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High-Order Implicit Multi-Block Navier-Stokes Code: Ten-Year Experience of Application to RANS/DES/LES/DNS of Turbulence

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OUTLINE

- Requirements framing the code design
- Strategic choices made in 1994
- Overview of the code
- Details of block interface treatment
- Examples of applications
  - RANS and URANS (ECS Inlets, 3D Airfoil)
  - DES (Circular cylinder in free air and on ground plate,
    Tilt-rotor aircraft in hover, Raised runway in cross-wind,
    Simplified Landing-Gear truck)
  - LES and Noise of Subsonic and Supersonic Jets
  - DNS (Boundary Layer with VG's and LEBU's for turbulence control)

Requirements framing the effort

- NTS code was designed in 1994 as a general purpose CFD tool for solution of aerodynamic and engineering turbulent flow problems. Considering the industrial nature of the effort, the following requirements have been kept in mind when designing the code:
  - Complex geometry capability
  - Steady and time-accurate capabilities
  - Wide range of Mach number (including incompressible limit)
  - Both RANS-based and Turbulence-Resolving approaches to turbulence modeling/simulation
  - Low numerical dissipation

Strategic choices made in 1994

- Based on these requirements the following strategic choices were made:

➢ **Complex Geometry**

↓

Structured/Unstructured grids → Multi-block structured overset (Chimera) grids

➢ **Time Integration**

↓

Implicit/Explicit → Implicit for both steady and unsteady problems (crucial for high-Re flows)

➢ **Spatial Approximation**

↓

Upwind/Centered → Hybrid: weighted high order upwind and centered

➢ **Compressible/Incompressible** → Both (incompressible branch permits to save up to 50% of cpu)

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Overview of the Code

- Numerical Schemes
  - Implicit flux-difference splitting methods (based on MUSCL approach)
    - Rogers and Kwak (for incompressible flows)
    - Roe (for compressible flows)
    - Weiss and Smith with low M preconditioning (for compressible flows at arbitrarily low M)
- Spatial discretization
  - Inviscid fluxes
    - 3^{rd} or 5^{th}-order upwind-biased
    - 4^{th}-order centered
    - Hybrid (weighted upwind/centered) with blending function dependent on solution or specified by user (these are needed for turbulence resolving approaches - DES, LES, or DNS)
    - Set of flux limiters for compressible flows with shocks
  - Viscous fluxes
    - 2^{nd}-order (default); 4^{th}–order (optional) centered schemes

Overview of the Code

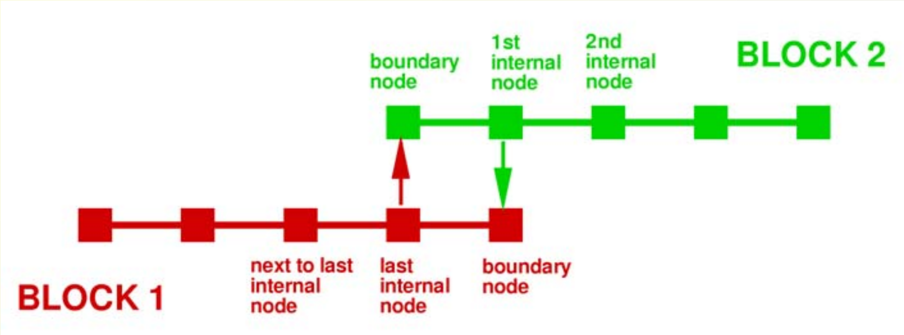
- Time integration
  - Three-layer backward 2nd - order scheme with dual time-stepping and sub-iterations in pseudo time with “infinite” pseudo-time step
  - Types of implicit relaxation (can be different for gas-dynamic and turbulence model equations)
    - Gauss-Seidel relaxation by planes/lines
    - LU relaxation
    - Diagonally dominant approximate factorization (DDADI)
- Block-linked numerical features
  - Type of implicit relaxation
  - Spatial discretization and limiters (for shocked flows)

Overview of the Code

- Parallelization
  - Hybrid concept combining MPI and Open MP technologies (permits to adjust the code to hardware with shared, distributed or mixed memory structure)
- Turbulence treatment
  - RANS and URANS with a wide variety of turbulence models (S-A and SARC, Secundov, Wilcox, Menter SST, Launder-Sharma k-ε, Reynolds-Stress Transport Speziale-Sarkar-Gatski)
  - Turbulence Resolving Approaches (DES, LES, and DNS)

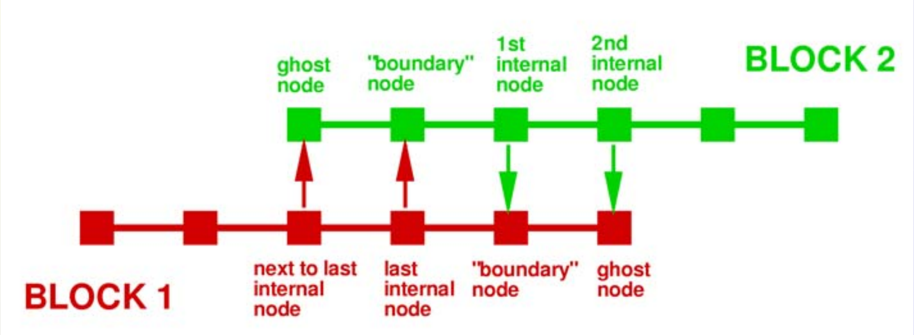
Details of Block-Interface Treatment

- At least one-cell overlap
- Two types of inter-block communication
  - Recipient nodes only at block boundaries



- Special approximations are needed at near-boundary nodes (2nd order centered approximation of inviscid fluxes)

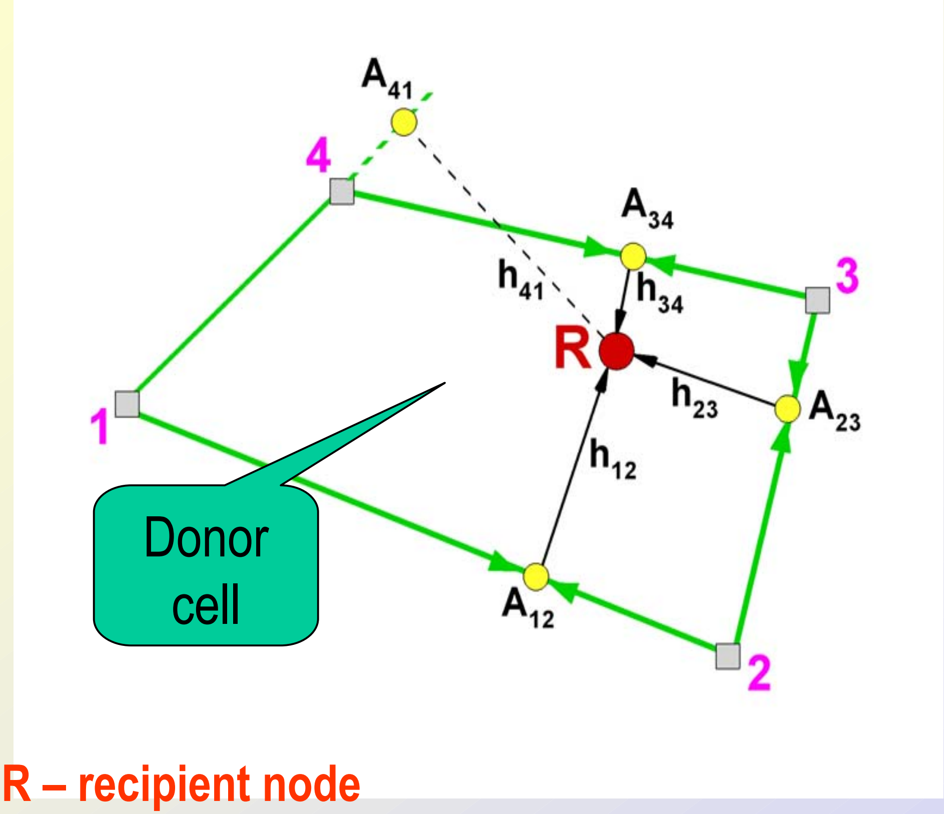
  - Recipient nodes at block boundaries and at least one ghost node



- At least 3 cells overlapping
- Special approximations may be needed only with the 5th order upwind scheme
- This approach is always used for artificial blocks introduced for MPI-parallelization

Details of Block-Interface Treatment

• Interpolation Procedure (2D case)



R – recipient node

1,2,3,4 – vertices of the donor cell (tetragon)

h_{ik} and A_{ik} – normals to cell sides and their bases

Algorithm

i. Define normals from recipient node to donor cell sides (h_{ik} and A_{ik})

ii. Obtain parameters at points A_{ik} by linear interpolation (extrapolation is forbidden, i.e., normals starting outside the donor cell are not used)

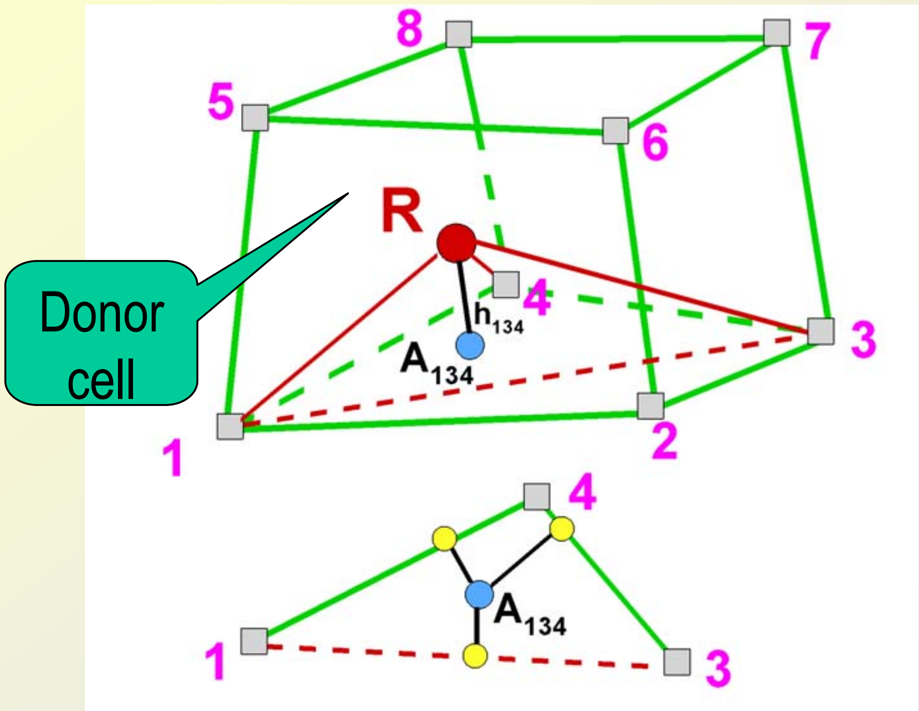
iii. Obtain parameters at recipient node R by $(1/h_i)^4$-weighted interpolation:

$$f_R = (\sum_i f_{A_i} / h_i^4) \, / \, (\sum_i 1 / h_i^4)$$

• If R gets to a physical boundary (wall), the boundary conditions are satisfied automatically

Details of Block-Interface Treatment

• Interpolation Procedure (3D case)



R – recipient node
1 … 8 - vertices of the donor cell
h_{ikm}– normals to tetrahedrons' bases

Algorithm

i. Divide donor cell into 12 tetrahedrons
ii. Define normals h_{ikm} from recipient node to tetrahedrons' bases
iii. Obtain parameters at points A_{ikm} inside triangles (tetrahedrons' bases) as in 2D case
iv. Obtain parameters at recipient node R by $(1/h_{ikm})^4$-weighted interpolation

Details of Block-Interface Treatment

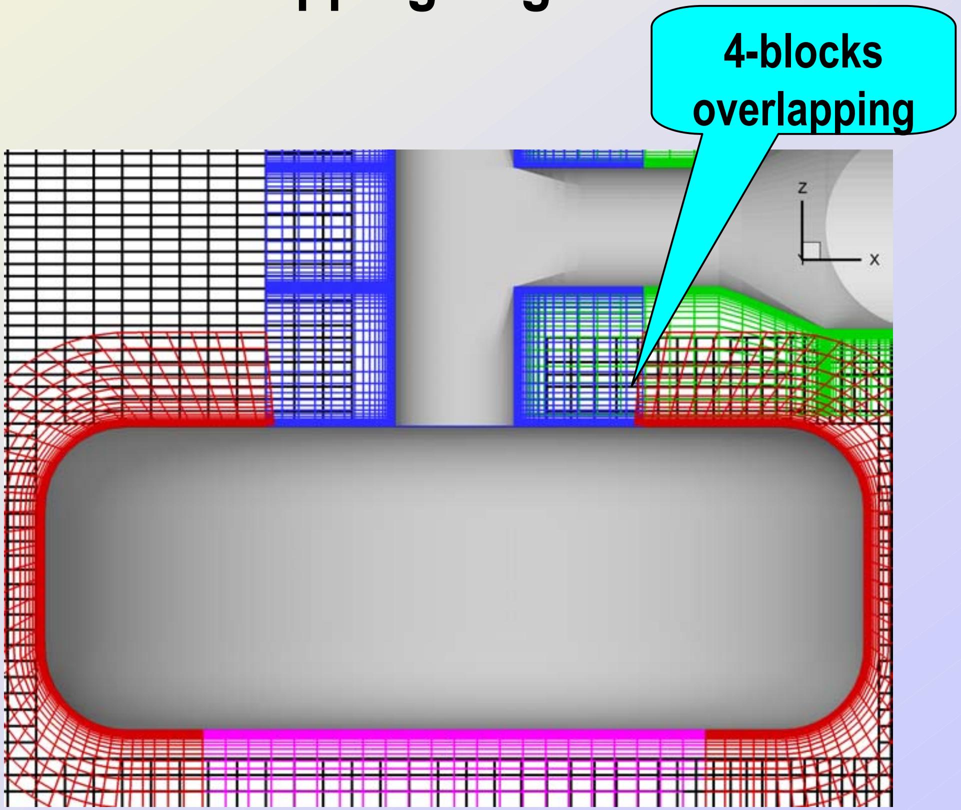
- Choice of Donor Cell in Multiple Blocks Overlapping Regions

3 options of choosing the "best" donor cell are available in the code:

i. Cell with volume closest to the volume of recipient cell (default)

ii. Cell with minimum volume

iii. According to user-specified block priorities

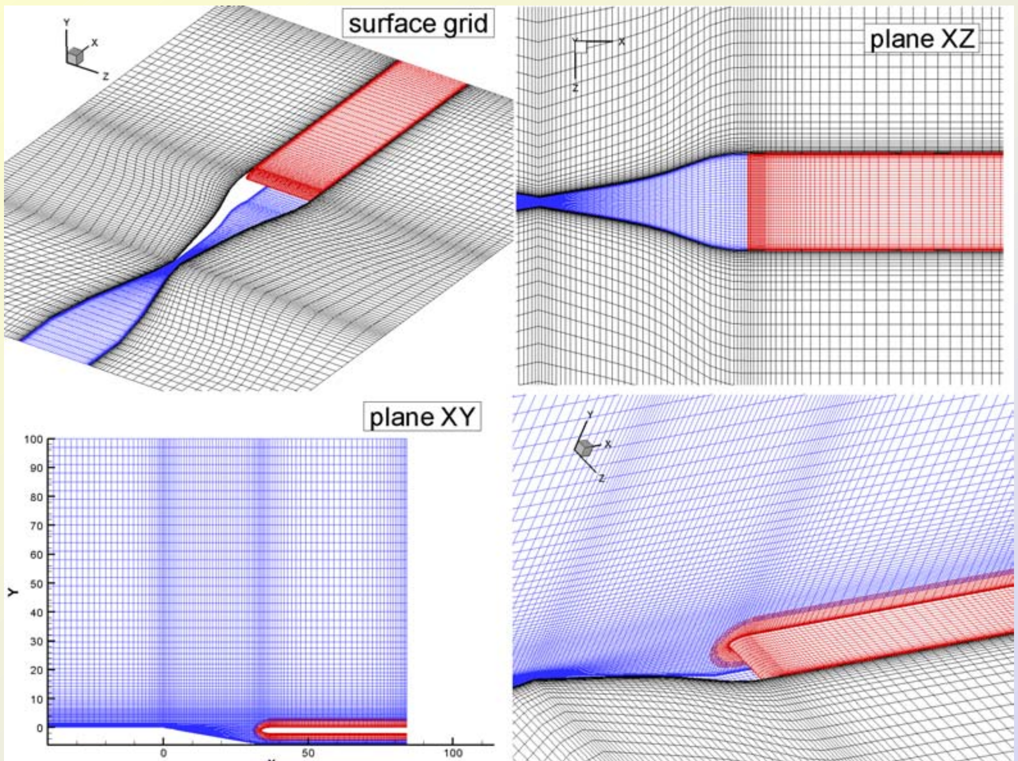


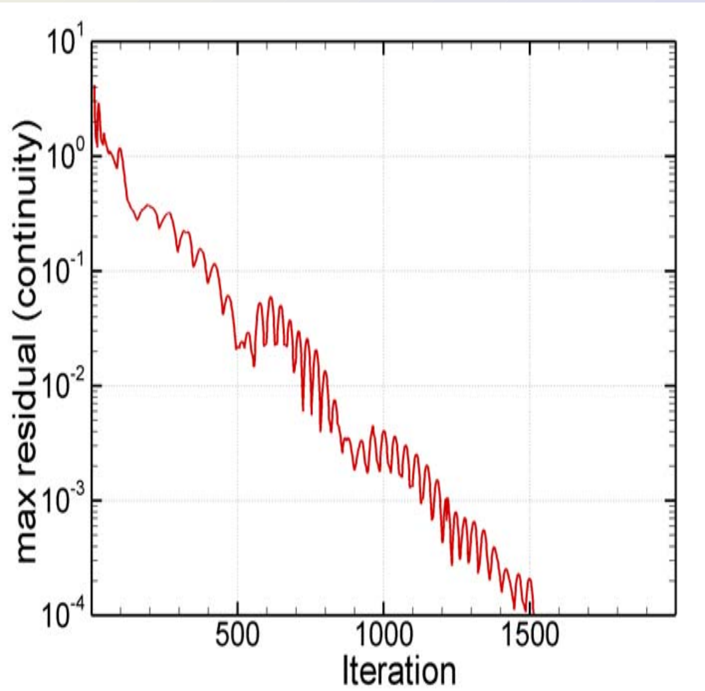
Fragment of grid for DES of Landing Gear Truck

RANS and URANS Applications

- A wide range of RANS computations have been performed with the code
- Typical practice is:
  - 3^{rd} order upwind approximation of the inviscid fluxes
  - Inter-block communication only via block boundary nodes
- A few typical examples are considered below

