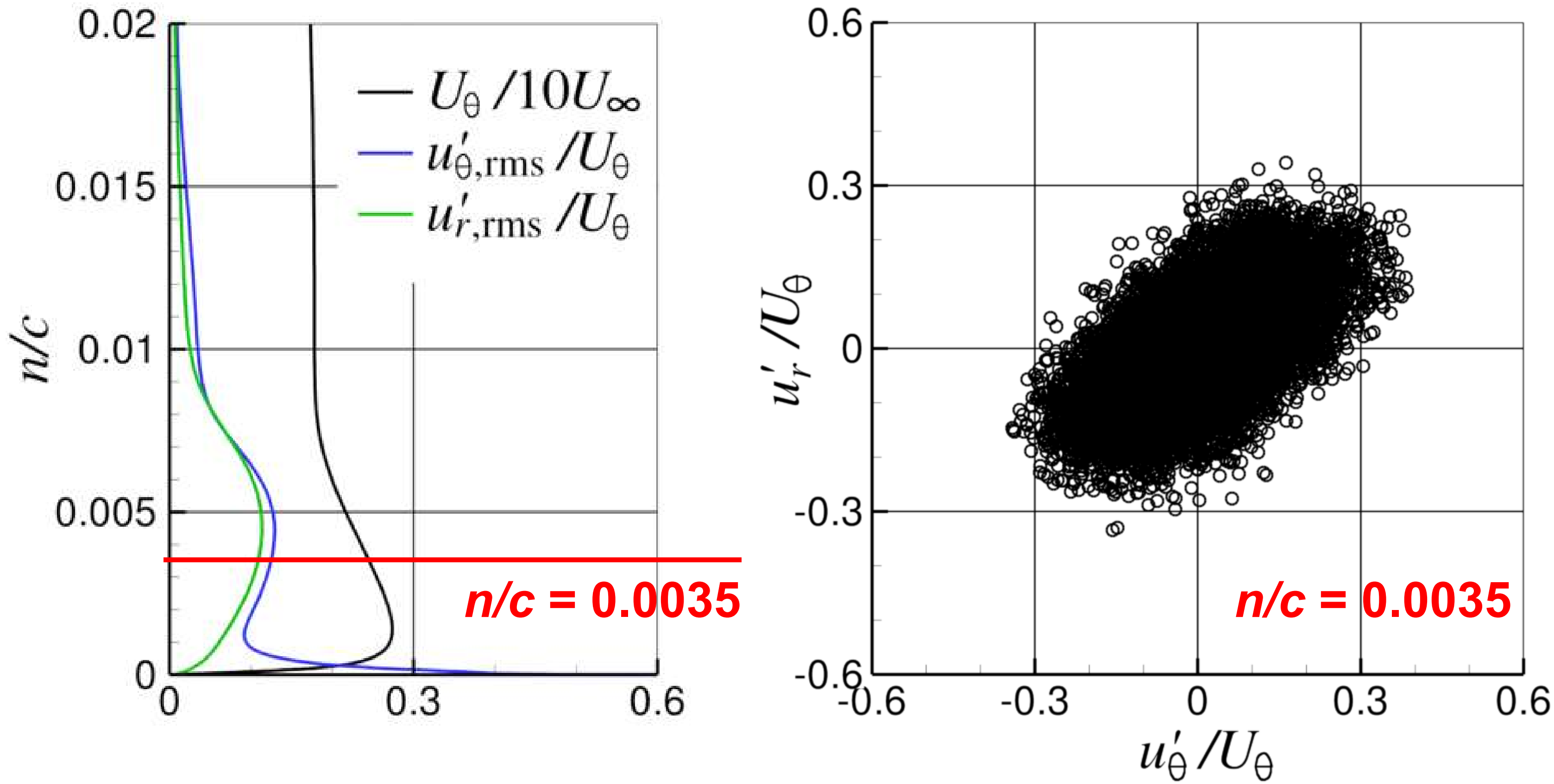
Radial (r) velocity outside the hairpin

- Backward-tilted (*i.e.*, head of each hairpin is located upstream of its legs)
- Located above the high-momentum jet flow
- Creating a strong upwash between the legs

