APS DFD 2004

Seattle

# Research Directions in Unsteady Aerodynamics

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Boeing Commercial Airplanes

*with Strelets and Squires

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# Outline

- Theory: )-:
- Computational Fluid Dynamics
  - Resolved and modeled motion in ~ LES
  - SRANS; 2DURANS; 3DURANS; DES; LES
  - Resolution issue in DES/LES publications
  - Different "kinds" of unsteadiness?
- Diversion: LES of Jets and their Noise
- Experiments
  - Motivation
  - Number of dimensions
  - Transition
  - Circular cylinder, a wish list
- Summary

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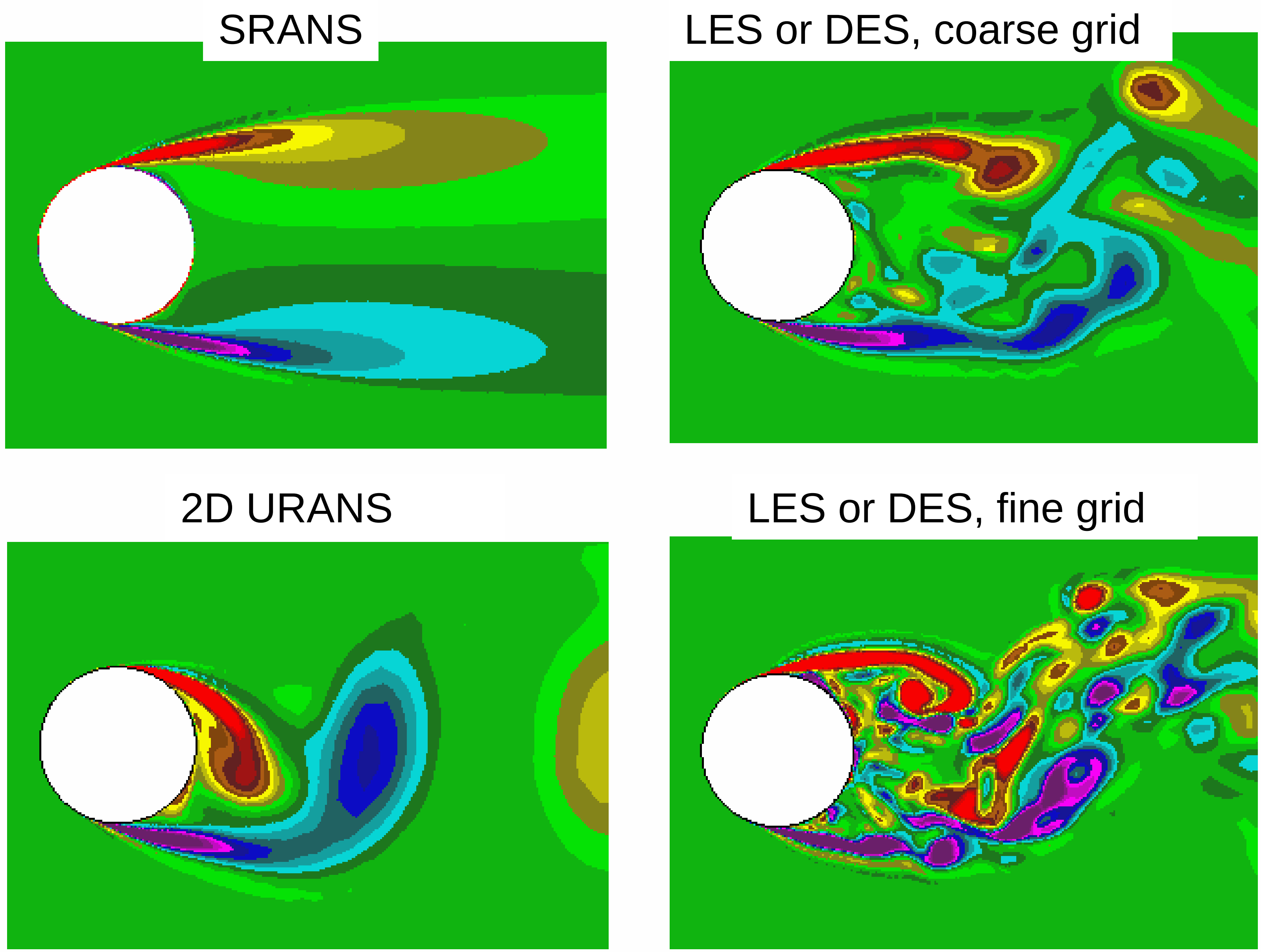
(other diversion: DNS of a LEBU?)

# Computational Fluid Dynamics

- Resolved and modeled motion in ~ LES
  - Ideally, the split follows clear filtering or averaging operation
  - Concretely, the split is controlled by the eddy viscosity, be it called RANS or SGS
  - Fundamental difficulty in LES remains "wall modeling"
    - QDNS, Quasi-Direct Numerical Simulation (e.g., channel at $Re_\tau$ = 1000, with $\nu_t / \nu$ ~< 2) is un-interesting. Aim at $\Delta z^+ = 1000$, then $10^4$!
    - Accounting for the filter is especially tricky.
- Acronyms
  - RANS
    - Steady: SRANS
    - Unsteady: URANS
      - Two-dimensional: 2DURANS
      - Three-dimensional: 3DURANS (even in 2D geometry)
  - DES (3D Unsteady, boundary layers by RANS)
  - LES (3D Unsteady, boundary layers by LES, due in 2045, EVEN with wall modeling)