3D S-A RANS of NACA Inlet for Environmental Control System

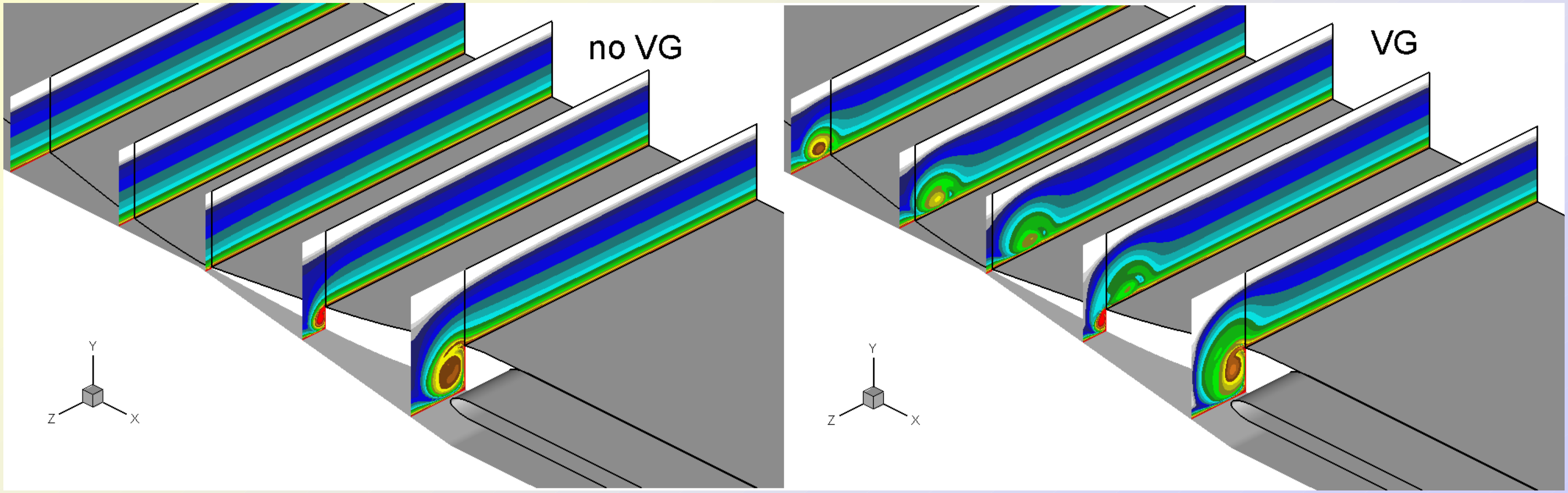




Typical convergence history

- <u>Three-block grid (1.3M nodes total):</u>
  - Main block
  - Lip block
  - Body, ramp, and duct block

SARC RANS of NACA Inlet with VG's modeled by body force



Effect of Vortex Generators on flow structure

- No non-smoothness at the block interface is observed
- VG's result in a significant increase of the Inlet efficiency

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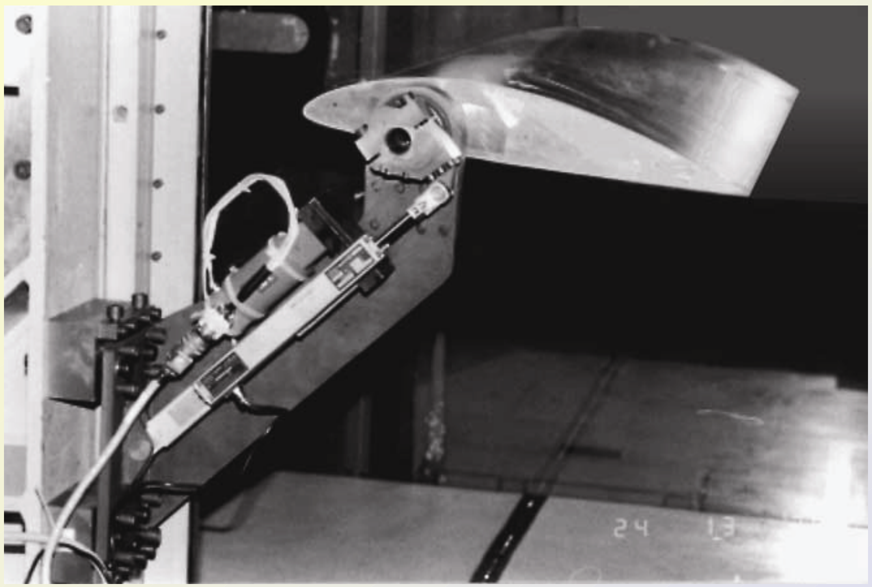
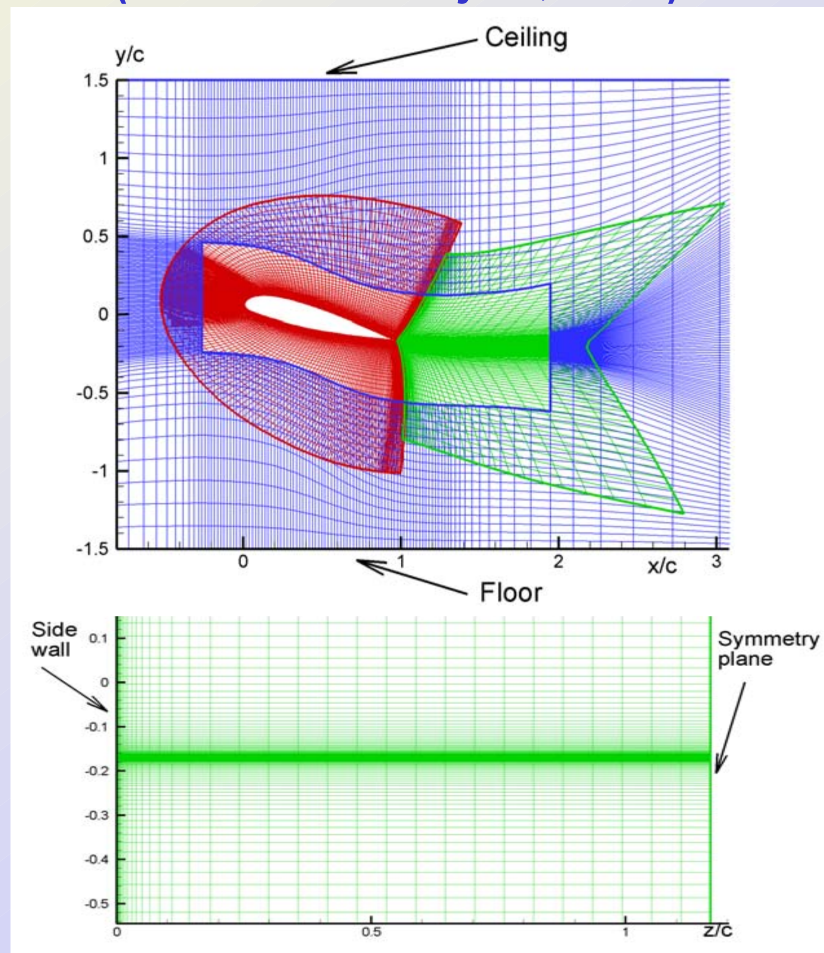
3D RANS of Aerospatiale A-Airfoil in Rectangular Test-Section ($Re=2.1x10^6$, $aoa=13^o$, $M=0.15$)

A.Garbaruk, D.Magidov, M.Shur, M.Strelets (FLOMANIA Project, 2003)



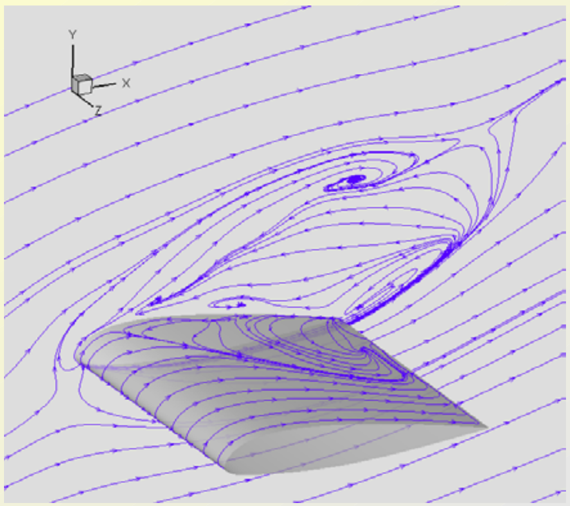
Experimental setup



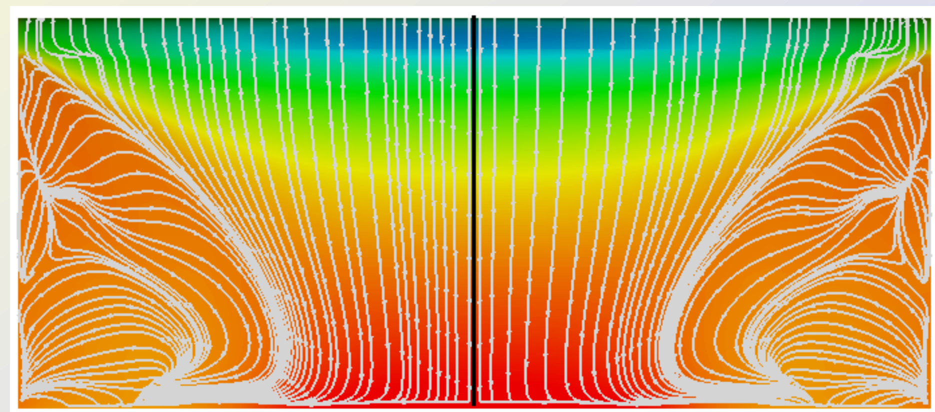
- **Three-block grid (2.4 M nodes total):**
  - Main block
  - Airfoil (C-type) block
  - Wake block

3D RANS of Aerospatiale A-Airfoil in Rectangular Test-Section

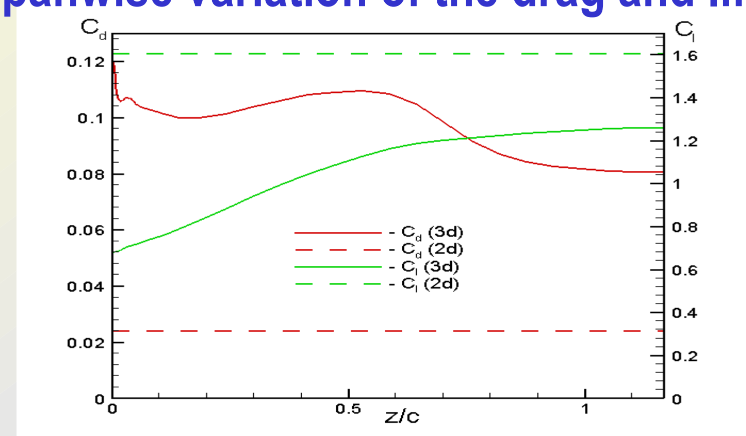
Surface and side-wall streamlines



CFD streamlines and pressure



Spanwise variation of the drag and lift



- Comparing with experimental oil-flow viz, CFD significantly over-predicts effect of sidewalls (size of separation zone at the airfoil - wall junction)
- Side-wall BL thickness was based on educated guess
- Similar result was obtained for RAE 2822

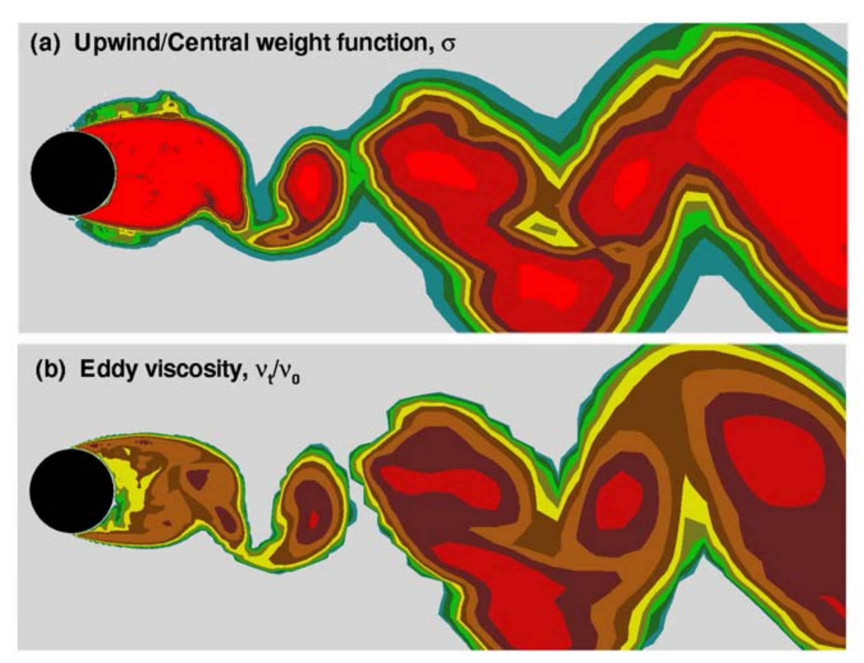
DES Applications

- DES was implemented for the first time in this code (1997)
- Typical practice is:
  - Inter-block communication
    - Via block boundary nodes and additional ghost, nodes in case of periodicity bc's and artificial blocks for MPI parallelization
    - Via block boundary nodes only in all other cases
  - Hybrid (3rd order upwind / 4th order centered) approximation of the inviscid fluxes with solution-dependent blend function

Hybrid Upwind / Centered Approximation

$$F = \sigma F_{CTR} + (1-\sigma) F_{UPW}, \quad 0 \le \sigma \le 1.0$$

where σ is “empirical” solution-based blending function

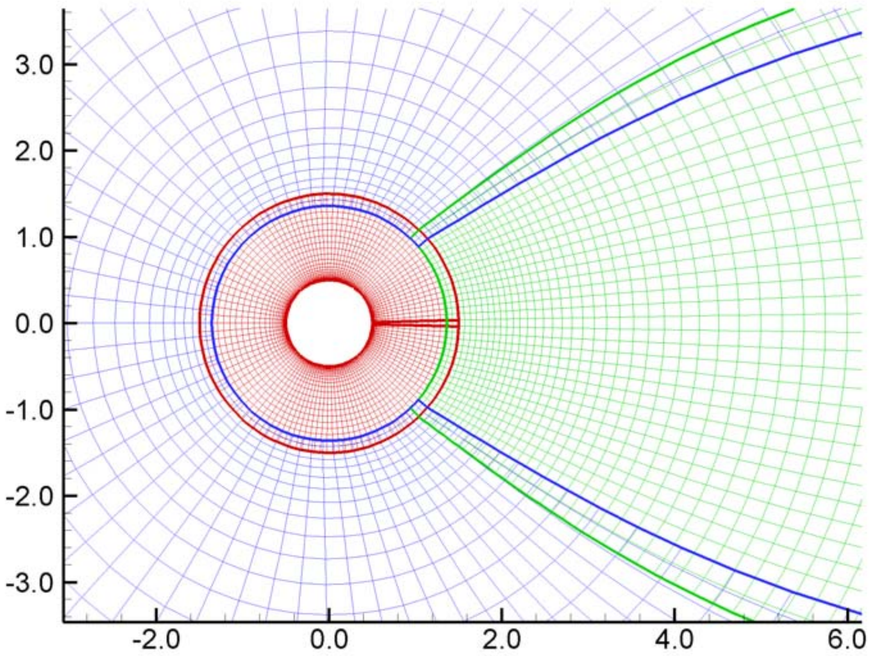


Snapshots of the blending function and eddy viscosity from DES of circular cylinder with laminar separation

- Provides for nearly centered differences in the LES region and nearly upwind ones in RANS and irrotational regions.

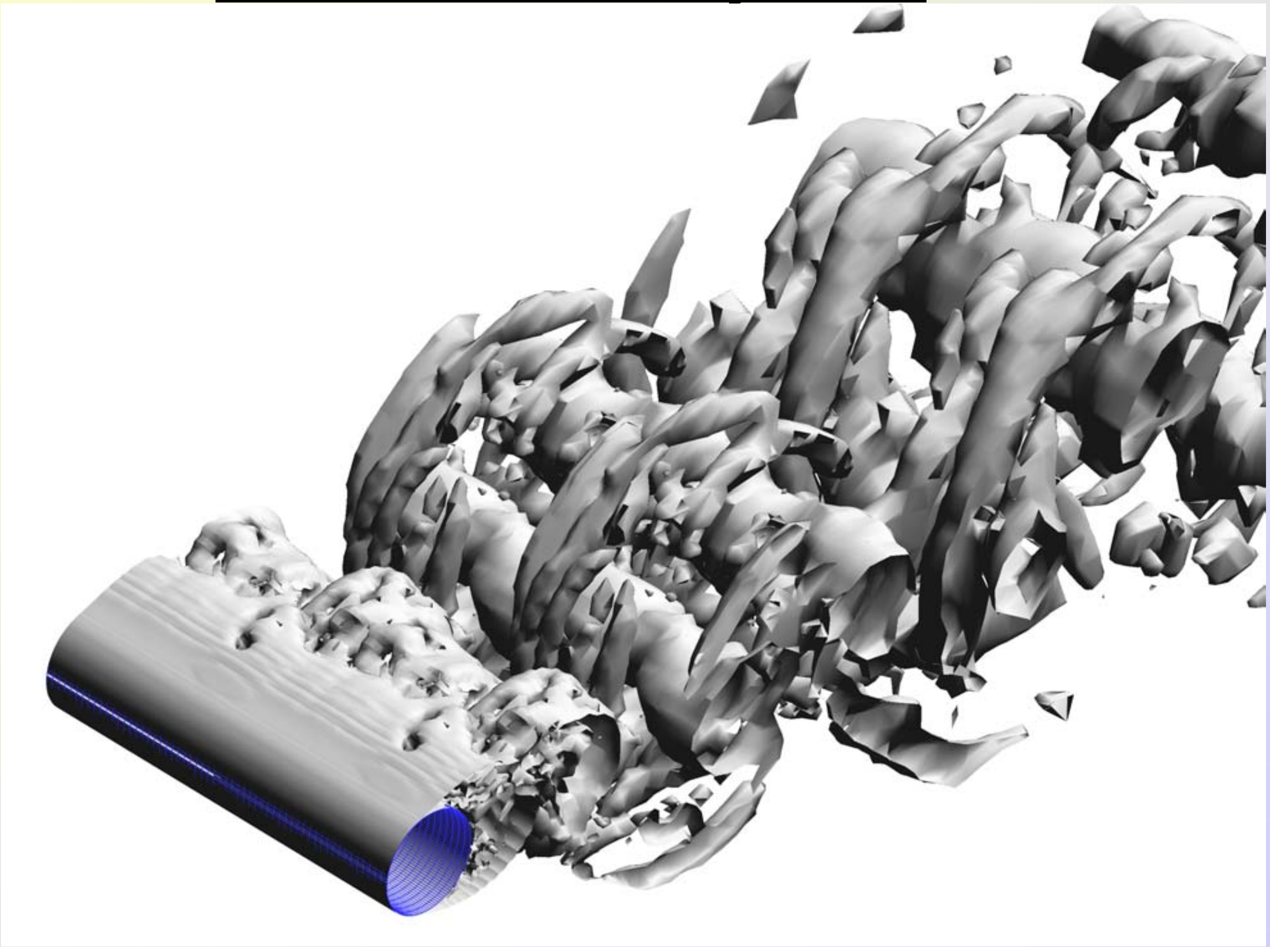
DES of Incompressible Circular Cylinder Flow
Subcritical flow regime, Re=50,000