→ Lifting the high-momentum flow upward → Turbulent mixing enhanced

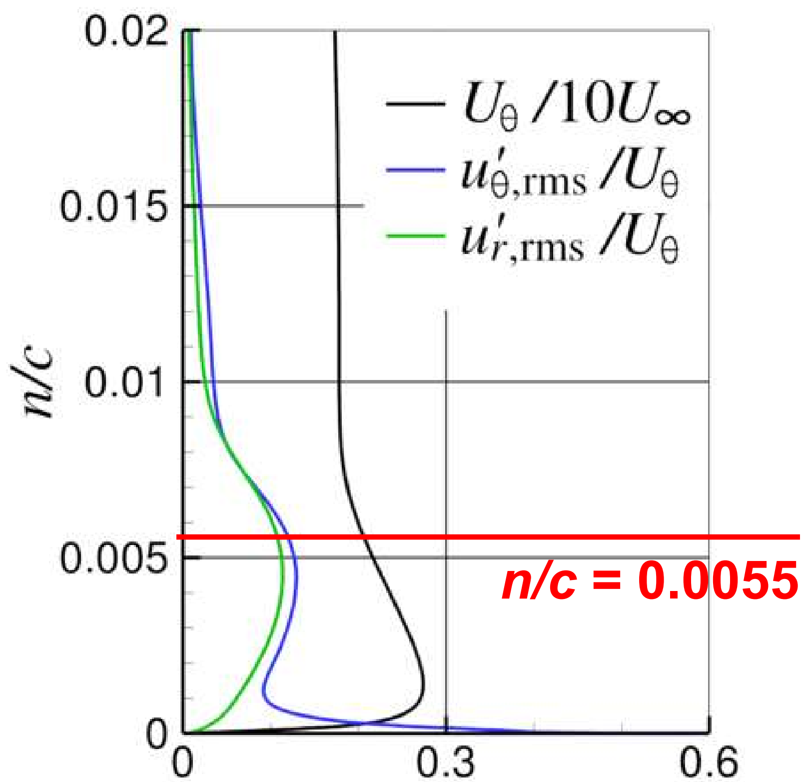
LES results: Plots of velocity fluctuations