# Resolved Solution in Different Approaches



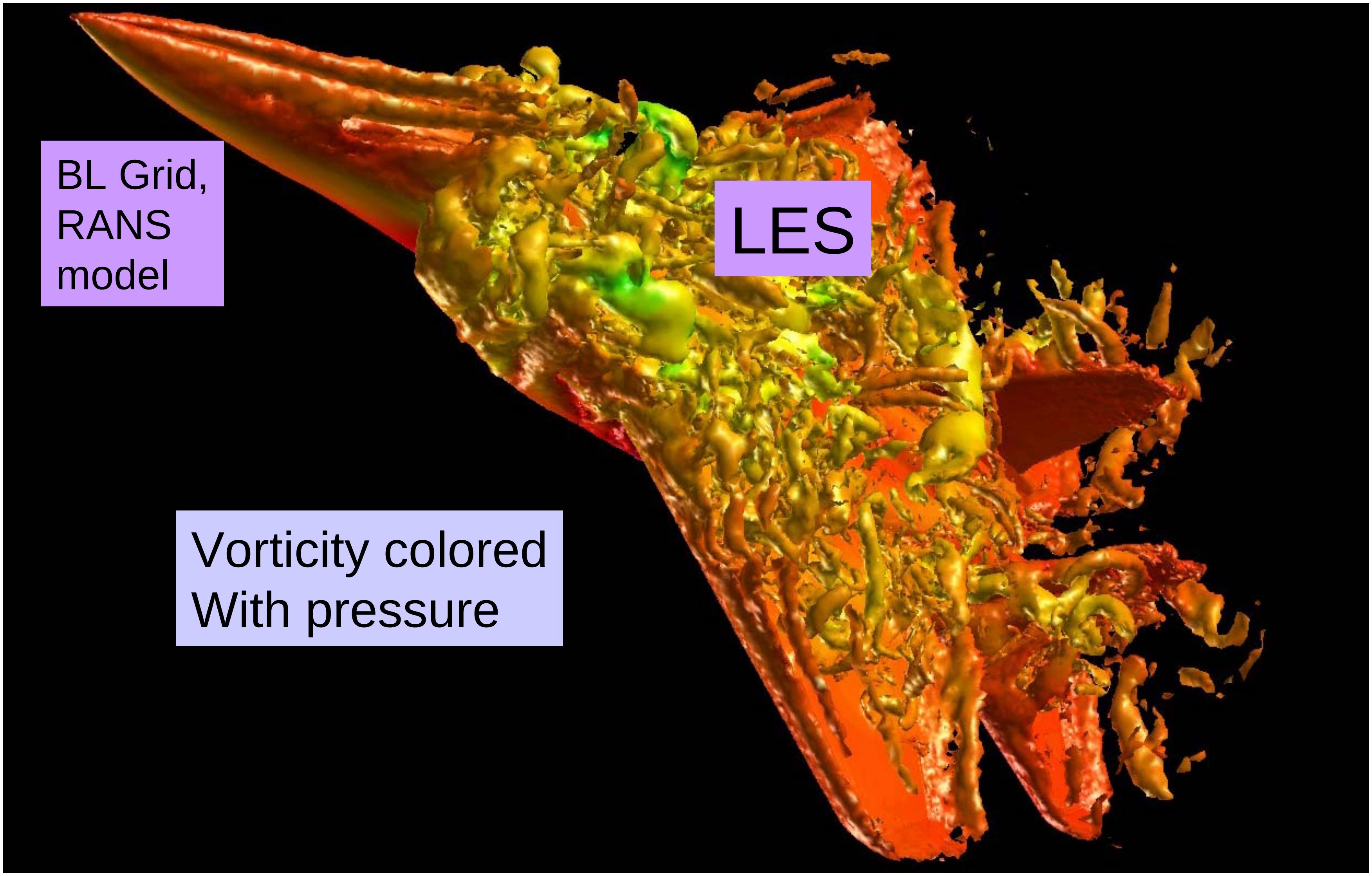

Cylinder with laminar separation

By Strelets group

# DES of F-15 at 65° $\alpha$

## Courtesy of Forsythe, Squires, Wurtzler






Re = 13.6 $10^6$; lift, drag, moment within 5% BOEING $10^7$ cells/side, Cobalt code, US DOD CPU

# Turbulent CFD: Resolution Issue

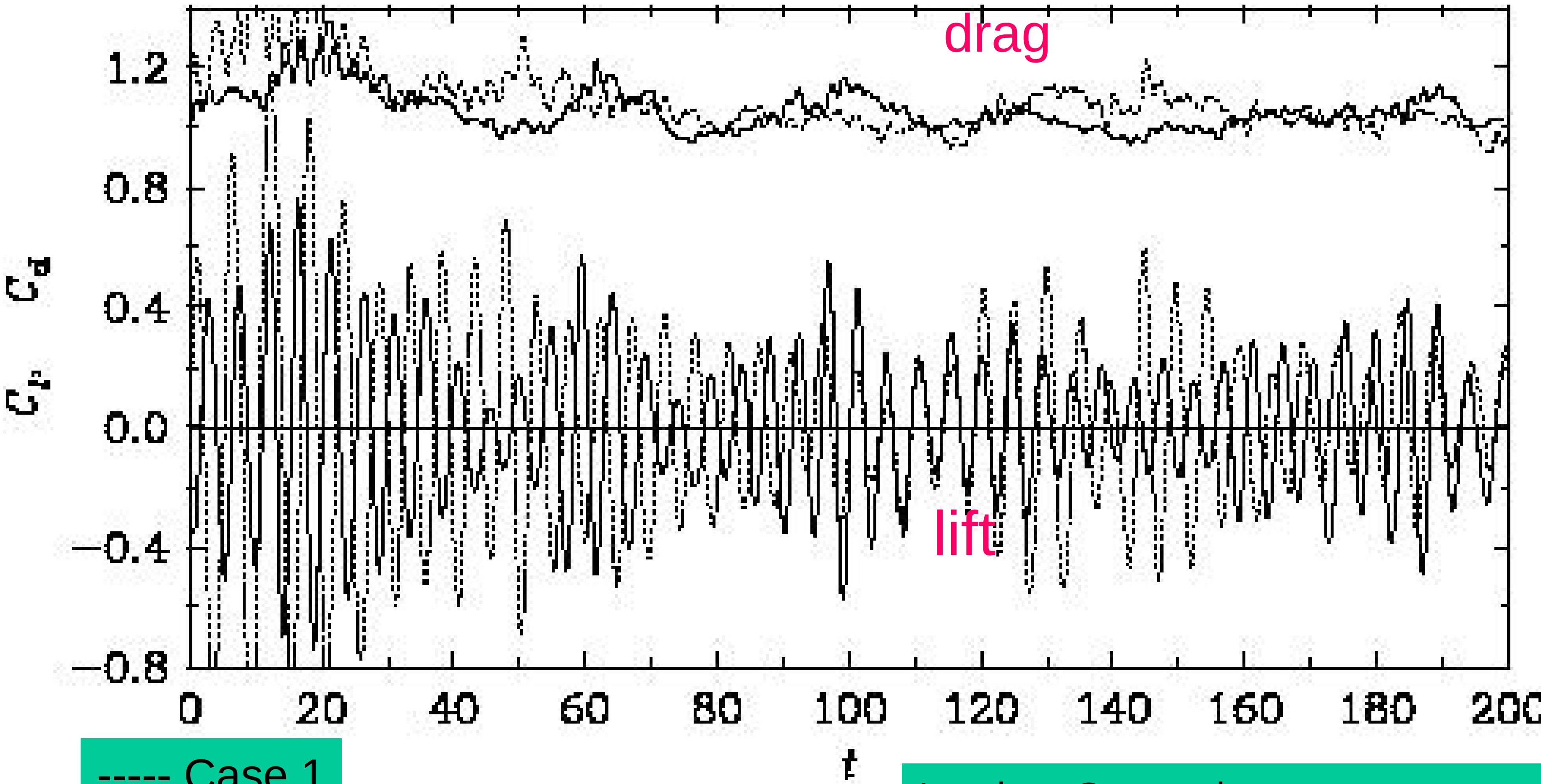
- RANS
  - Grid convergence is easy to define…
  - And easy to achieve, even to “overkill”
- DES, LES
  - Grid convergence is not easy to define
  - The order of numerical convergence is unclear
  - We “know” a flow field with more, smaller eddies is “better”
  - It is difficult to please journal editors, as author or reviewer
  - Ideally, we’d show a neat LES, and run one 16 times bigger, simply as a check…
- DNS
  - Grid convergence again easy to define
  - We limit ourselves with the Reynolds number
  - We never “overkill”   (almost never…)