(A.Travin, M.Shur, M.Strelets, P.Spalart, 2000)



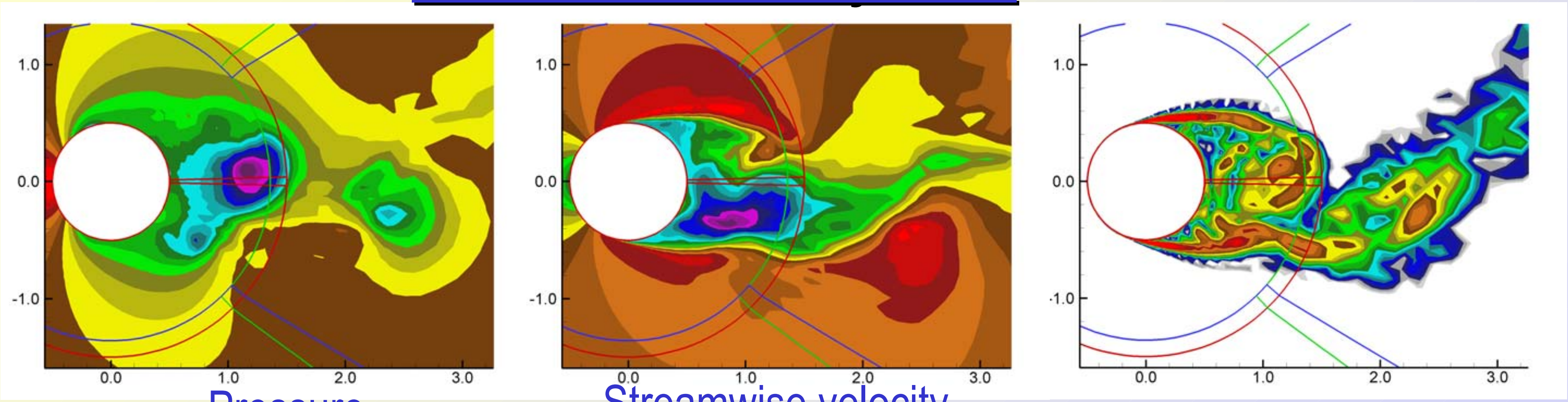
- **Typical ("classic") DES grid**
  - Outer block - Euler Region
  - RANS (Viscous and Outer) and LES (Focus) Regions
  - LES (Focus, and Departure) Regions
- **Total number of nodes from 300,000 to 1,200,000**

DES of Circular Cylinder



General flow pattern (swirl isosurface)

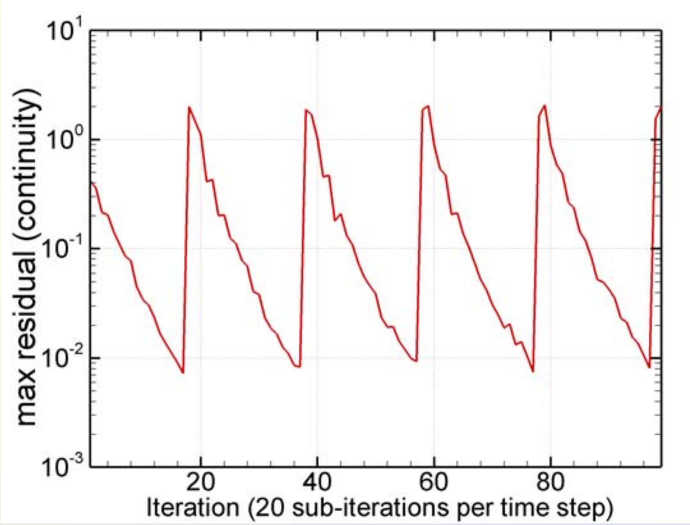
DES of Circular Cylinder



Pressure

Streamwise velocity

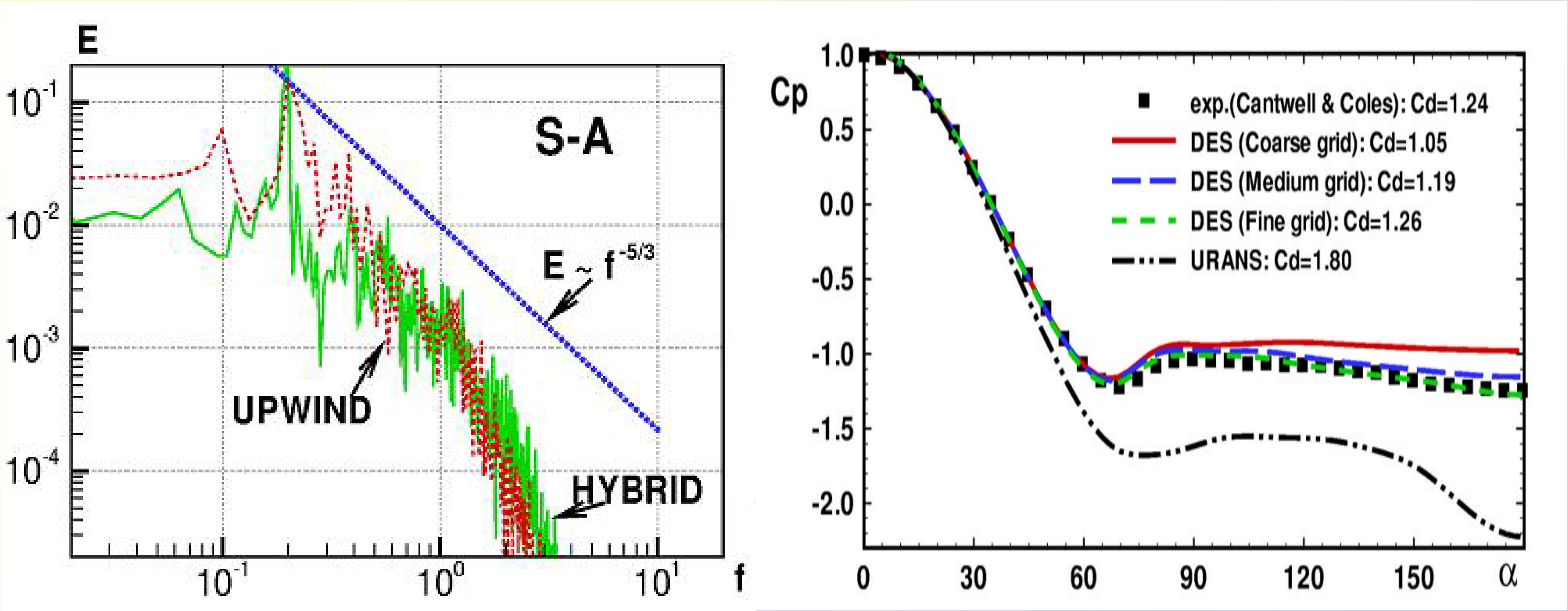
Vorticity



Sub-iterations convergence history

- Fast convergence and smooth solution in the overlapping regions
- Fast convergence of the sub-iterations

DES of Circular Cylinder



- Hybrid upwind/centered differencing noticeably improves the spectrum
- Fairly good turbulence resolution; grid-convergence seems to be reached on a quite modest grid of about 1.2 million nodes

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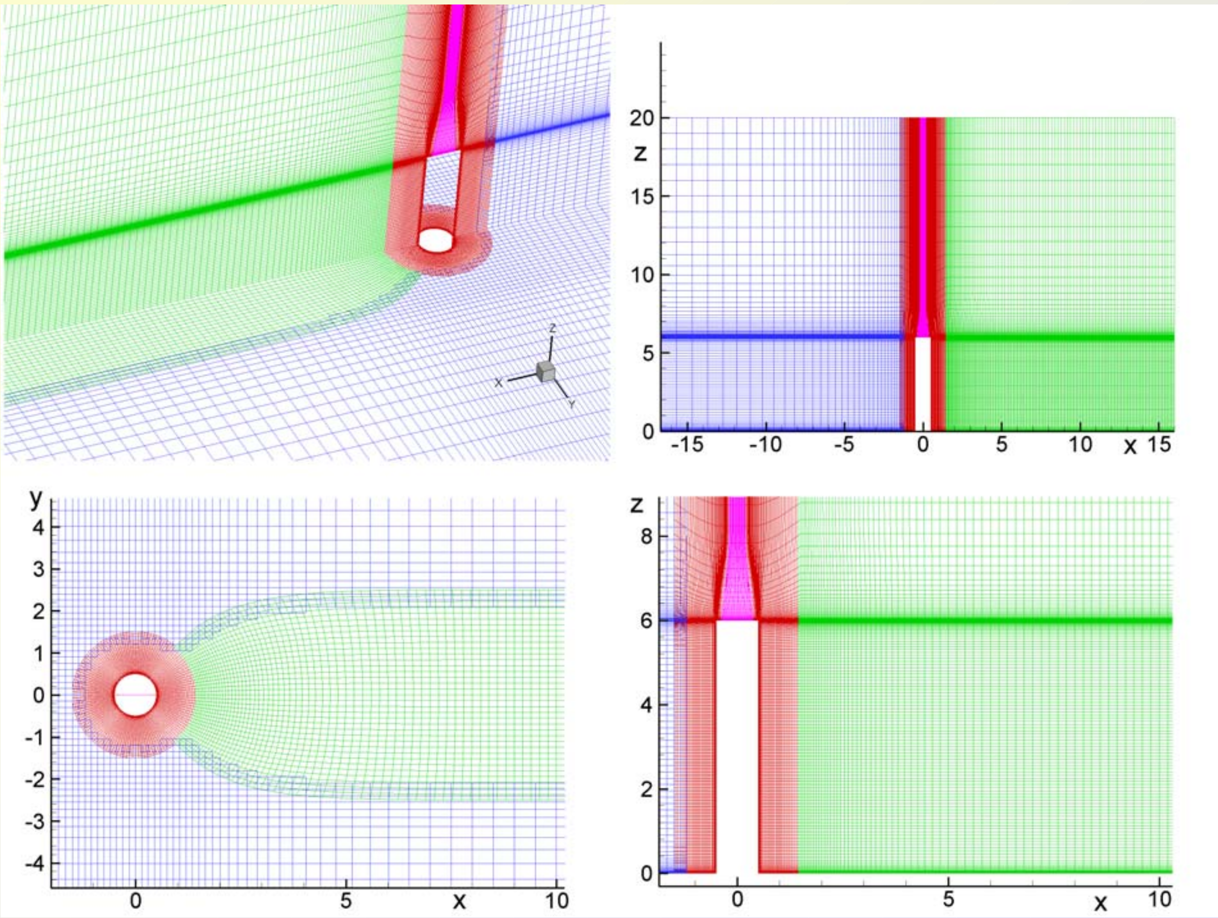
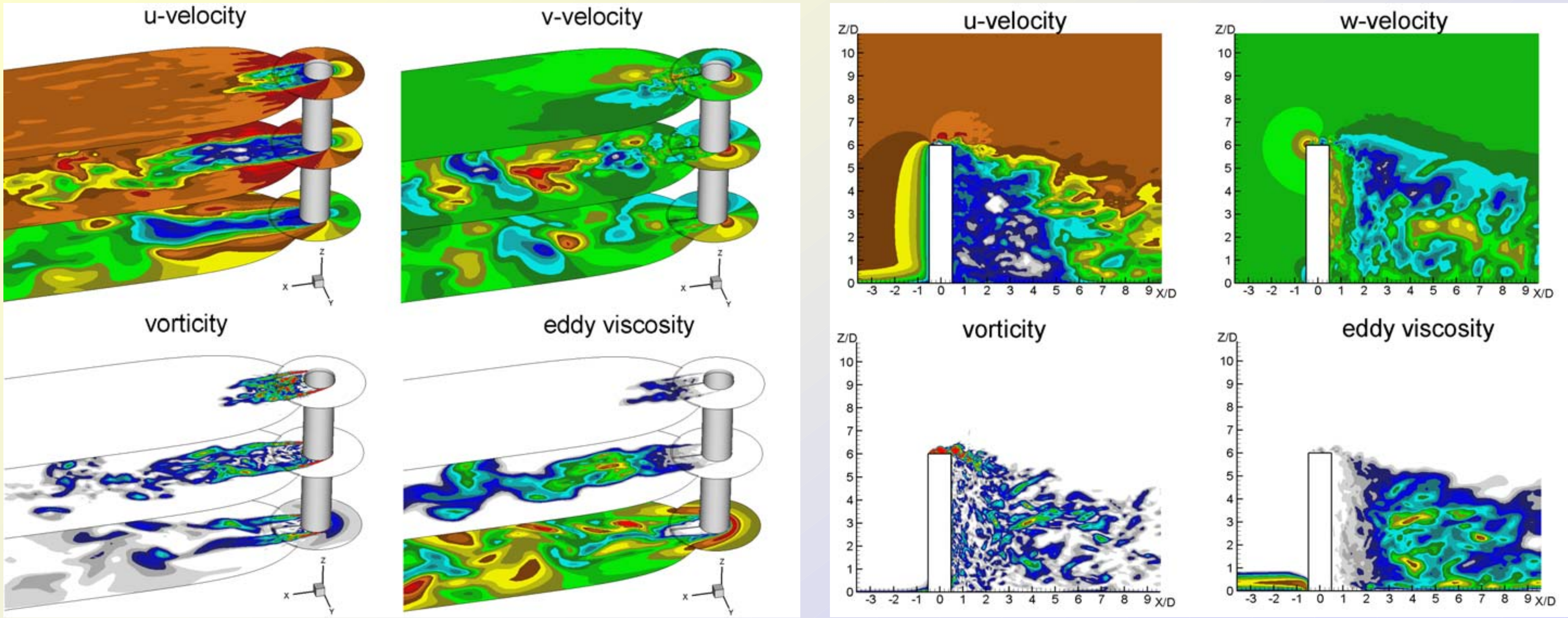
DES of Circular Cylinder on Ground Plate in a Channel (Re=20,000)

M.Shur, M.Strelets, A.Travin (DESider EC Project, 2004)



- **4-block grid (2,300,000 nodes total)**
  - Outer (cartesian) block
  - Near cylinder block
  - Wake block
  - **Cartesian block (to remove cylinder axis singularity)**

DES of Circular Cylinder on Ground Plate

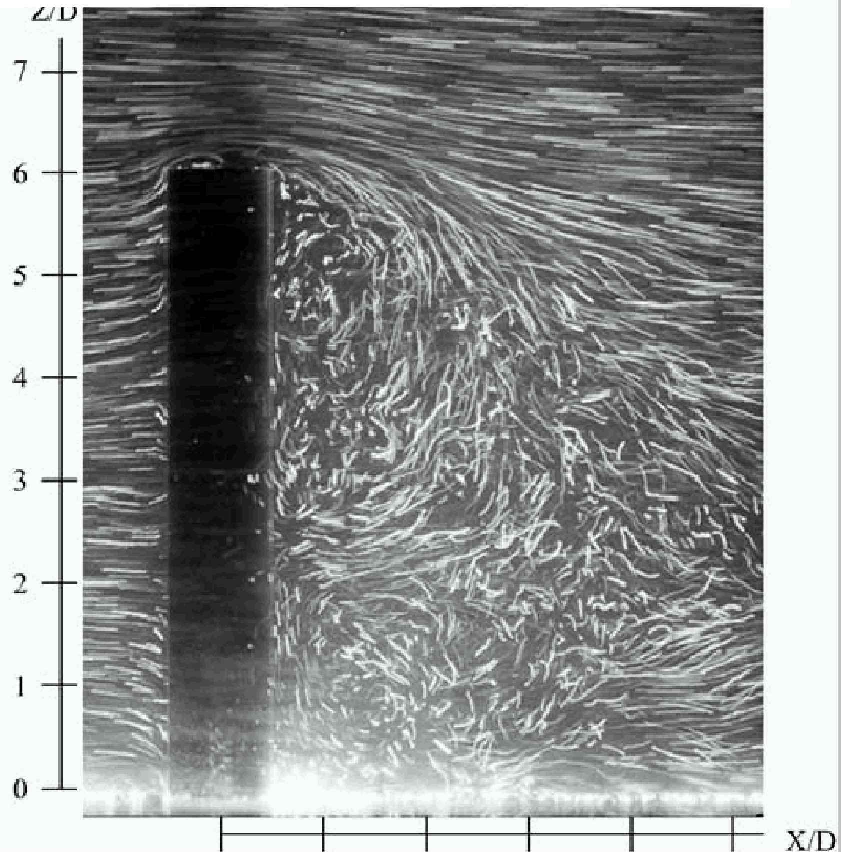


Flow visualization (velocity, vorticity, and eddy viscosity snapshots)

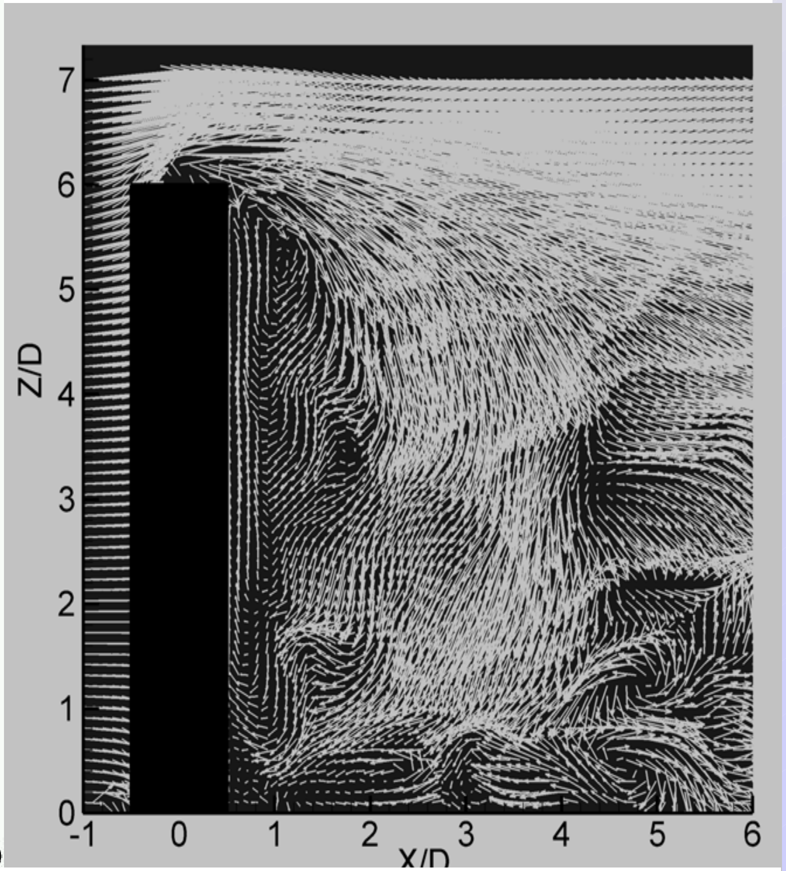
- Smooth solution in the overlapping regions