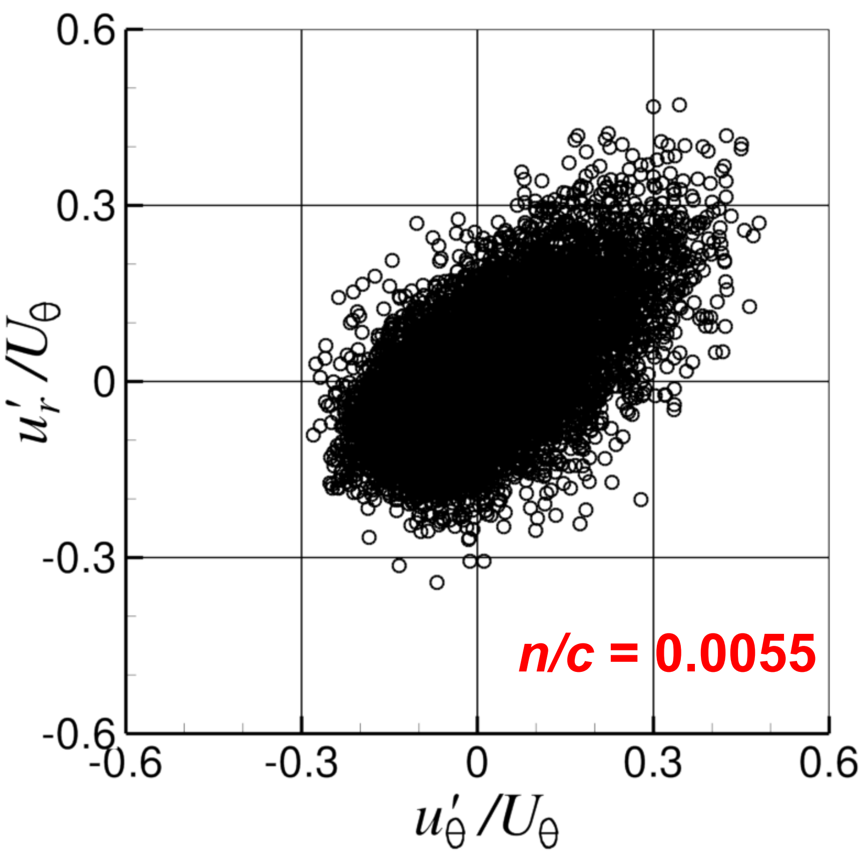
θ = 30 degrees



LES results: Plots of velocity fluctuations

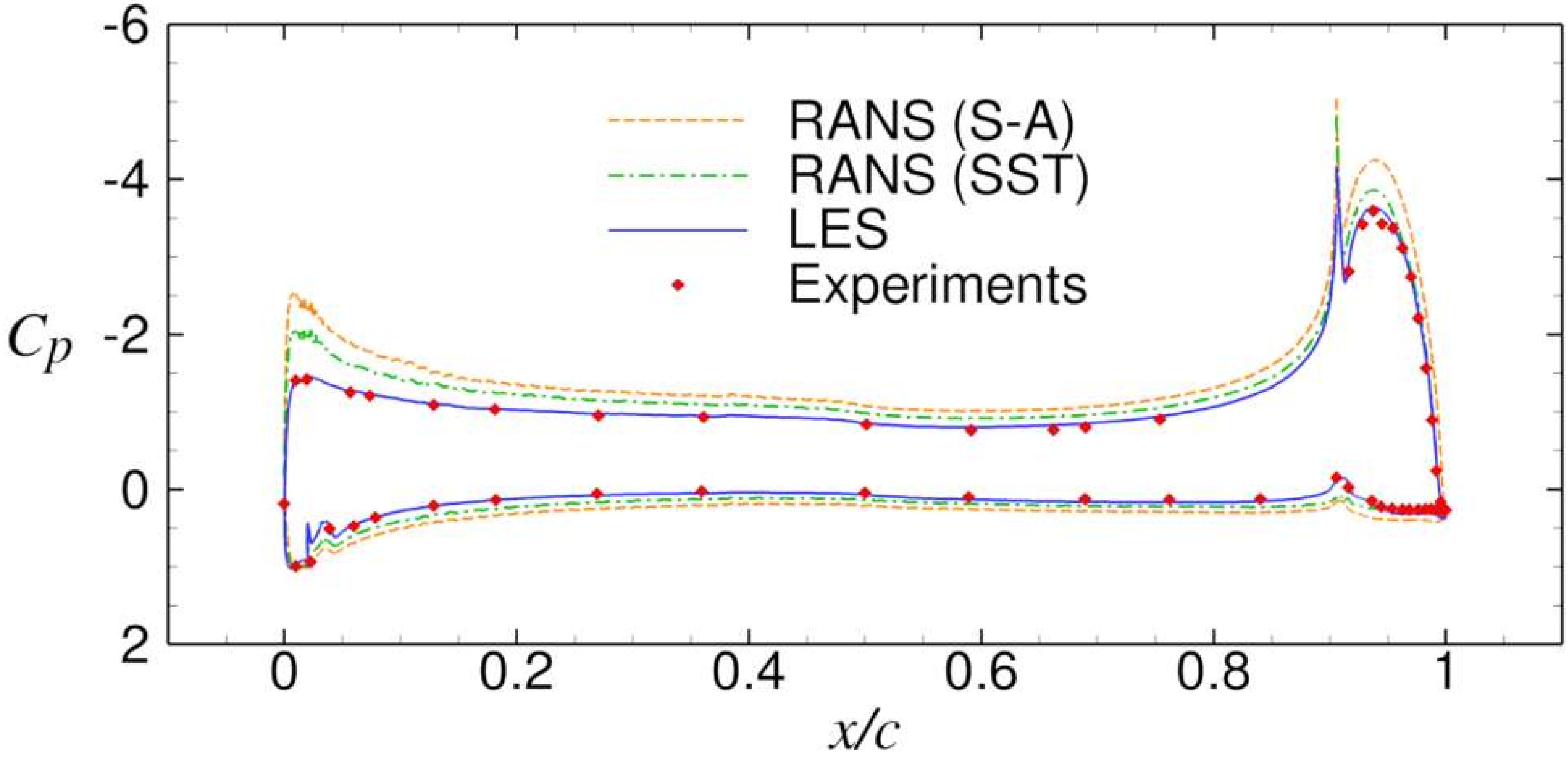
θ = 30 degrees





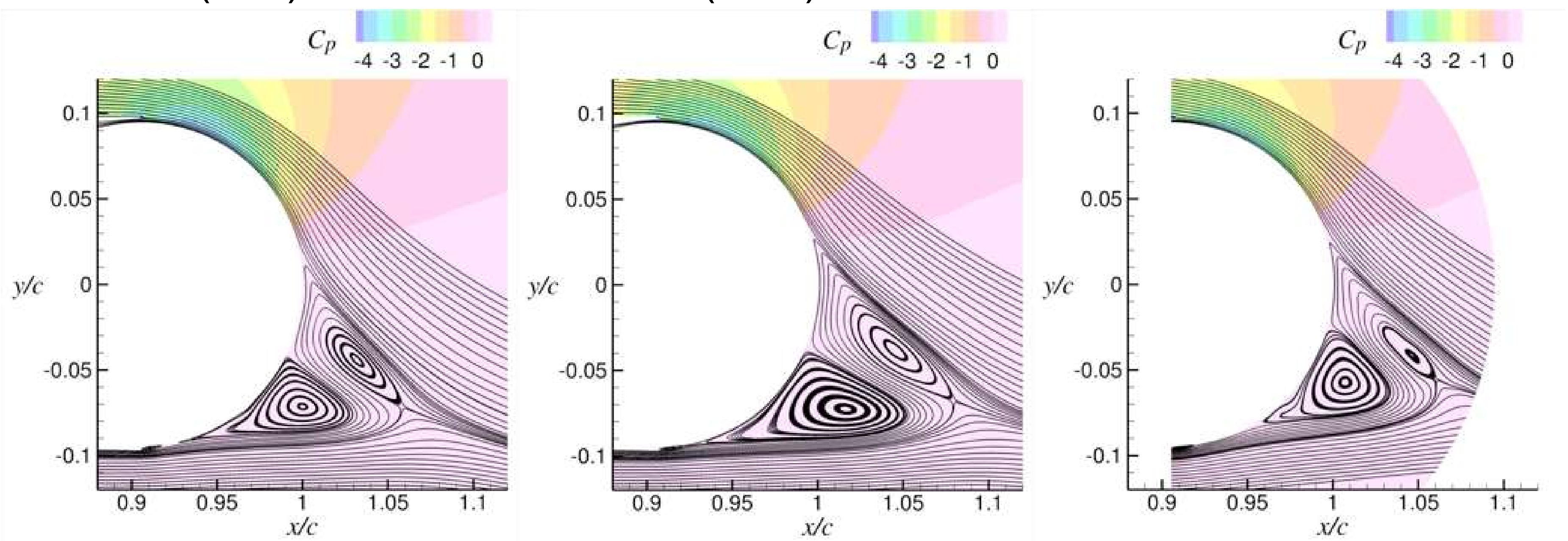