# Different "kinds" of unsteadiness?

- Driven by boundary conditions
  - Low-frequency. No particular trouble
  - Medium- or high-frequency. Trouble for RANS
- Spontaneous
  - All turbulent flows have unsteadiness
  - Some have a "gross" unsteadiness, e.g., vortex shedding
    - Exists even in non-turbulent cases (e.g., cylinder at Re = 100)
    - Easy to capture, even in 2D CFD
    - Not as simple as it seems
    - Strong modulations destroy the motivation for phase-averaging. Seen in LES/DES, AND in Cantwell-Coles Expt.
    - 2DURANS is easy, highly periodic… and inaccurate!

# Force Histories on a Circular Cylinder






----- Case 1
- - - Case 2

Laminar Separation
Forces Averaged over 2*D spanwise

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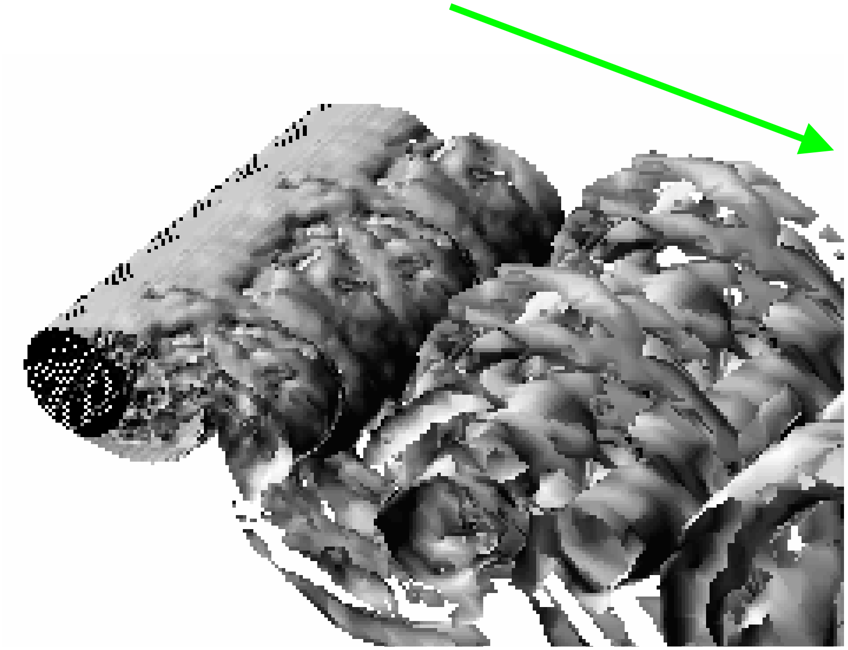
# The prospects for 3D URANS

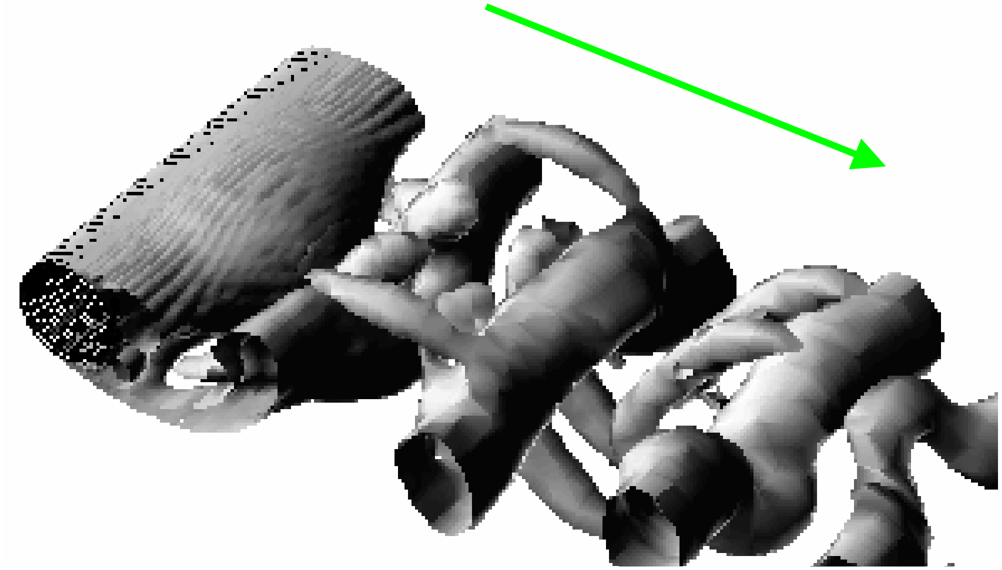
- Work with Shur, Strelets, Travin, and Squires
- 3D simulations in 2D geometries, with periodicity
- Prompted by findings of Vatsa and Singer
- We used to expect RANS would force 2D
- Will show cylinder (airfoil and square-cylinder act similar)
- Findings:
  - Most often, the three-dimensionality survives
  - It is much less fine-grained than in DES or LES
  - It does not improve with grid refinement
  - The global results (pressures, drag) are much better than from 2D URANS…
  - But they depend on the spanwise period and the RANS model, and usually do not catch up to DES