DES of Circular Cylinder on Ground Plate

Experiment



DES



- Fairly good agreement with experiment

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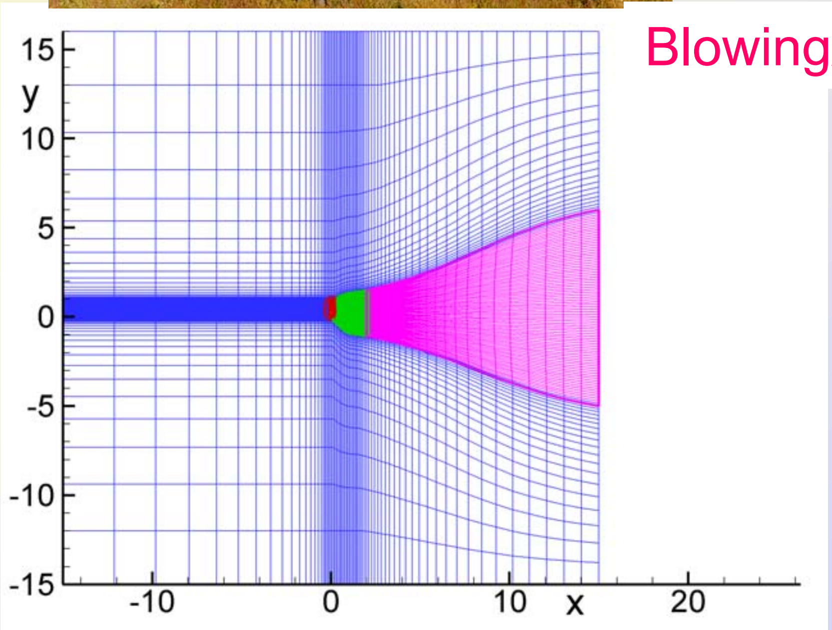
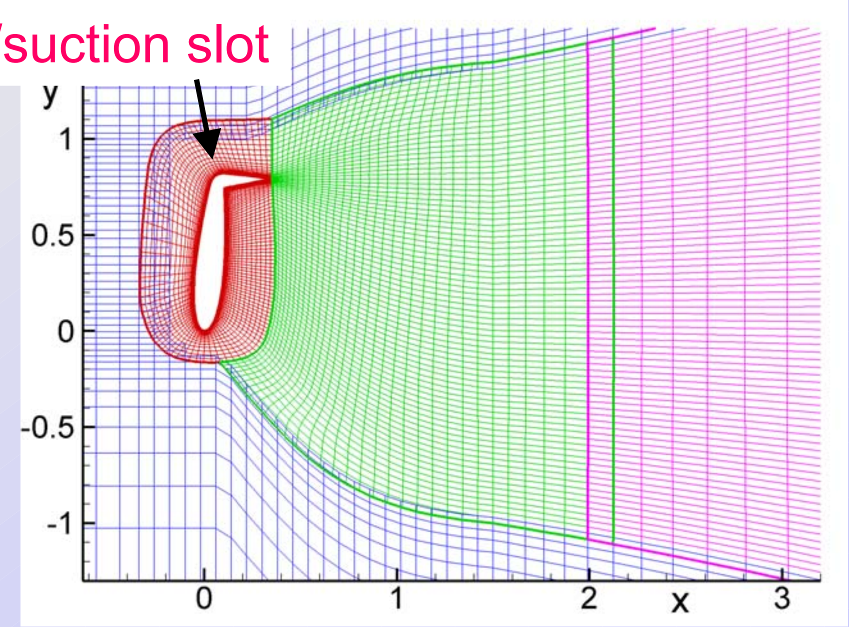
DES of Tilt-Rotor Aircraft in Hover with Active Flow Control

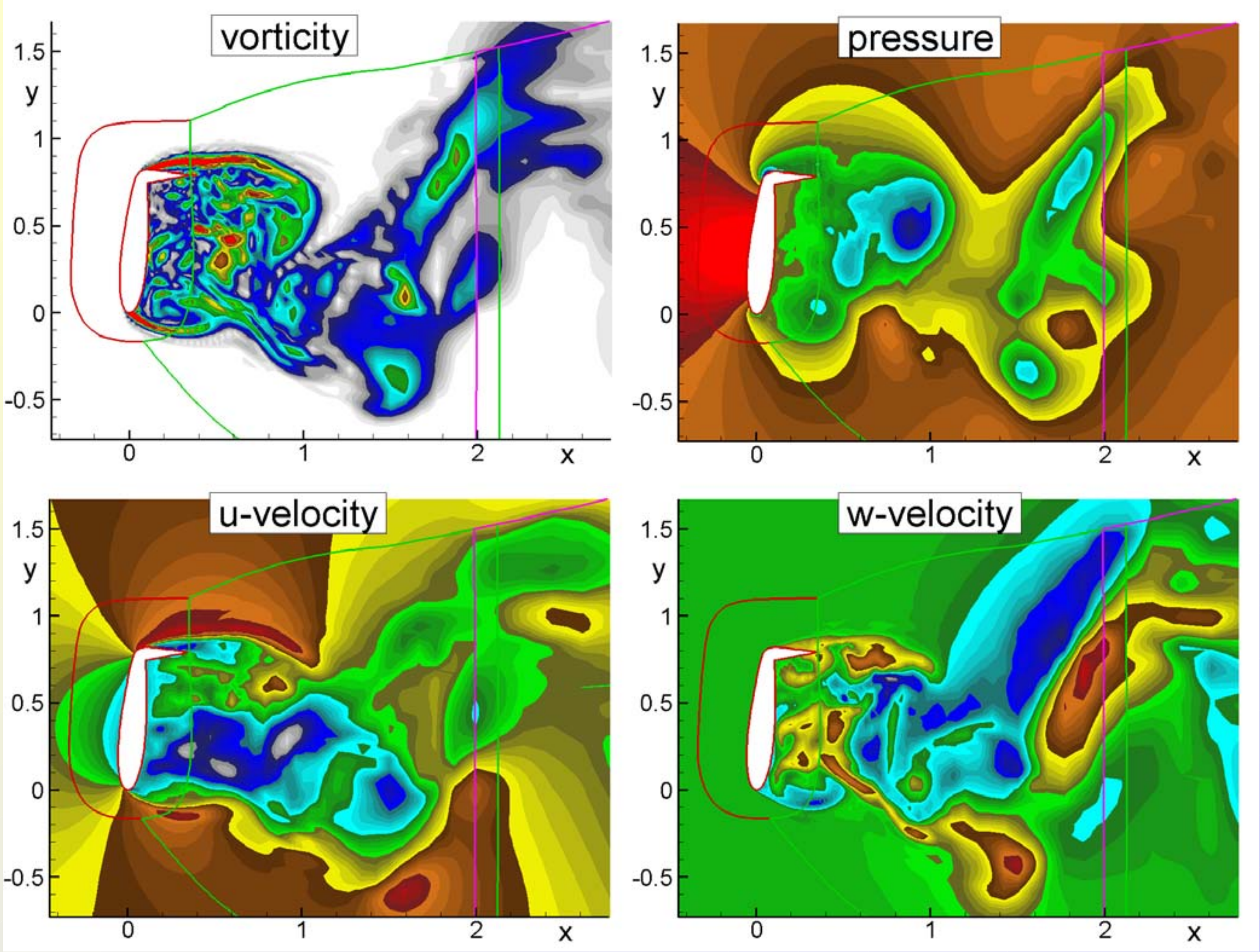
(P.Spalart, L.Hedges, M.Shur, A.Travin, 2002)

- 4-block snail-like grid (530,000 nodes total):
  - Outer block (enlarged span-grid spacing)
  - Snail (near airfoil) block
  - Near-wake block
  - Far-wake (enlarged span-grid spacing)





DES of Tilt-Rotor Aircraft in Hover

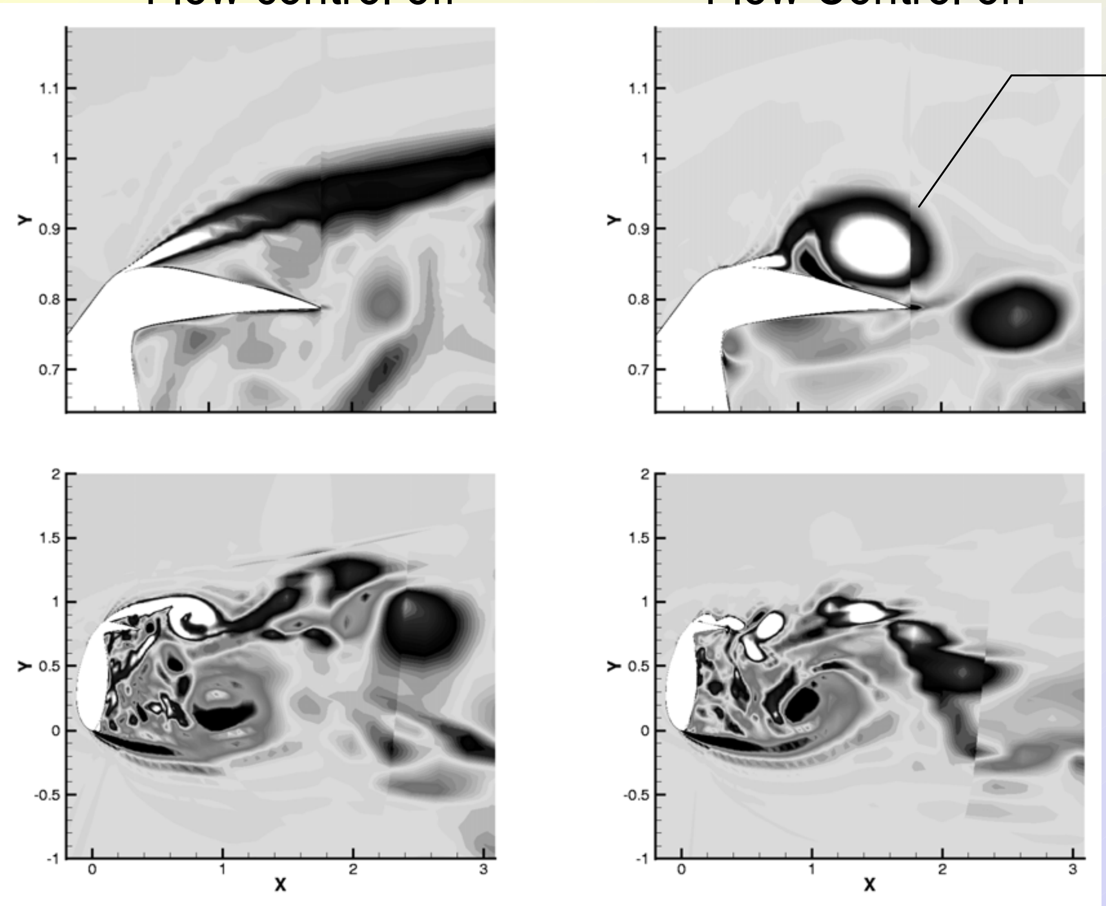


Flowfield with no flow control

- No visual defects in the overlapping regions

DES of Tilt-Rotor Aircraft in Hover

Flow control off — Flow Control on



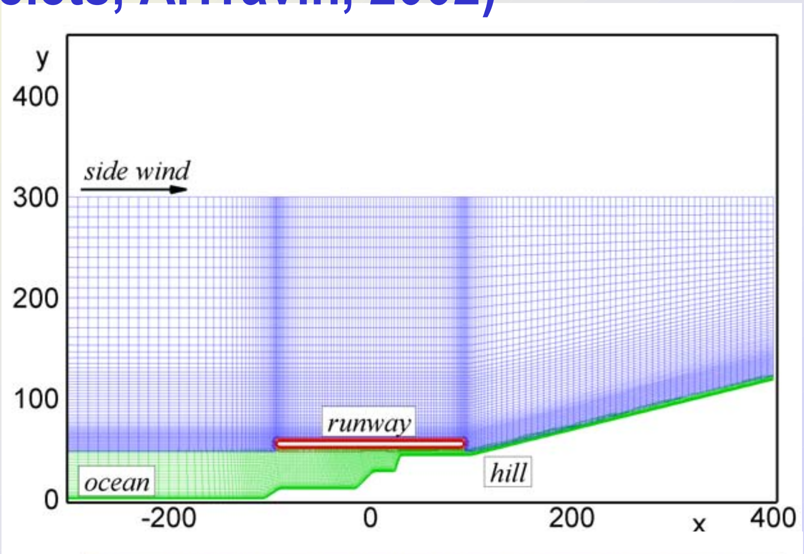
Minor non-smoothness of the vorticity in the overlapping region

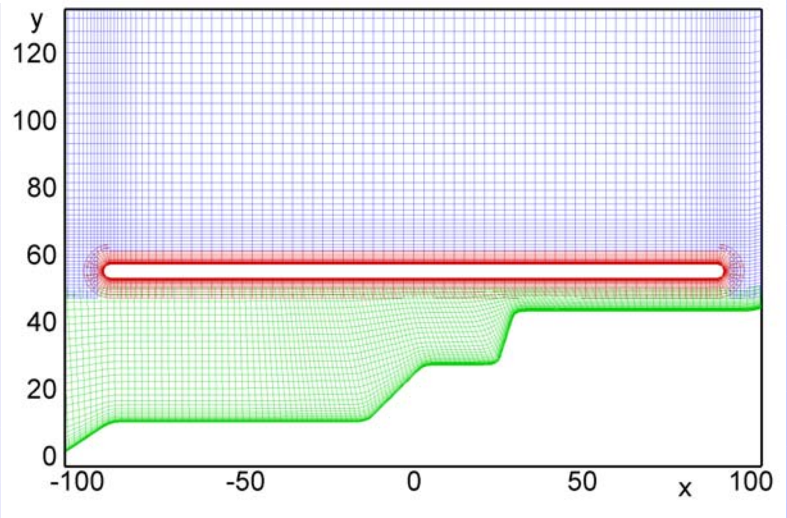
Effect of Flow Control

DES of Raised Runway in Cross-Wind

(M.Shur, P.Spalart, M.Strelets, A.Travin, 2002)

The runway supported by pillars at 50m above ocean surface





- 3-block grid (750,000 nodes total):
  - ➢ Outer block
  - ➢ Runway block
  - ➢ Near-ground block