Comparisons between LES and RANS

Mean pressure distributions



Comparisons between LES and RANS

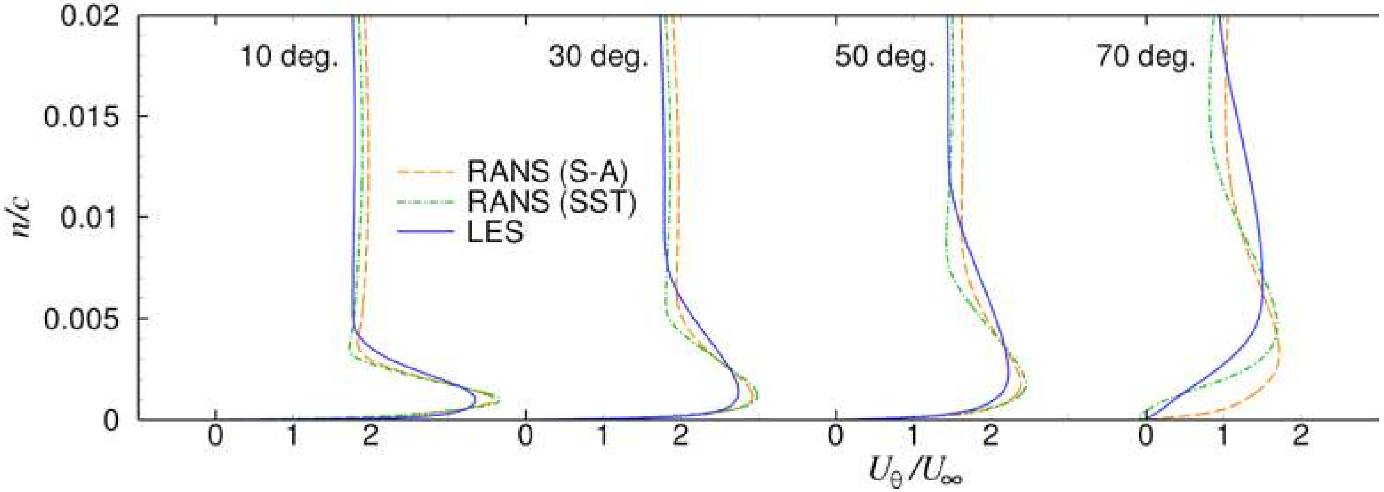
RANS (S-A) | RANS (SST) | LES