# The "Look" of DES and 3DURANS
# Flow past a Cylinder, Laminar Separation





DES, period repeated



URANS, single period

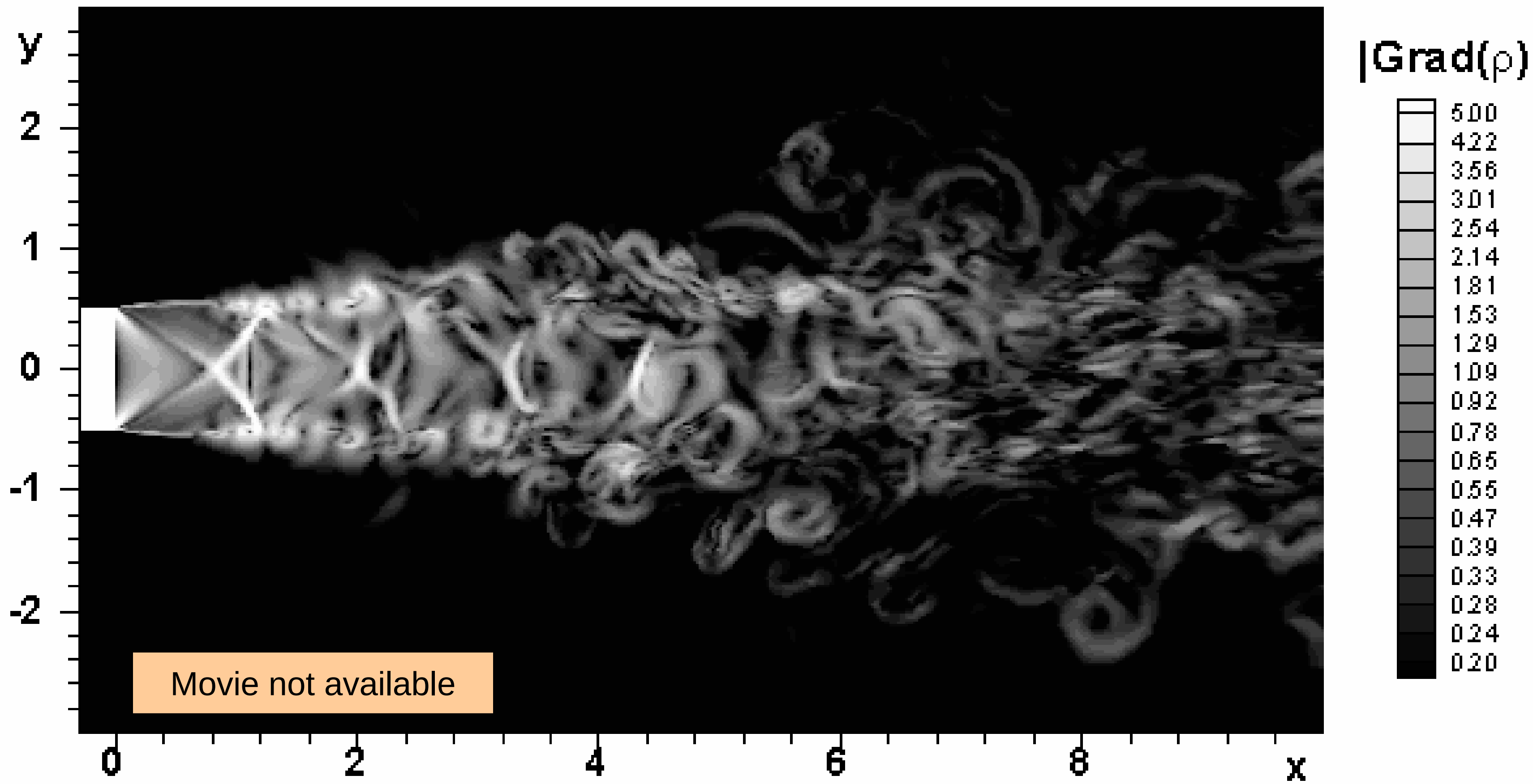
# Prediction of Jet Noise from First Principles



- Work with Shur and Strelets in St-Petersburg
- Turbulence:
  - LES
  - ~ 2 million points, on a PC
  - SGS model disabled, for now
- Sound:
  - Ffowcs-Williams/Hawkings formula, “adapted”
  - Permeable surface close to jet
- Performance:
  - Able to treat dual nozzles in co-flow, hot jets, chevrons, and imperfectly-expanded jets with shocks
  - Accurate within 2-3dB over a relatively wide range
  - Limited to Strouhal number ~ 2 (300Hz, for 777)