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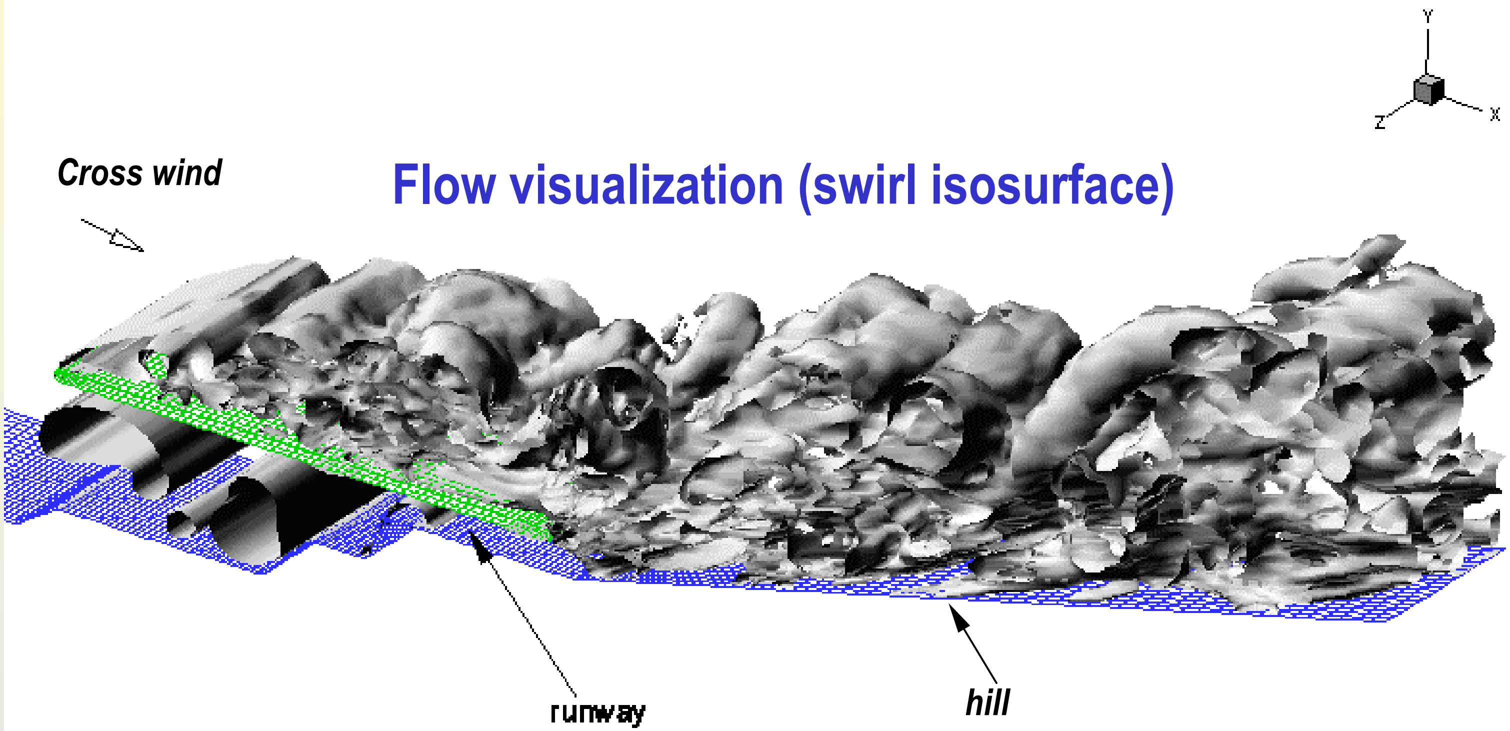
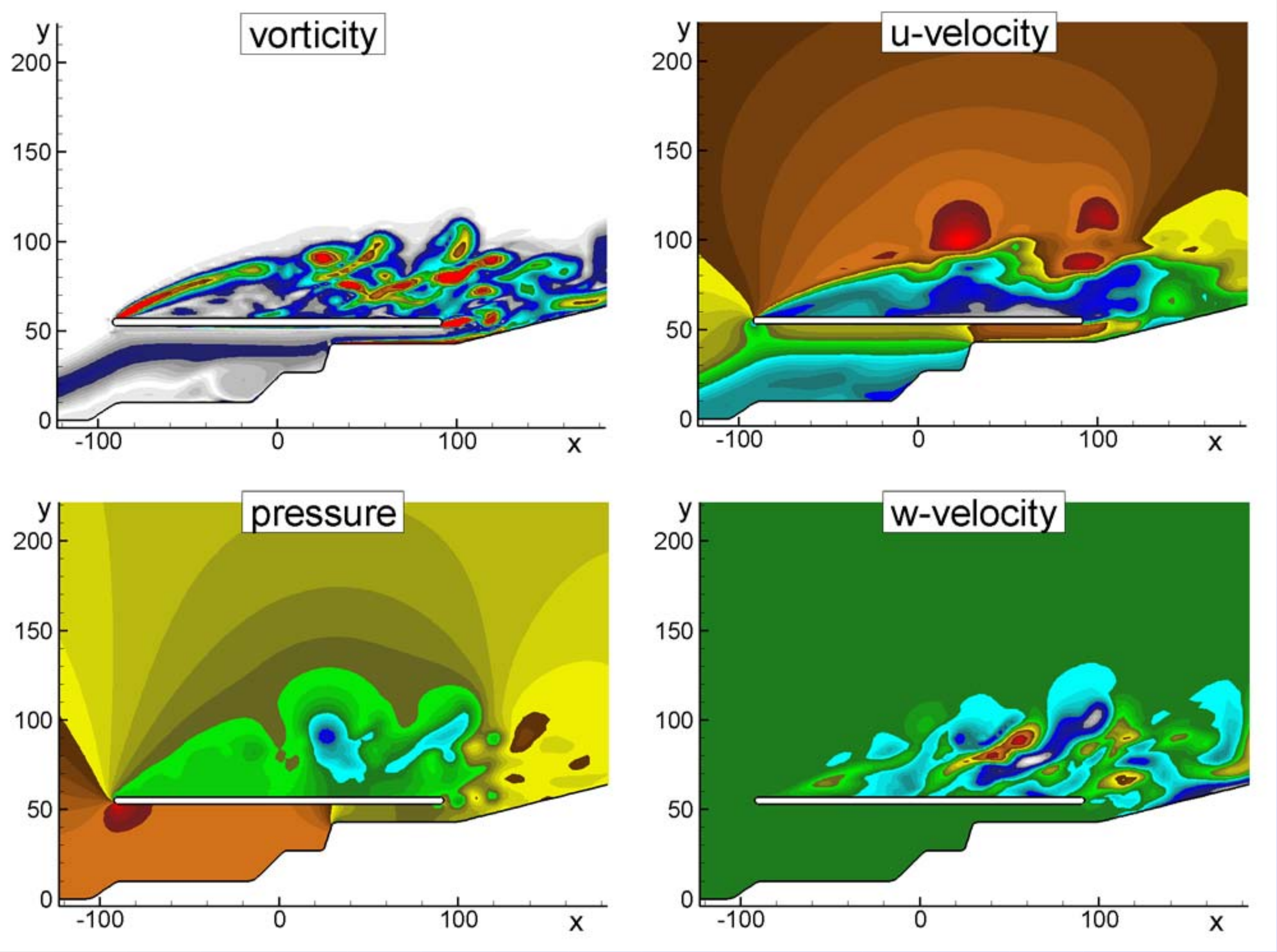
DES of Raised Runway in Cross-Wind

Flow visualization (swirl isosurface)



• DES predicts wind gusts up to 100% of average wind velocity

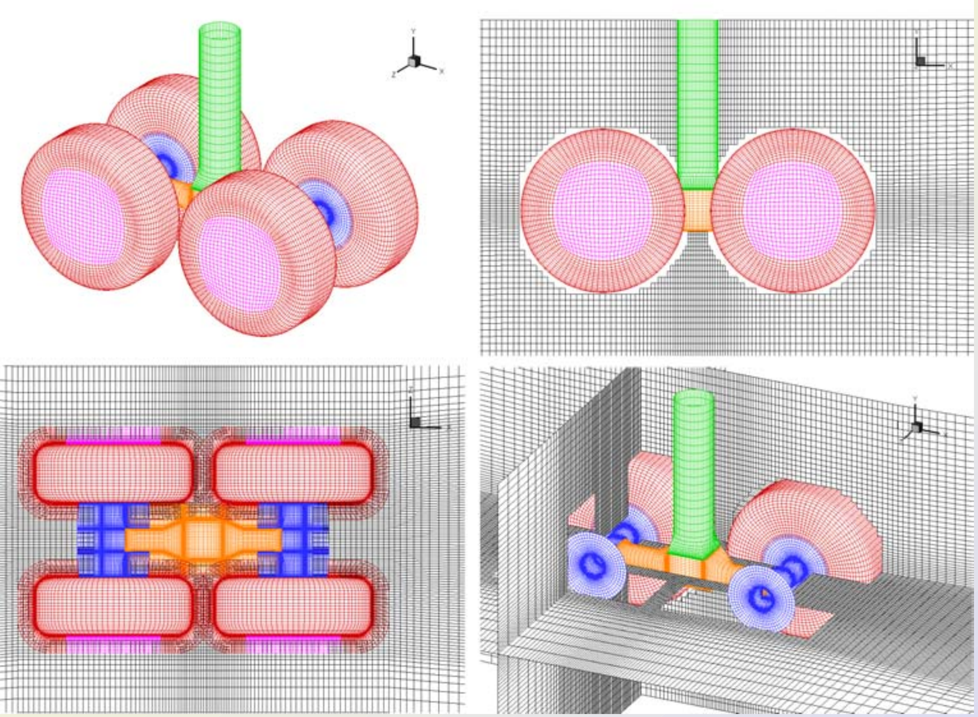
DES of Raised Runway in Cross-Wind



Flow visualization (vorticity, pressure and velocity snapshots)

DES around Simplified Landing Gear Truck

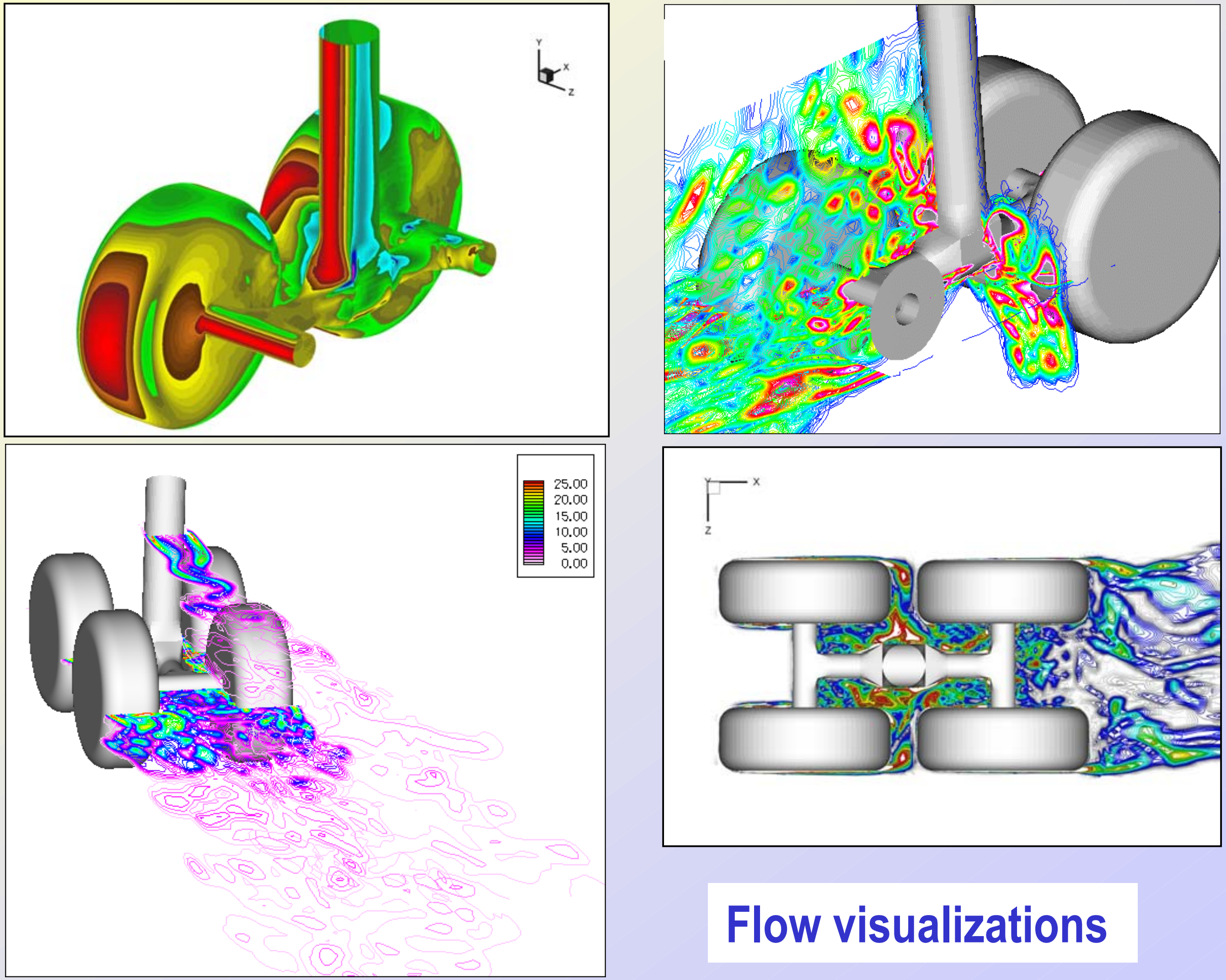
(L.Hedges, P.Spalart, A.Travin, 2002)



- 13-block grid (2,500,000 nodes total):
  - 12 blocks are internal and wrap around the wheels, posts and axles
  - 13th block is an external block that covers the entire computational domain, overlapping with the internal blocks

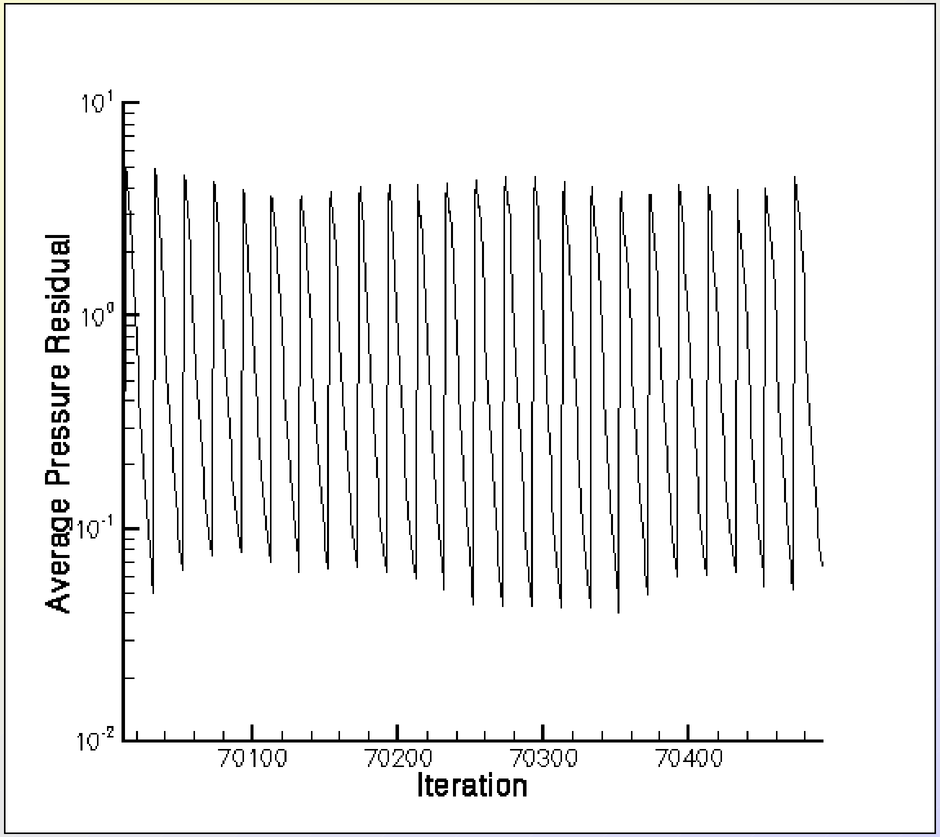
- The geometry is modified slightly from the experimental model, particularly at the junction of the vertical post and longitudinal beam

DES around Simplified Landing Gear Truck



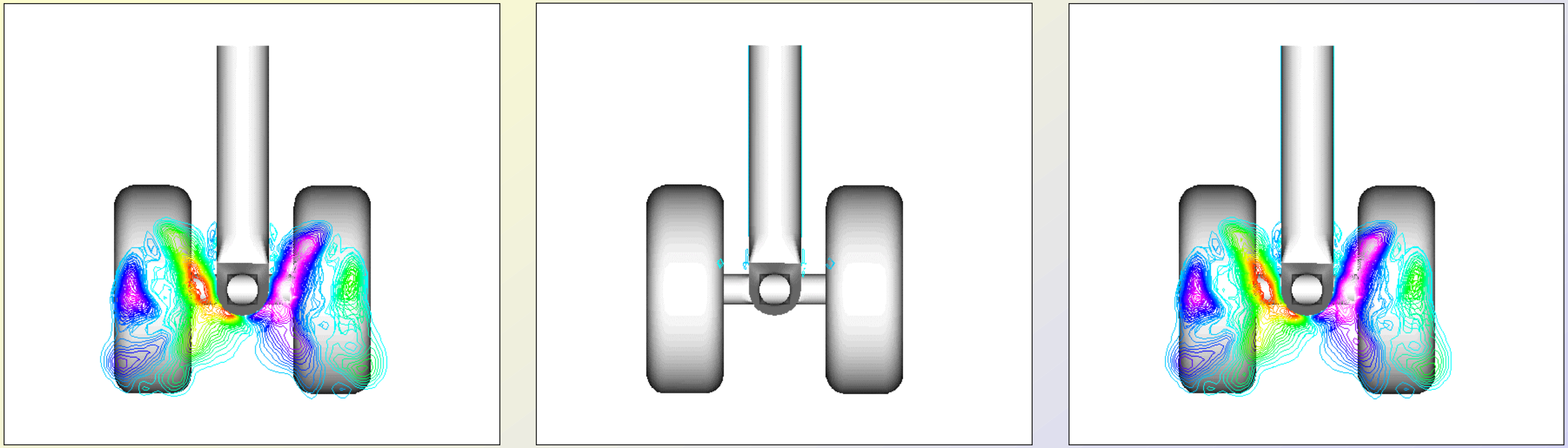
Flow visualizations

DES around Simplified Landing Gear Truck



Sub-iteration convergence

DES around Simplified Landing Gear Truck



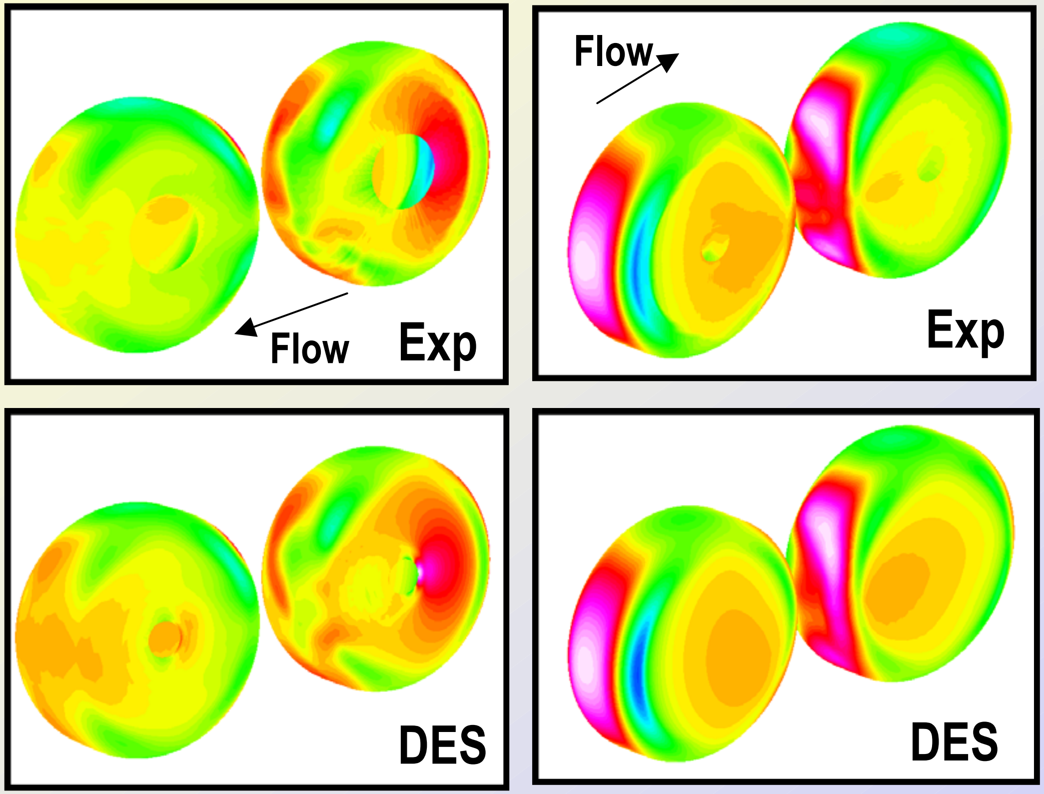
U'W' Resolved U'W' Modeled U'W' Total

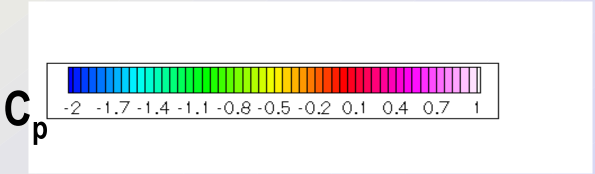
Resolved and modeled shear stresses between front and rear wheels at X=0