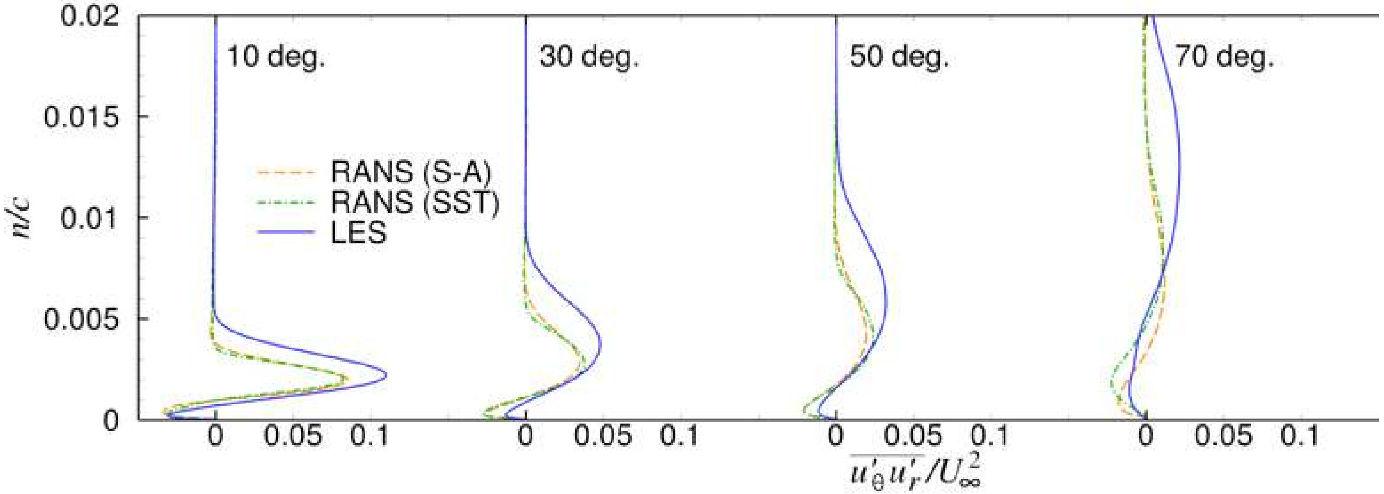
	RANS (S-A)	RANS (SST)	LES
Jet separation:	75.0 deg.	69.0 deg.	69.5 deg.
Bubble size:	0.058*c*	0.080*c*	0.060*c*
Lift coefficient:	1.85	1.60	1.36