# Turbulence + Shock Cells in Sonic Jet
## by Shur & Strelets

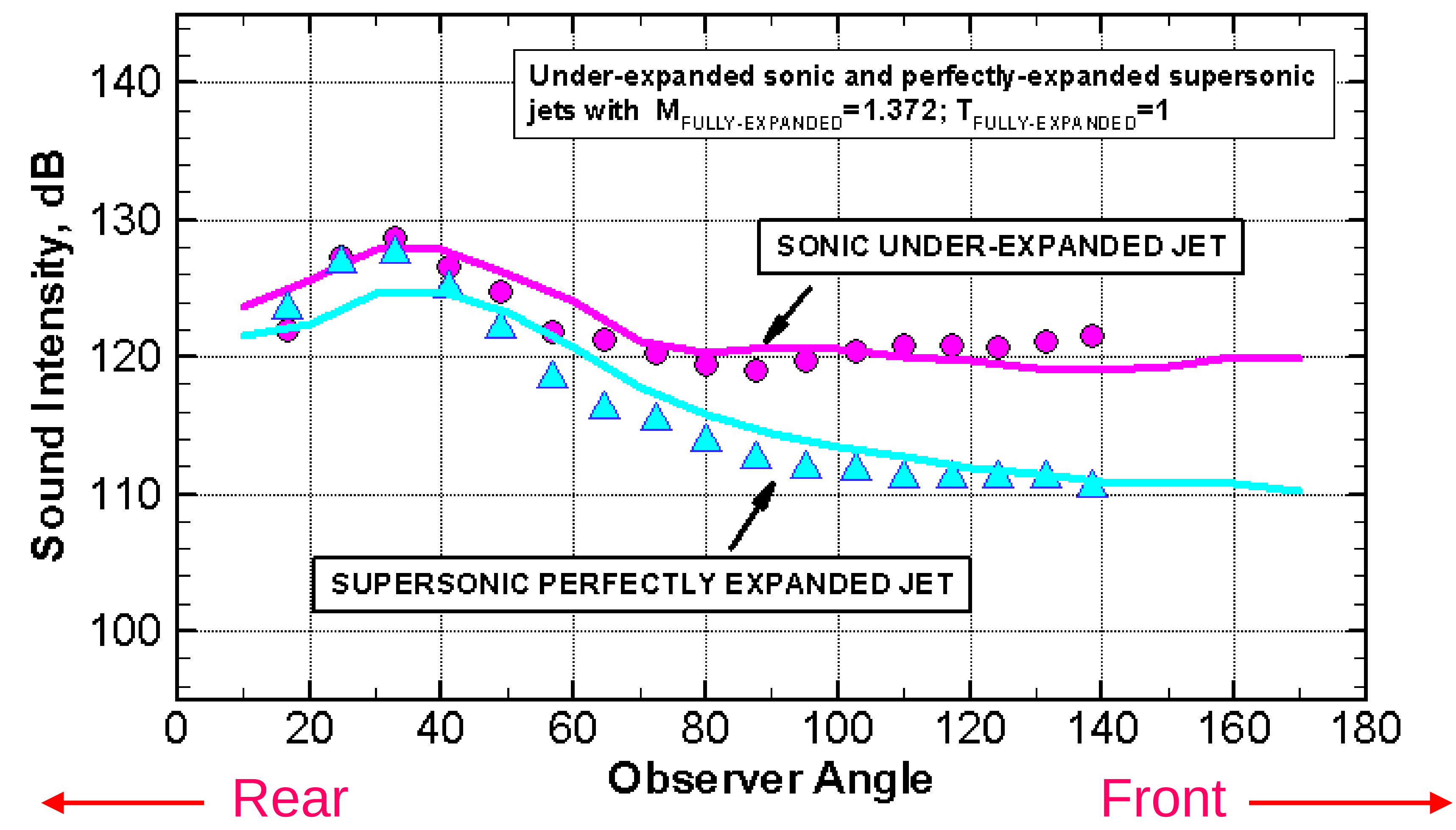





**Numerical "schlieren" from LES of under-expanded sonic jet**

# Broad-band Noise due to Shock Cells in Sonic Jet

## LES and Experiment



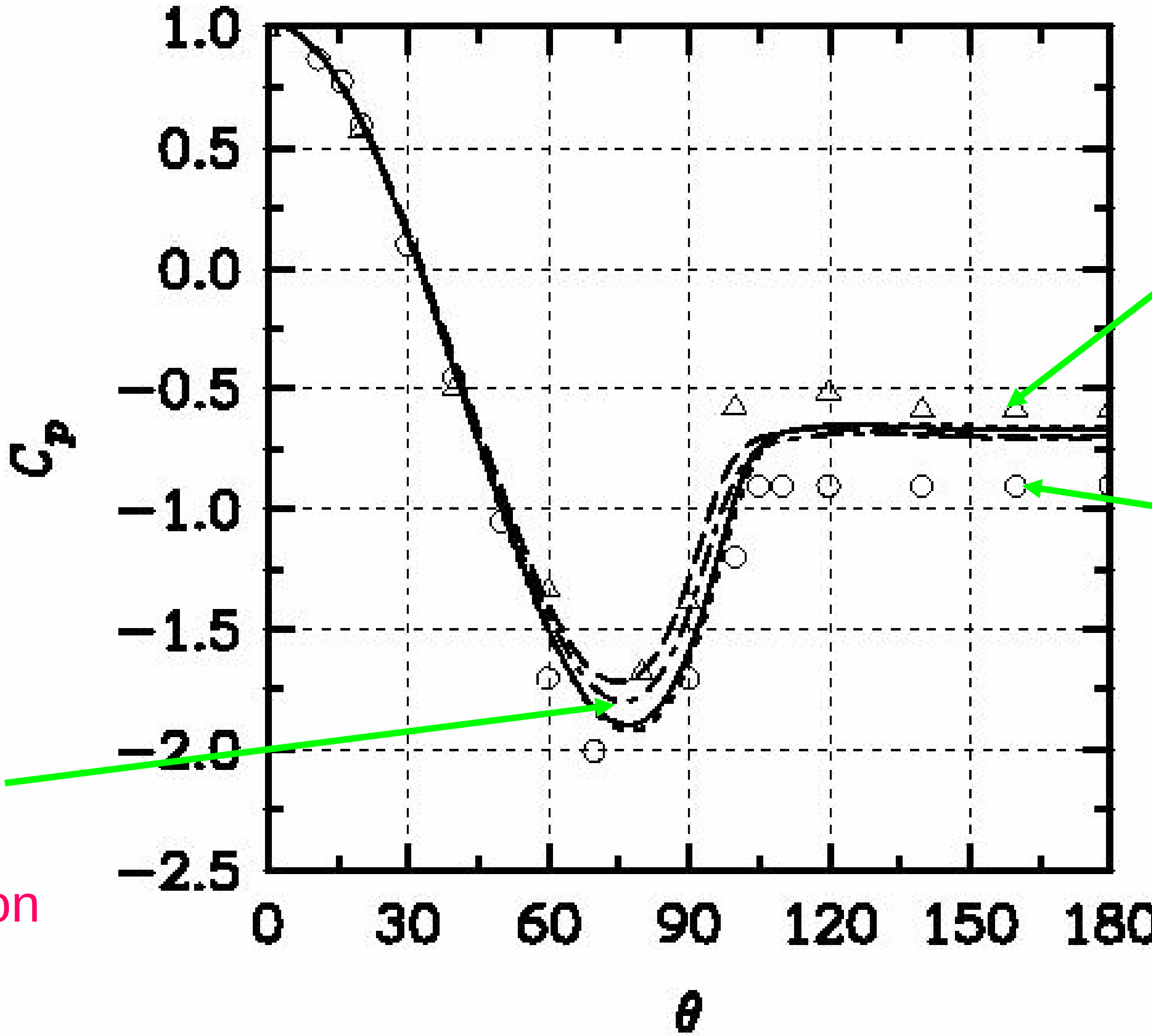
# Experiments

- Motivations
  - DNS, “Definitive Numerical Simulation” not possible
    - Geometry
    - Reynolds number
    - Small perturbations that control transition
      - Inflow
      - Noise
      - Surface
    - New, finer quantities needed
      - Far-field noise
      - Flow structure over very large scales
  - Study the instrumentation, not the flow?
- Two or three dimensions?
  - “3D issues” were already big at the Stanford Olympics
  - The value of “2D” flows is much lower because of:
    - Higher CFD power
    - Higher accuracy standards