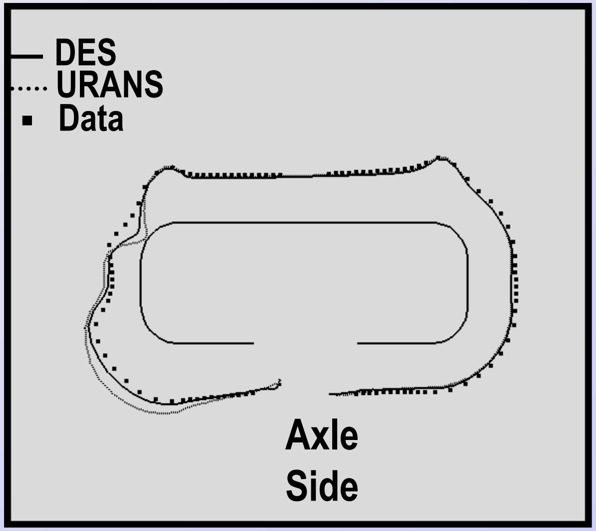
- The grid provides for a high level of resolution and smoothness of stresses

DES around Simplified Landing Gear Truck

Cp on the wheels







- DES predicts surface pressures well for the most part on the wheels

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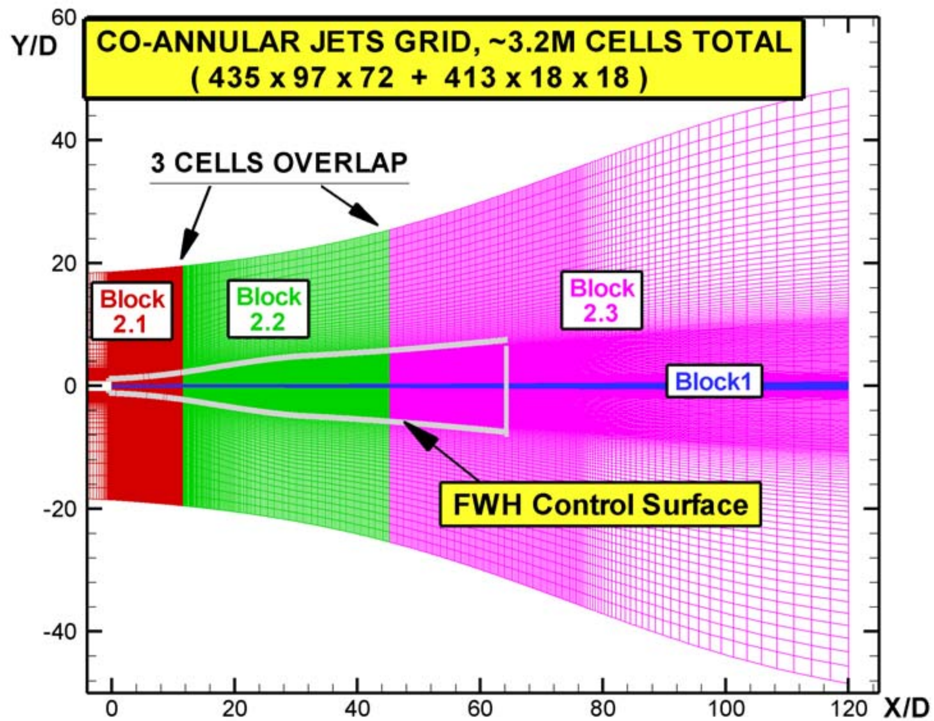
LES of Jets and Noise Computation

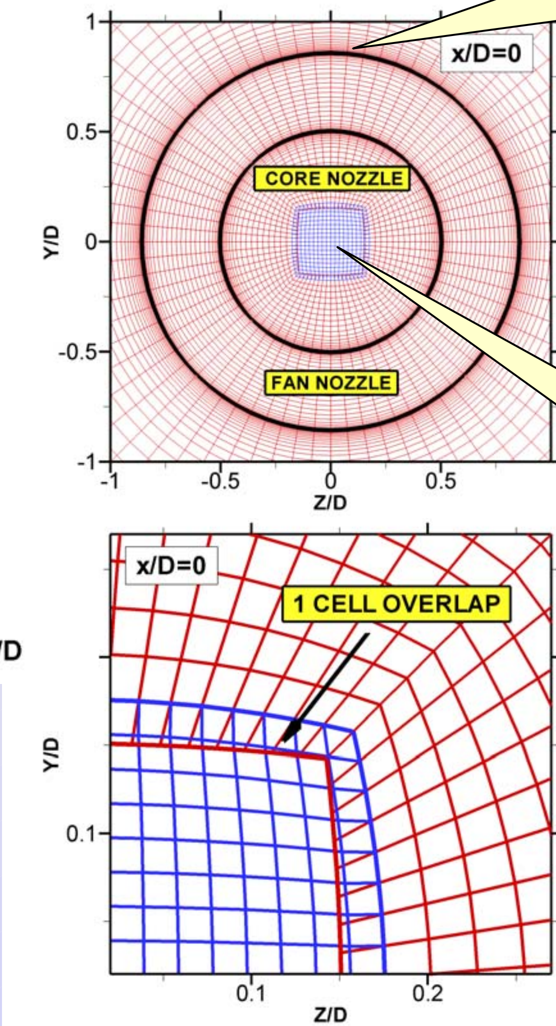
(M.Shur, P.Spalart, M.Strelets, A.Travin, 2001-2004)

- Project started in 2001 with the long-term objective of creating an industrial tool for jet noise predictions based on “first principles”
- Typical practice is:
  - With currently affordable grids, SGS model is not active
  - Hybrid (5^{th} order upwind / 4^{th} order centered) approximation of the inviscid fluxes with user-specified blend function (virtually centered scheme in turbulent region)
  - Inter-block communication
    - Via block boundary nodes and additional ghost, nodes for artificial blocks for MPI parallelization
    - Otherwise, via block boundary nodes only

Grid Topology and FWH-Surface Position



End view of grid

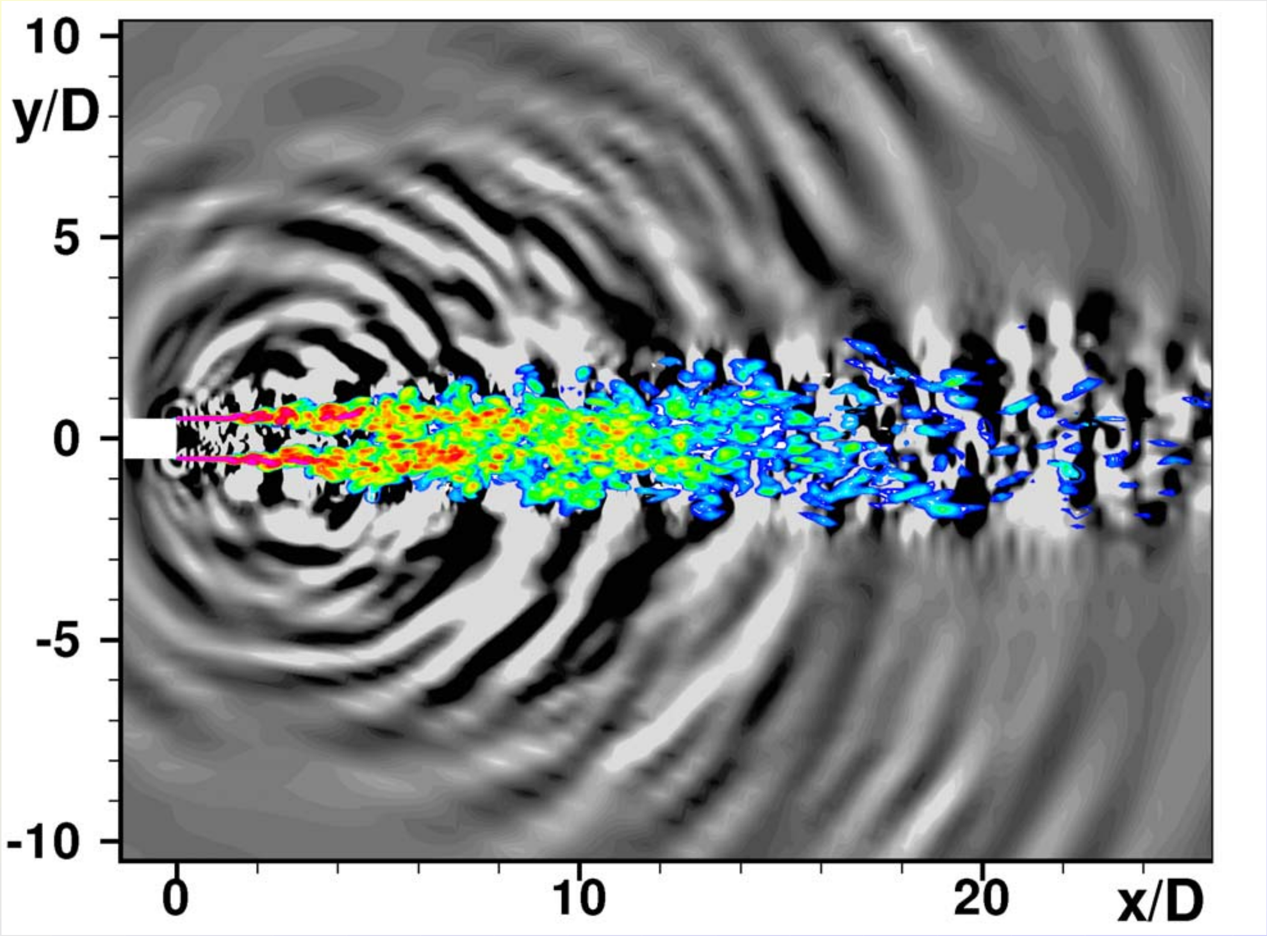


Full control of spacing, axisymmetric or not

No parasitic refinement near axis

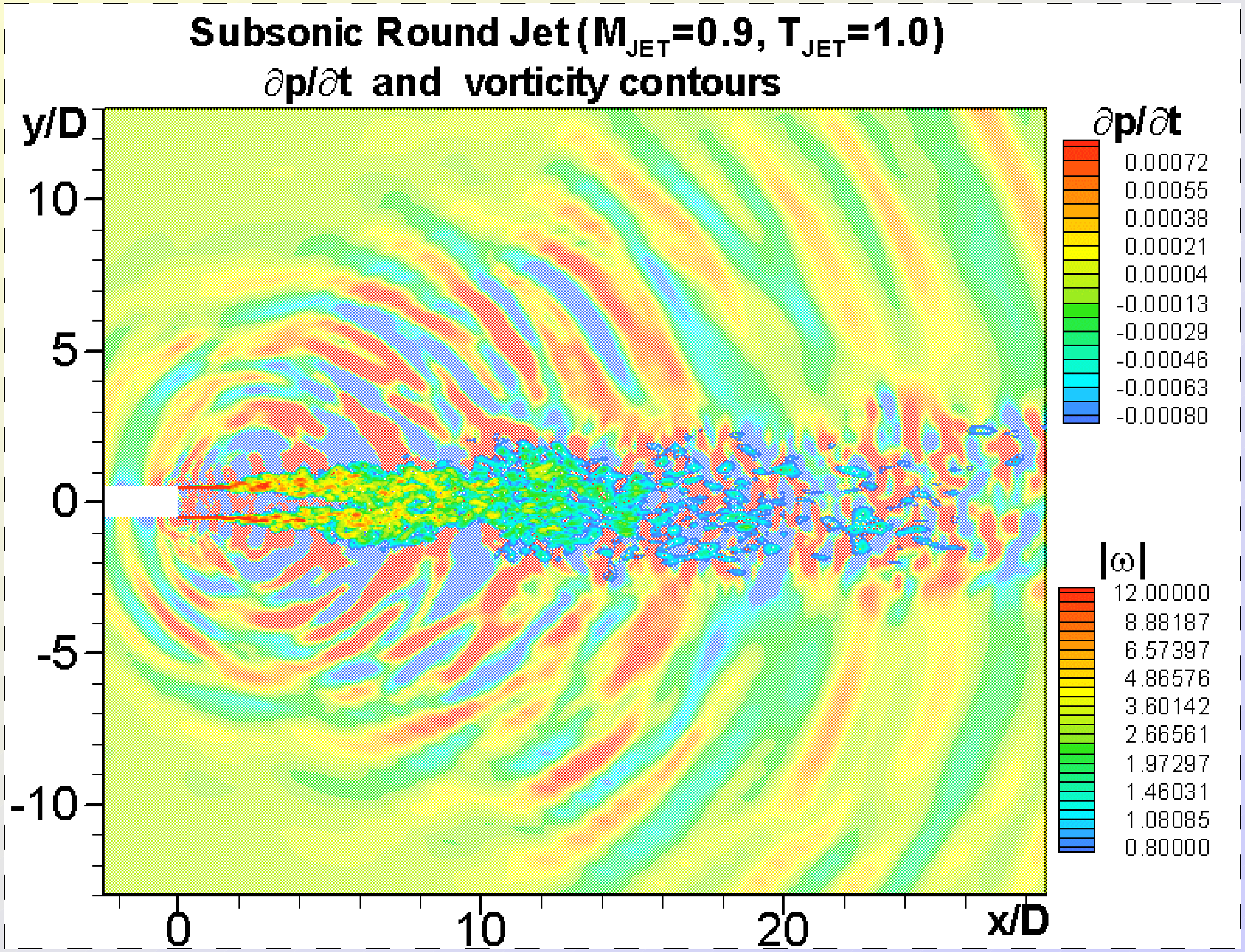
- <u>4-block grid (3.2M nodes total):</u>
  - Inner (cartesian) block
  - 2.1, 2.2, 2.3: Outer O-type block sub-divided into 3 blocks (for MPI parallelization)

LES of Subsonic (M=0.9) Isothermal Round Jet



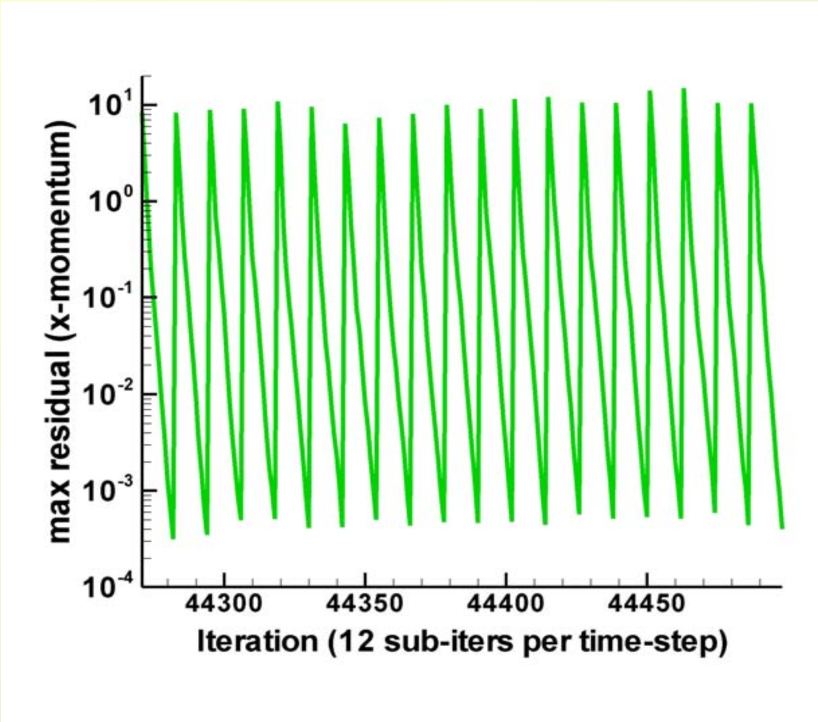
Vorticity and sound pressure snapshots

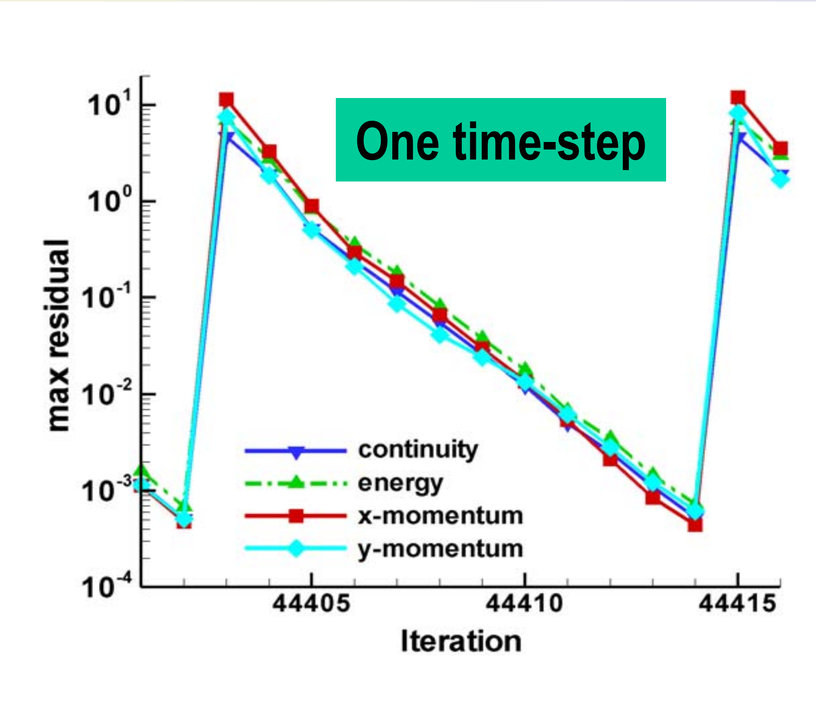
Flow Animation



- No visual defects (non-smoothness) of sound waves at blocks interface

LES of Subsonic (M=0.9) Isothermal Round Jet





Sub-iterations convergence history for M=0.9 isothermal jet (4-block grid, ~3M nodes total, $\Delta t=0.02(D/U_{JET})$)

- Rather fast convergence of the sub-iterations (~4 orders of magnitude in 12 iters); that "deep" convergence is obligatory for sound computation

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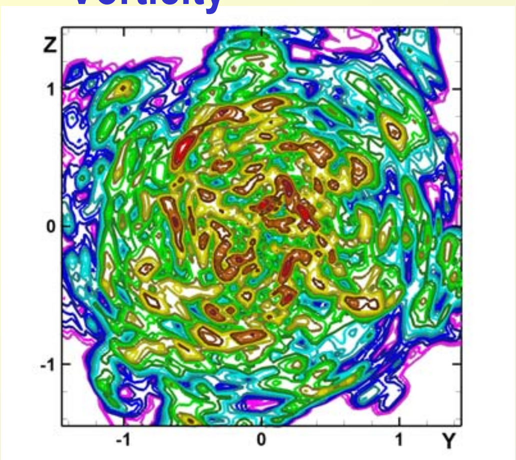
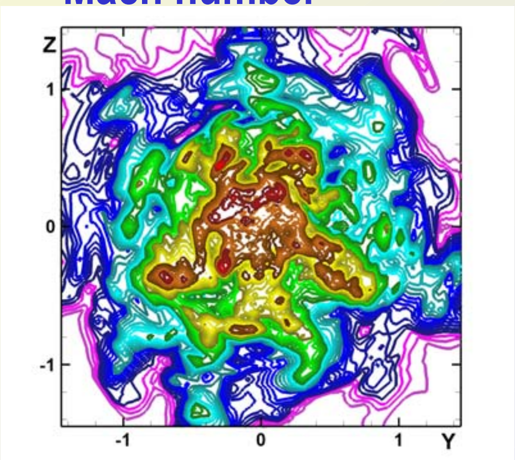
LES of Hot Subsonic Dual Jet