Comparisons between LES and RANS

Streamwise velocity



Reynolds shear stress



Conclusions

High-resolution LES of a turbulent Coanda jet (applied to a circulation control airfoil) was performed and was compared with RANS results

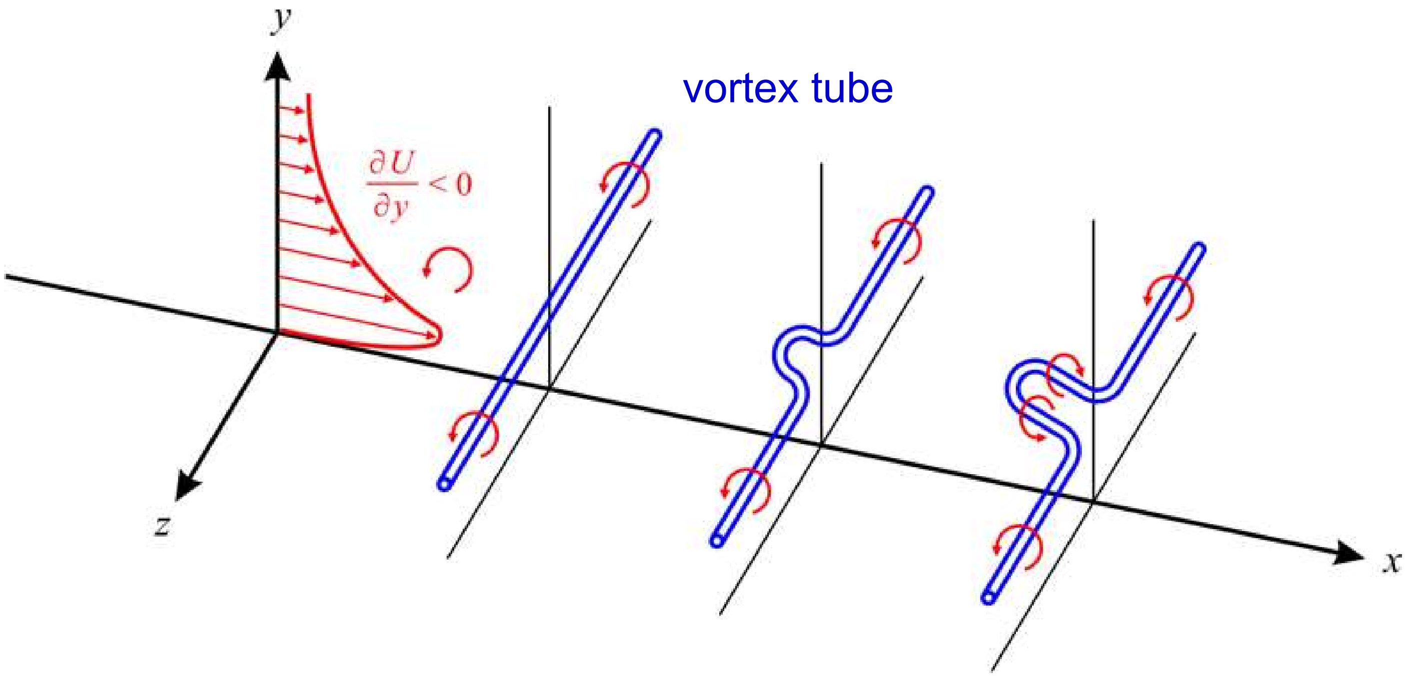
LES results:

1. Pressure distributions agreed well with the preliminary experiments
2. Many “backward-tilted” hairpin vortices were observed in the outer shear layer of the jet; the hairpins lift high-momentum flow upward

Comparisons between LES and RANS:

3. S-A and SST models predicted a larger circulation and a higher lift, even though SST model predicted a correct jet separation location
4. Both models predicted a smaller jet spreading rate than the LES as the eddy viscosity was too small in the outer shear layer of the jet

(backup slide)



Similar but opposite to "forward-tilted" hairpins in boundary-layer flows

Boundary-layer flows: $\partial U/\partial y > 0$
Wall-jet flows: $\partial U/\partial y < 0$