# Situation of the Circular Cylinder

- This flow is a Classic
  - Simple shape
  - Sensitive to transition, smooth-wall separation, and massive separation
  - Has odd flow regimes, such as permanent asymmetry
  - Good place to make CFD fail!
- The experimental job is not finished
  - Experiments disagree tangibly:
    - For Reynolds numbers in the millions
    - Just where we thought we had simpler physics!
  - Transition and separation appear mingled, even at $4\ 10^6$
    - Or else, we have reattachment, and turbulent re-separation?
    - Current RANS turbulence modeling is at a loss
    - RANS can do “Laminar Separation” OR “Turbulent Separation”
    - A “microscopic” DNS of the separation region could be neat

# Pressure on Circular Cylinder, Reynolds number in the Millions



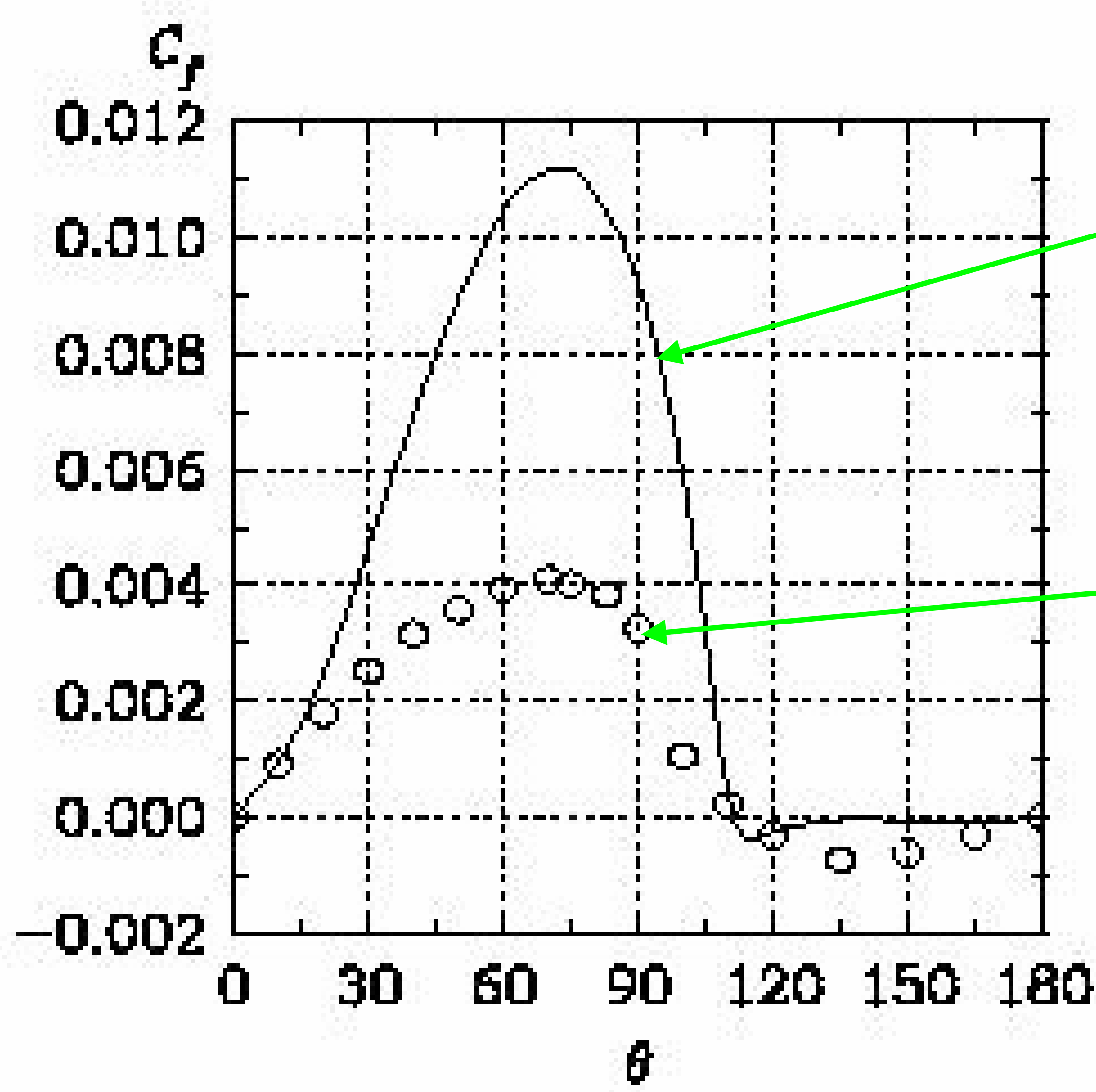

Van Nunen
1974
7.6 $10^6$

Roshko
1961
8.5 $10^6$

DES, with
various grids
and models.
Early transition
2000

The two best experiments differ by Cp ~ 0.3, which gives CFD a place to hide!

# Skin Friction on Circular Cylinder, Reynolds number in the Millions




DES, fully Turbulent BL, Re = 3 $10^6$

Expt, free transition, Re = 3.6 $10^6$

# A Wish List for the Circular Cylinder

- Reynolds number all the way:
  - From inception of drag crisis, ~ $10^5$
  - To fully-turbulent boundary layers, ~ ?? $10^6$
- Wind tunnel:
  - High aspect ratio. We could do the CFD with side walls
  - Acceptable blockage and Mach number
- Transition:
  - Natural
  - Tripped, at moderate Reynolds number, ~ $10^5$
  - Tripped on one side, compared with natural asymmetry
- Measurements:
  - Pressure and skin friction
  - Unsteady forces
  - Spanwise correlation
  - Reynolds stresses?