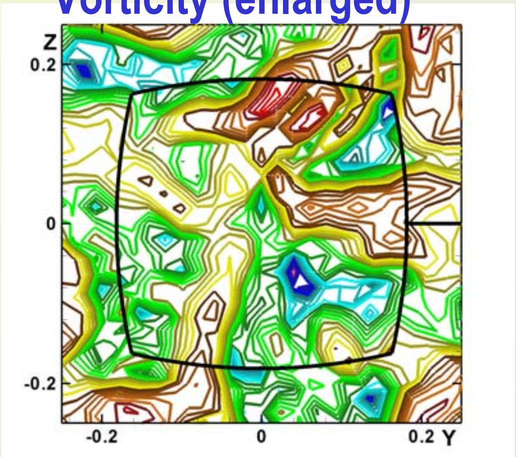
Vorticity



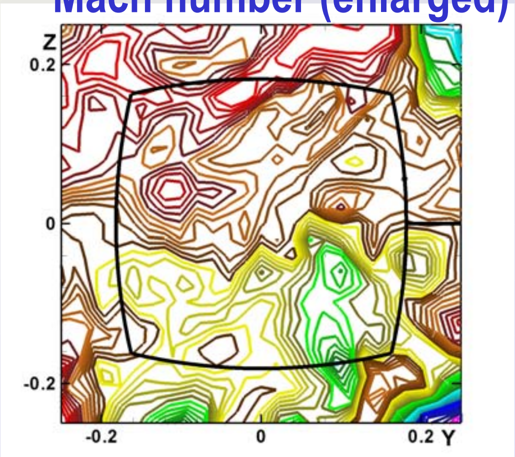
Mach number



Vorticity (enlarged)



Mach number (enlarged)

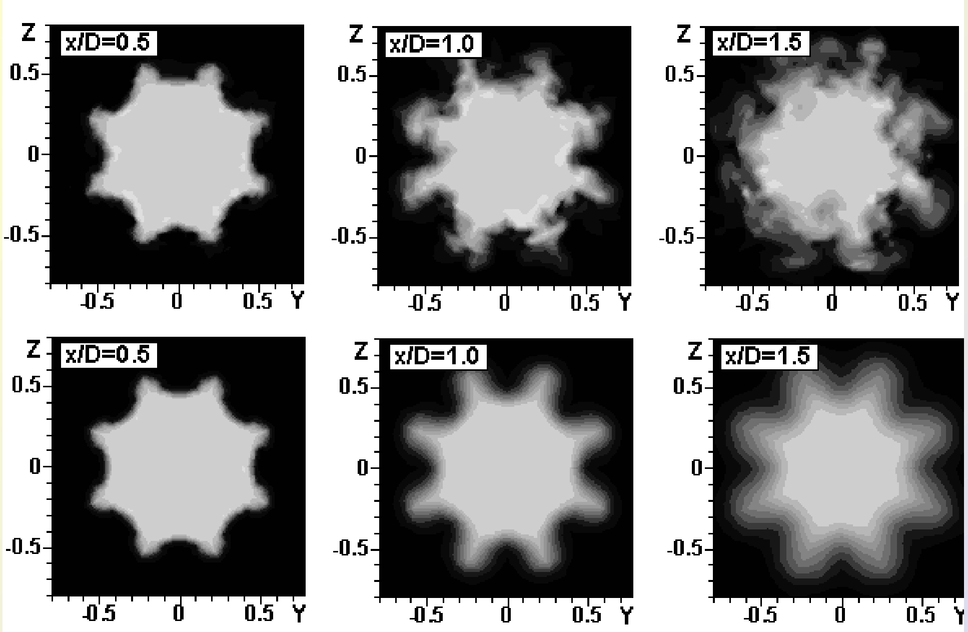


- No deterioration of the solution at block-interface and “wiggles” near cartesian block corners

Z-cut of vorticity and Mach number field at x/D=10 (near the end of potential core)

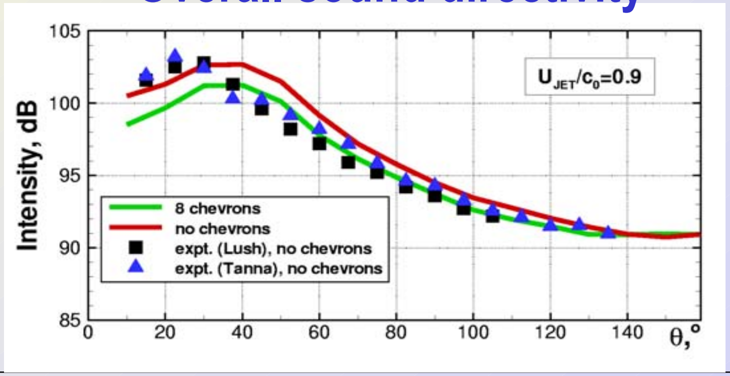
Subsonic Jet with Chevrons Emulated by Inflow Conditions

Instantaneous and time-average Z-cuts of velocity field



- Typical "daisy" shape of time-average fields

Overall sound directivity



- OASPL reduction:
  - ➢ Near 2dB
  - ➢ In downstream direction only

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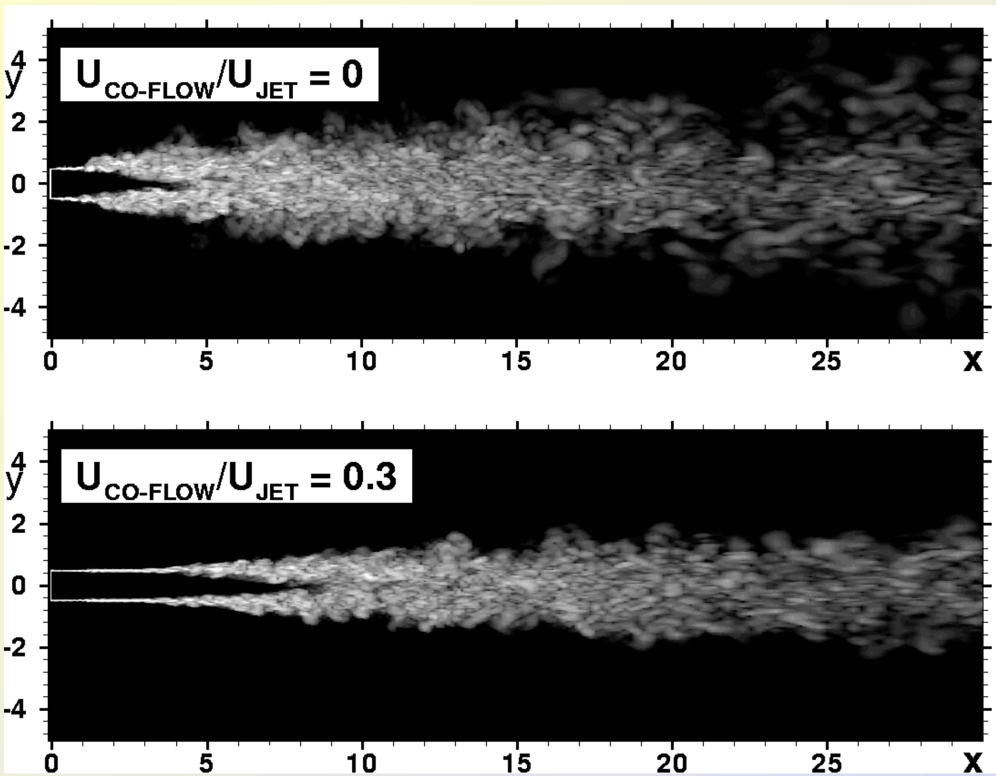
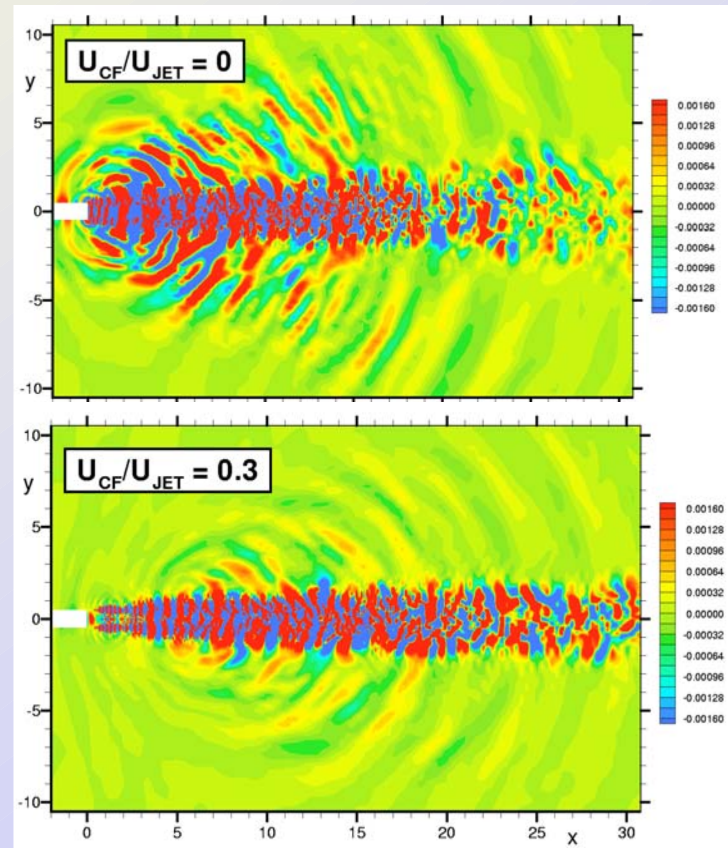
Subsonic Jets with Co-Flow (Forward Flight)

Vorticity contours



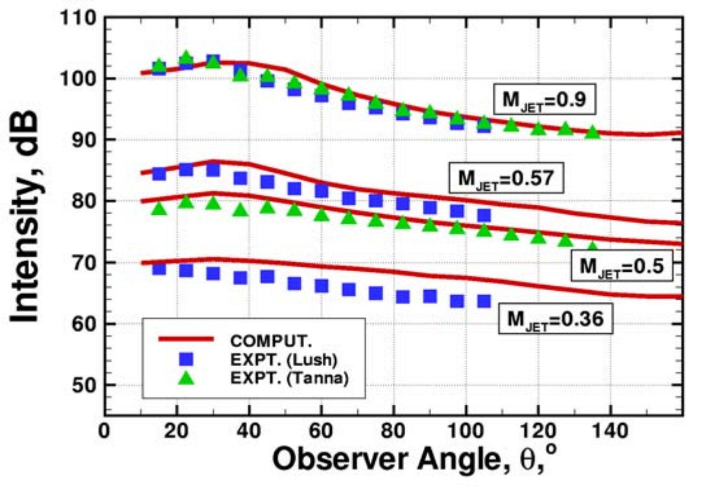
Acoustic pressure contours



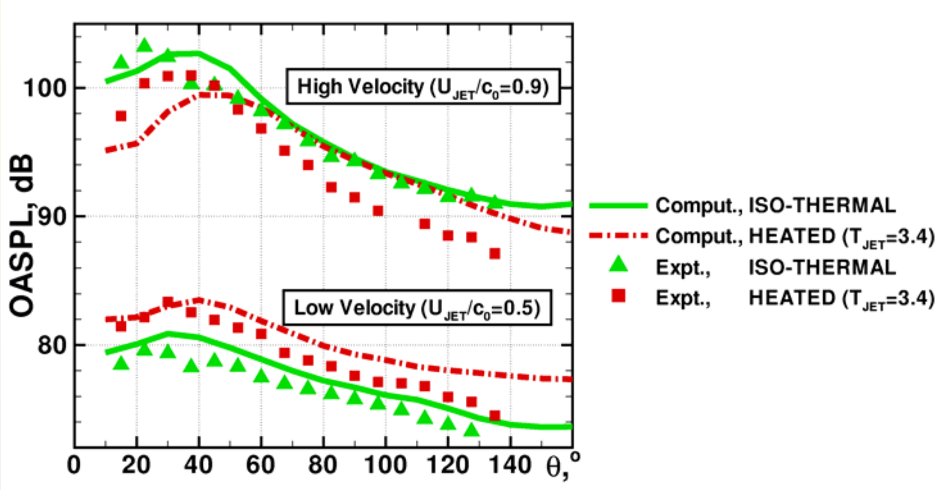
- Visual jet narrowing and noise reduction due to forward flight

Comparison with Far-Field Jet Noise Experiments (Subsonic Jets)

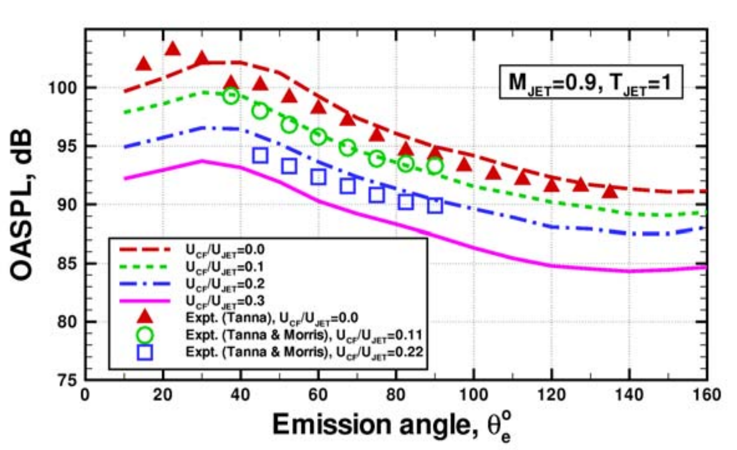
Effect of Mach number



Cross effect of Mach number and temperature

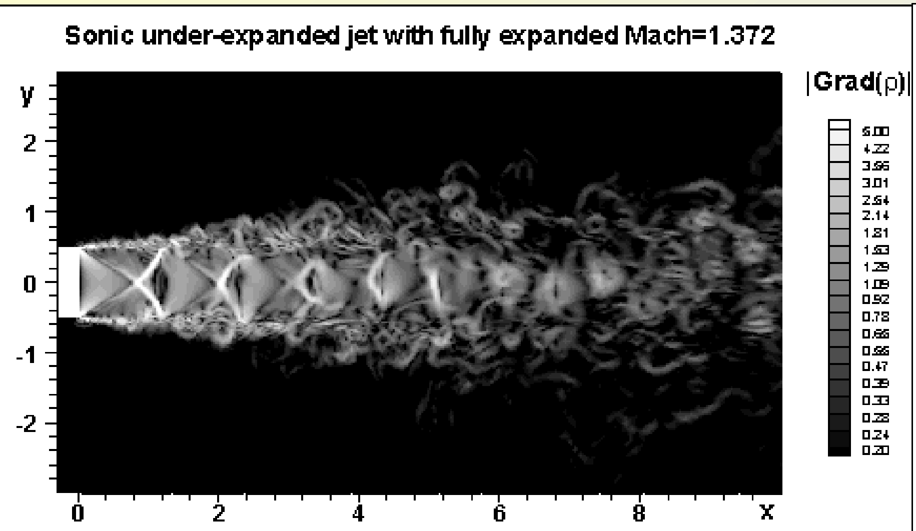


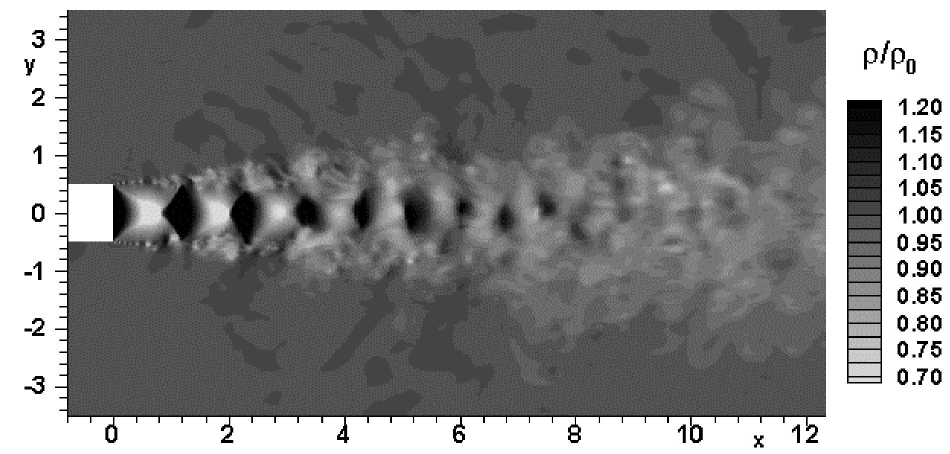
Effect of co-flow velocity



- Overall agreement with the data within 3dB

Broad-Band Shock-Cell Noise from Sonic Under-Expanded Jet (Flow Animation)

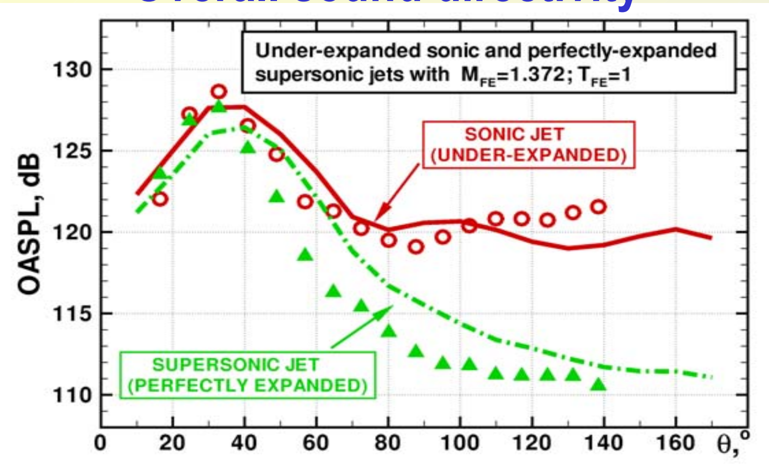




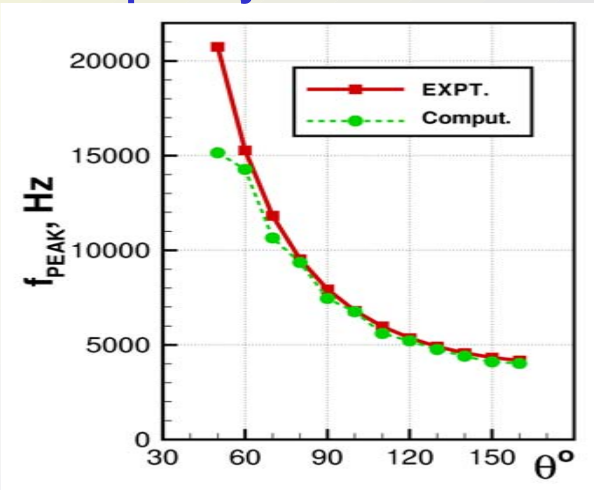
Density gradient (“numerical Schlieren”) and density fields