# Summary

- "Unsteadiness" is all over turbulence
- Turbulence simulations bring up "strategic decisions":
  - what to resolve, what to model?
  - beware of simplistic concepts of unsteadiness
- Sadly, the practice with RANS and SGS models
  - rarely is clearly tied to a filter
  - especially with wall modeling, which is a must
- Transition is the most delicate aspect in some cases

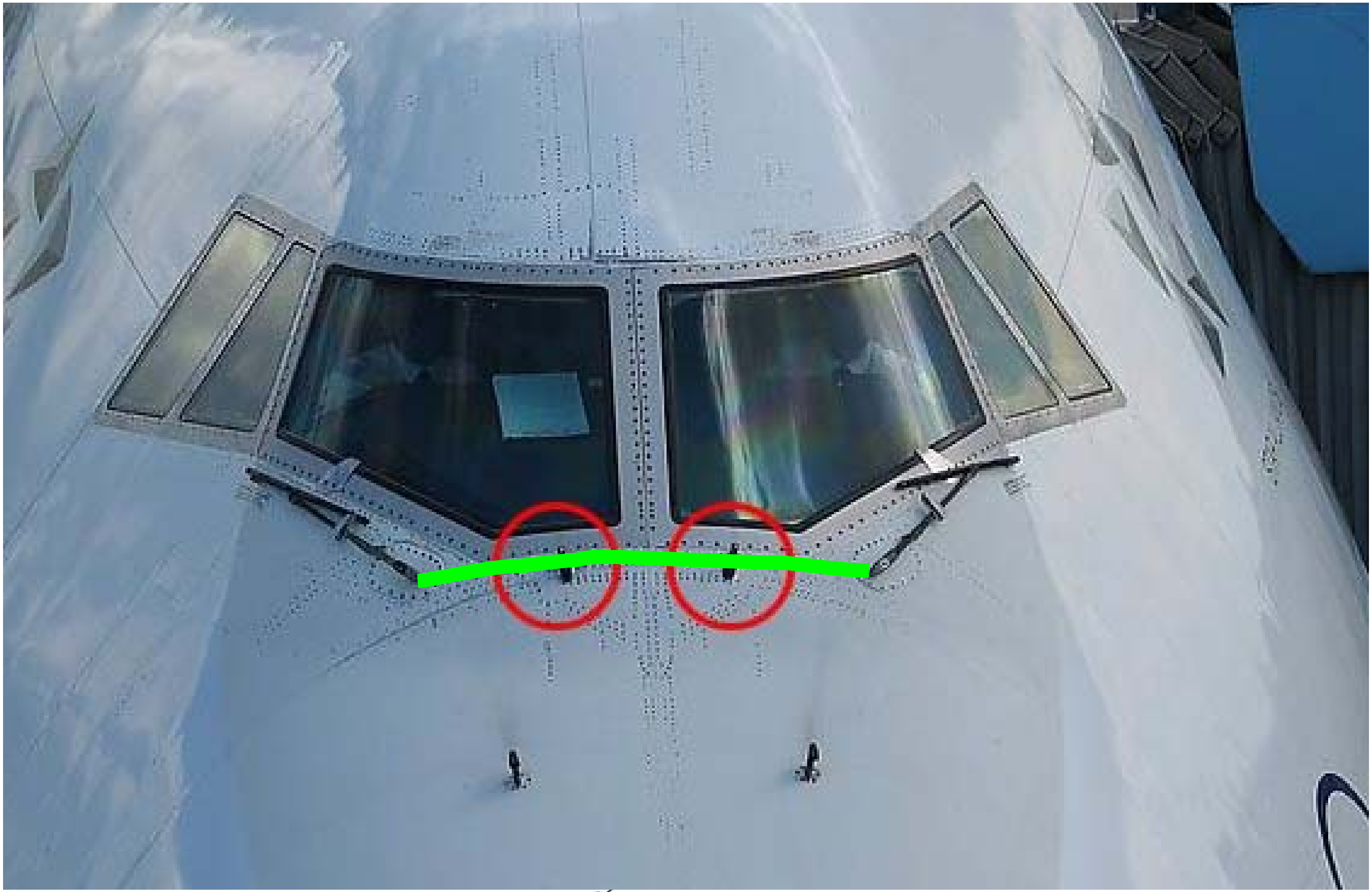
- Experiments must be very well-documented
- Being 2D is not that helpful any more
- They may often be limited by instrumentation
- Transition needs to be understood/dictated
- The circular cylinder remains a fabulous sand-box

# “Industrial” Direct Numerical Simulation: a Large-Eddy Break-Up (LEBU) device



- Work with Travin and Strelets
- Motivation
  - Aerodynamic noise in airliner cockpits
  - Value of a small, passive, simple device
  - Applicability to other vehicles?
- Objectives
  - Reduce wall pressure fluctuations of TBL (one that is attached to start with)
  - Reach benefit of several dB
  - Beat “rule of thumb” that a TBL recovers in 10 $\delta$

# Turbulence-Damping Device





(ignore red circles)

# "Industrial" Direct Numerical Simulation: a Large-Eddy Break-Up (LEBU) device

- Approach
  - DNS at $R_\theta \sim 1000$ (OK, since focus is on $St_\delta < 1$)
  - Multi-block high-order implicit code
  - Turbulent inflow by simplified Lund-Wu-Squires recycling; uses up less than 5 $\delta$
- Findings
  - Vortex generators tried first. They reduce TKE, as expected, but not the wall pressure rms
  - LEBU, looking like "highway bridge", lowers p' rms by 30% (or 3dB), but only over ~ 30cm
  - We have not optimized the design
- Experiment
  - In wind tunnel, with extensive measurements + structural model of window
  - In flight!

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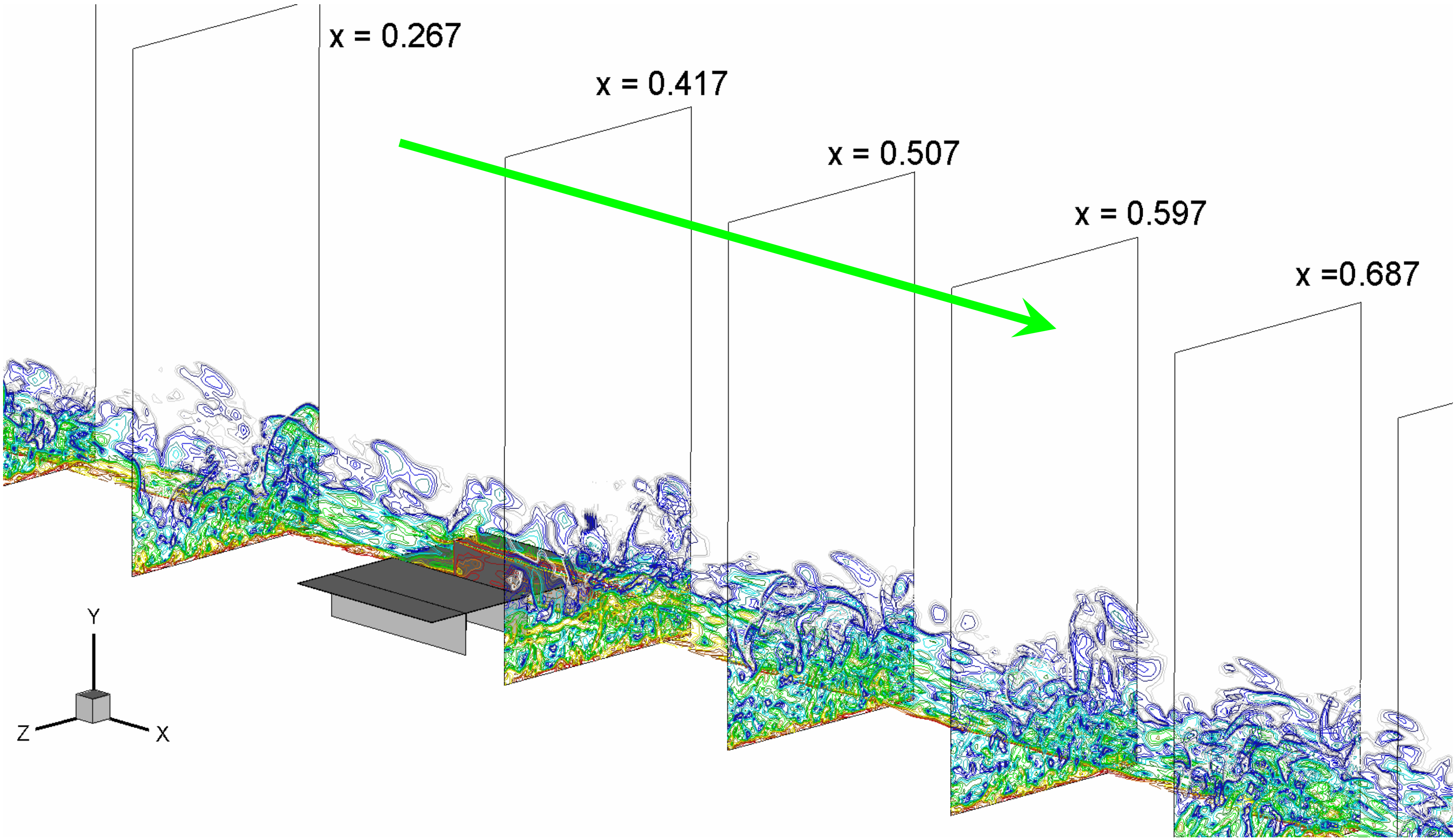
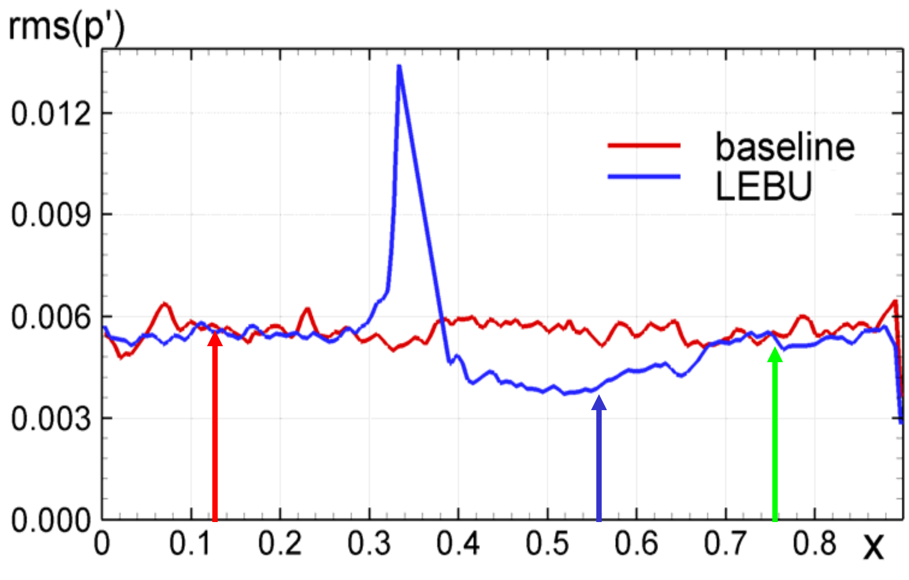
# Effect of LEBU in Turbulent Boundary Layer



# Effect of LEBU in Turbulent BL

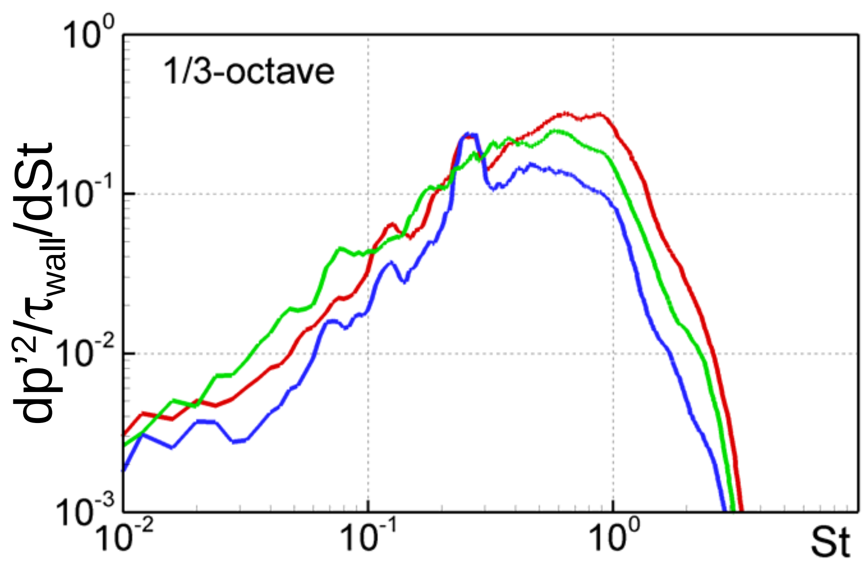


## Pressure rms




**(roughly in m)**

## Pressure spectra

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