Comparison with Far-Field Jet Noise Experiments (Broad-Band Shock-Cell Noise from Sonic Underexpanded Jets)

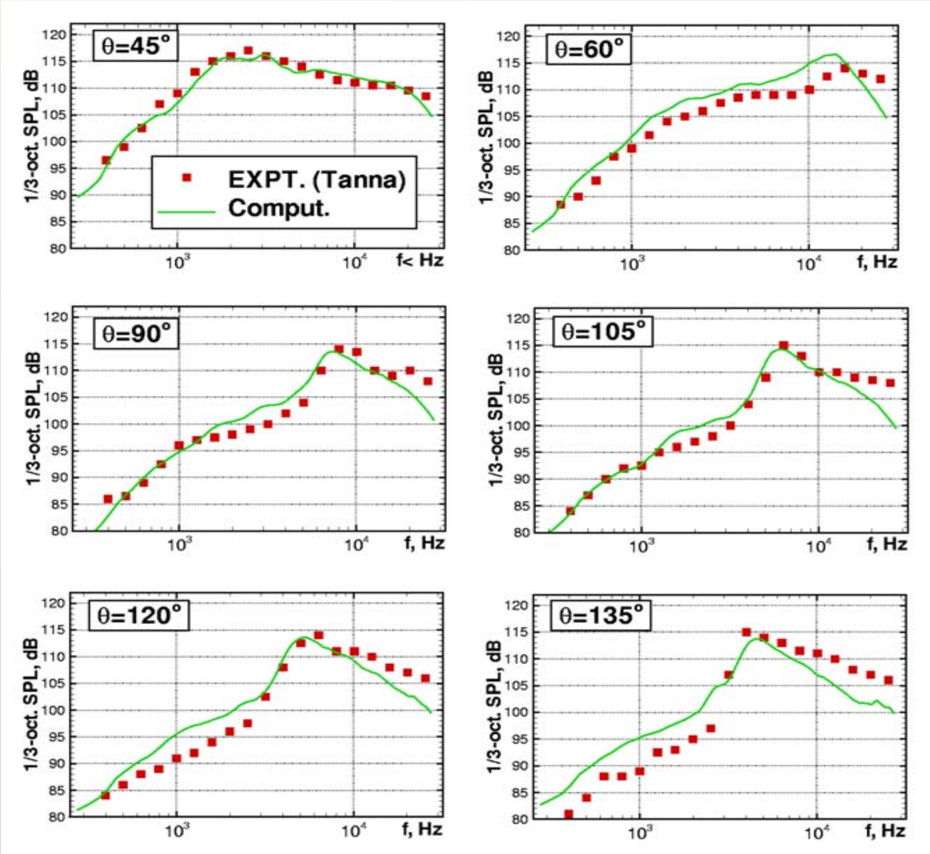
Overall sound directivity



Peak frequency of shock-cell noise



Sound spectrum for different observers

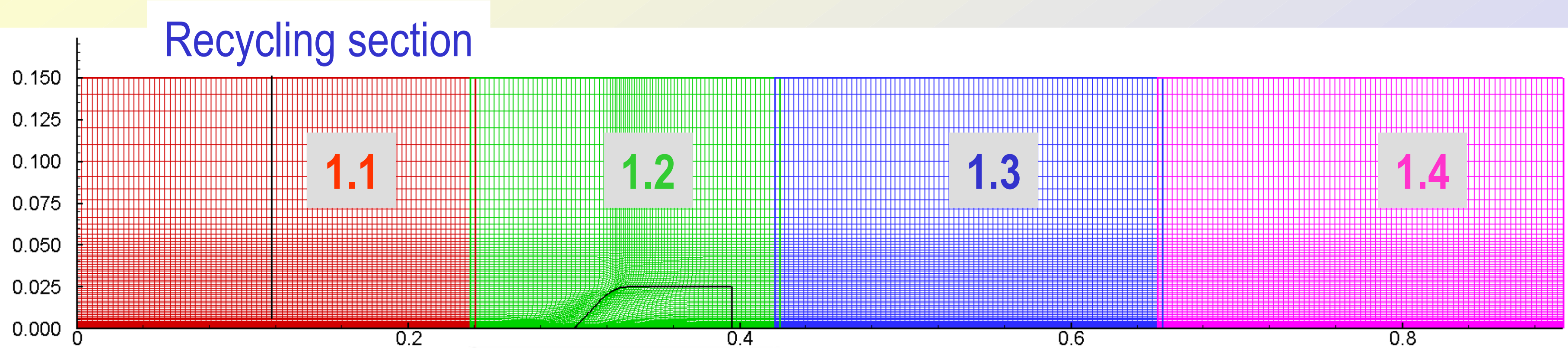


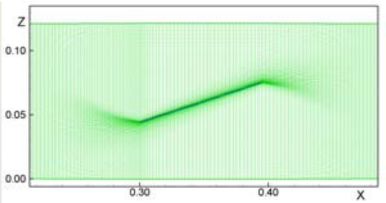
DNS Applications

- Only limited experience so far:
  - DNS of Turbulent Boundary Layer with VG's and LEBU's
  - Objective: to reduce the wall pressure fluctuations, which create noise in the cabin
- Domain decomposition into a several artificial blocks in streamwise direction for MPI parallelization
  - Inter-block communication via block boundary nodes and additional ghost, nodes (3-cells overlap)
  - Centered 4^{th} order approximation of inviscid fluxes everywhere except for close vicinity of the stagnation points (lines) of the devices

DNS of TBL with VG's: Re=2.2x10^5 m^{-1}

(P.Spalart, M.Strelets, A.Travin, 2004)





- The VG's are co-rotating, 0.025m tall and spaced by 0.12m, and at 18° α
- <u>4-block grid (~3M nodes total):</u>
  - 1.1, 1.2, 1.3, 1.4 - blocks for MPI parallelization

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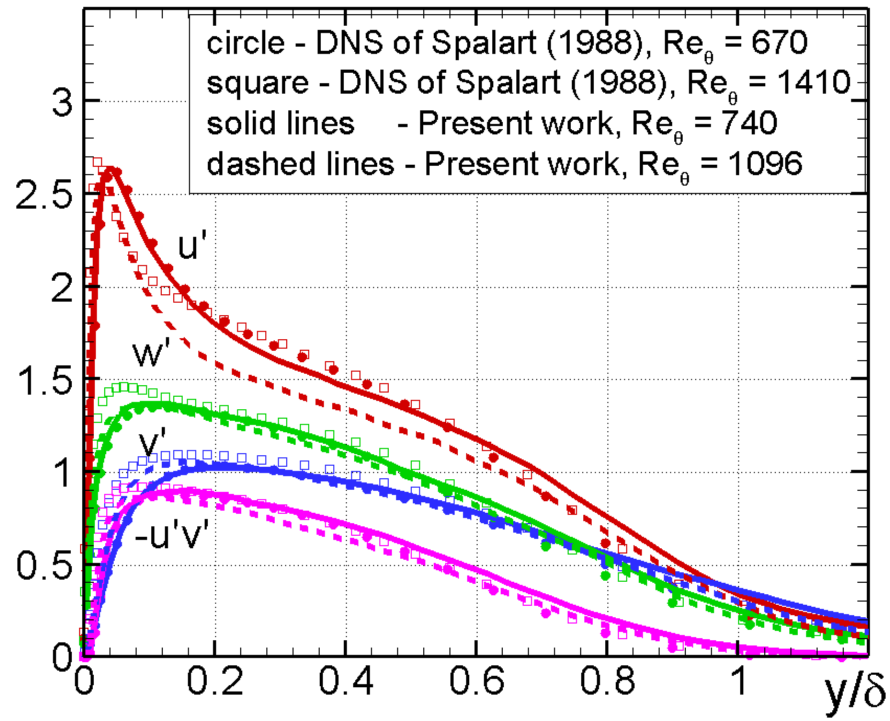
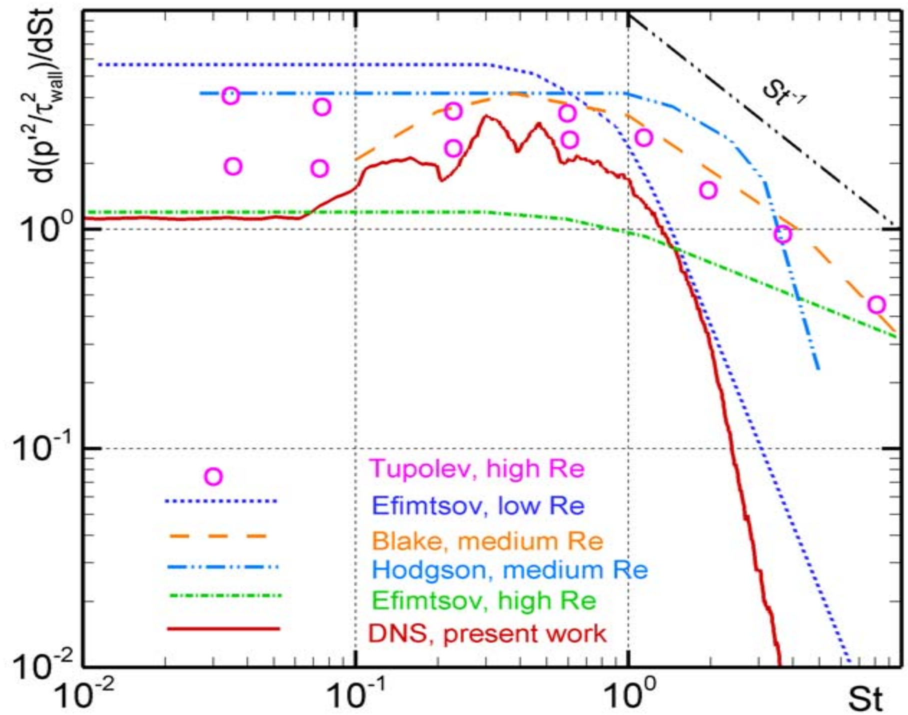
DNS of Baseline Turbulent Boundary Layer

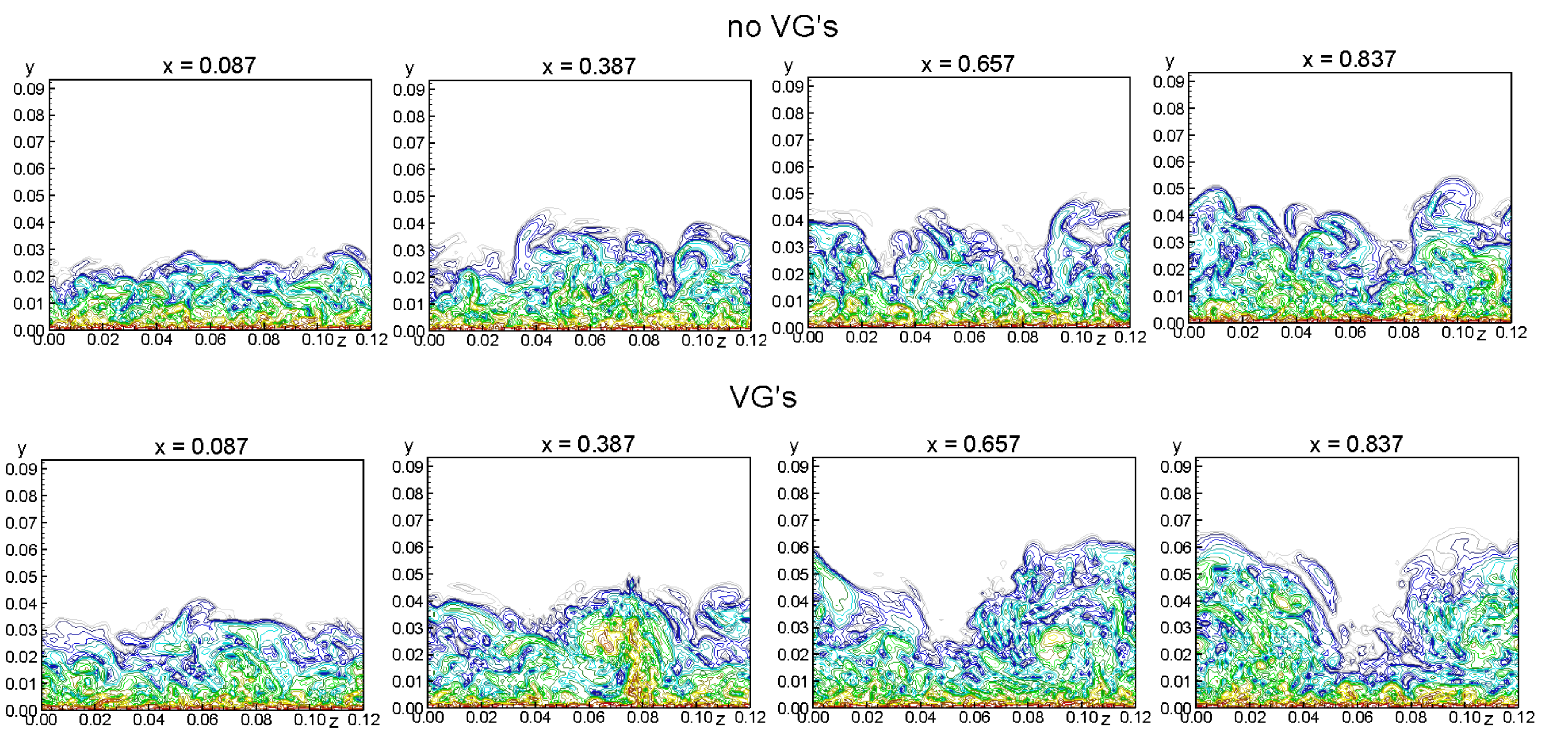


Comparison of Reynolds stresses with DNS of Spalart, 1988



Comparison of wall pressure spectrum with experiments and empirical correlations

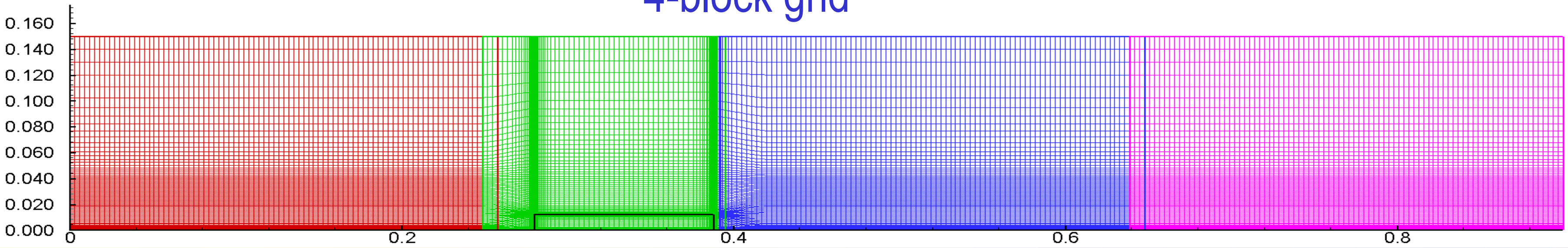
DNS of TBL with and without VG's

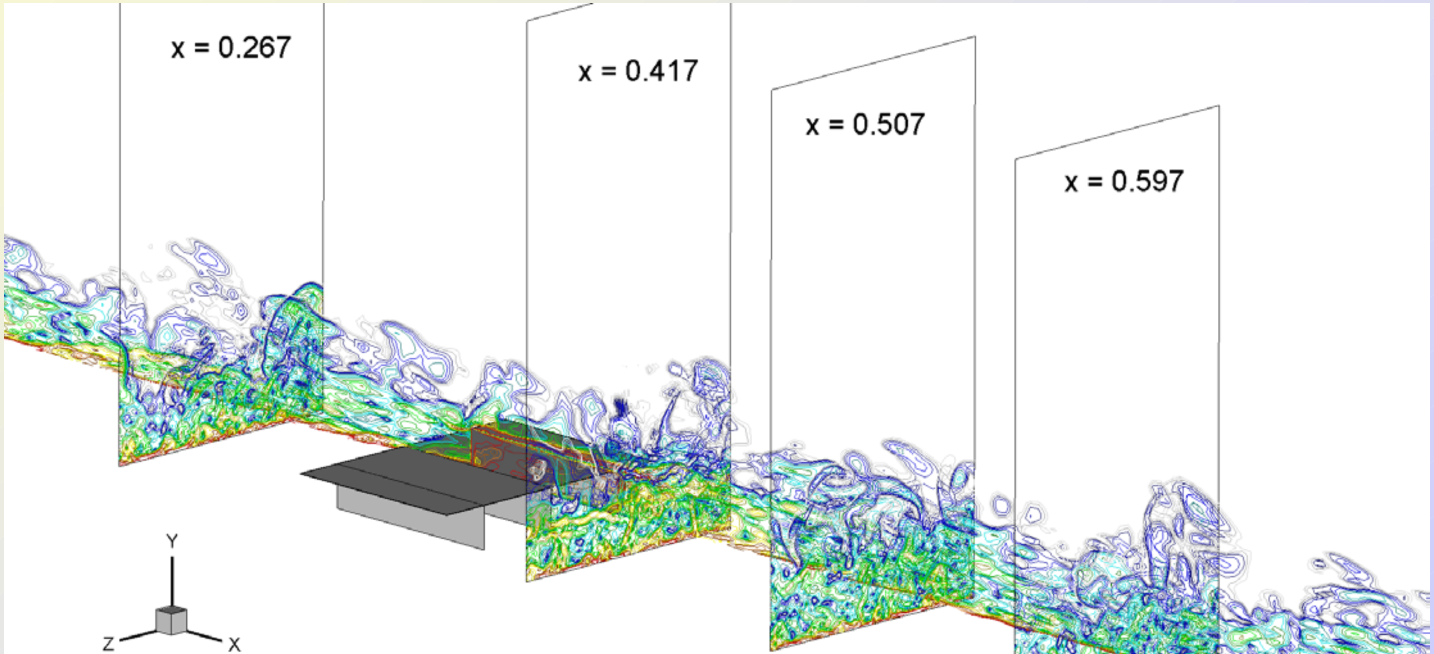


Vorticity snapshots without (upper row) and with VG's installed at x=0.3m (lower row) (looking into the flow)

DNS of TBL with Large-Eddy-Break-Up Device

4-block grid





Vorticity snapshot