LES Applications in Aerodynamics

Kyle D. Squires

School of Mechanical, Aerospace, Chemical and Materials Engineering
Arizona State University
Tempe, Arizona, USA

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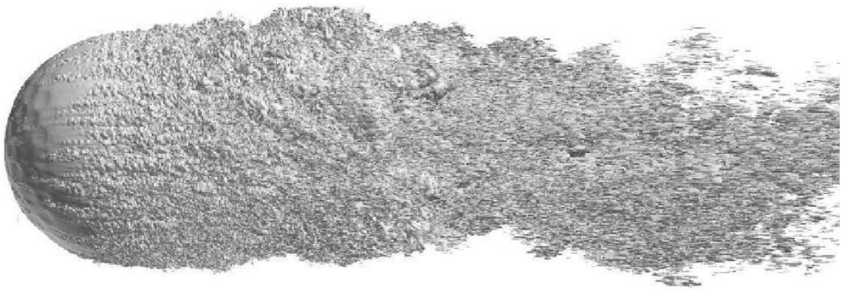
Outline

- Subgrid-scale models
  - Length scales in LES subgrid models vs. length scales in RANS models
    - Reminder of a key difference between the techniques
- Challenges for whole-domain LES in aerodynamics applications
  - Resolving the boundary layer at high Reynolds numbers
- Formulation of hybrid RANS-LES models
  - Detached Eddy Simulation
- Applications
  - Massively separated flows - from simple geometries to complex geometries
- Improvements and newer developments

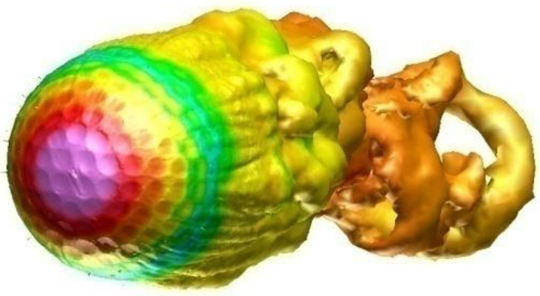
Motivation for modeling…

- Engineering models are meant to bypass the complex details of turbulent flows and predict the statistical features

DNS at Re = 110,000



DES at Re = 110,000



Goal is to construct methods/models that may be used to predict the statistical properties of turbulent motion

Modeling turbulent flows…

$$\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} = - \frac{1}{\rho}\frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j}$$

- By far the most widely used approach to model turbulent flows in applications is based on the introduction of an eddy viscosity…

$$\overline{u_i' u_j'} \approx \nu_t \left[\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right]$$

$$\nu_t = \text{turbulent eddy viscosity}$$

Objective of vast majority of engineering models is to predict the eddy viscosity in order to integrate the RANS equations

Eddy viscosity…

$$\underbrace{\nu_t = \mathcal{U}}_{\text{velocity scale}} \underbrace{l_m}_{\text{length scale}}$$

- Assumes that the turbulent eddies in a flow transfer momentum in much the same fashion as molecular interactions in a gas
  - Molecular interactions occur at much smaller scales as compared to the length scales over which flow properties are changing
  - Turbulent eddies have interactions at scales comparable to the length scales of the mean motion of the flow
- Mixing length characterizes (roughly) the distance traveled by an eddy before it gives up its momentum and loses identity

A simple idea…

- Assume equilibrium…

$$\mathcal{P} \approx \varepsilon \qquad\qquad \nu_t \mathcal{P} \approx \nu_t \varepsilon$$

$$\mathcal{P} = -\overline{u'v'}\frac{dU}{dy} \qquad\qquad -\overline{u'v'} = \nu_t \frac{dU}{dy}$$

- Combining the above relations…

$$\nu_t \varepsilon \approx \nu_t \left(-\overline{u'v'}\frac{dU}{dy}\right) = (\overline{u'v'})^2$$

$$\nu_t = \frac{(\overline{u'v'})^2}{\varepsilon}$$

A simple idea…

- To go further we need some knowledge of the flow
  - Let's assume that the ratio of the shear stress to the kinetic energy takes a constant value

$$\frac{\overline{u'v'}}{\mathcal{K}} \approx C$$

- We had…

$$\nu_t = \frac{(\overline{u'v'})^2}{\varepsilon}$$

- Now we have…

$$\nu_t = C^2 \frac{\mathcal{K}^2}{\varepsilon}$$

Important parts of the previous exercise…

- Expressed the eddy viscosity in terms of a velocity scale and length scale as…

$$\nu_t = \mathcal{U}\, l_m$$

$$\mathcal{U} = \text{velocity scale} \qquad l_m = \text{mixing length}$$

- The eddy viscosity depends on a velocity and a length scale that are properties of the flow

- Popular RANS turbulence models solve transport equations for the velocity and length scales or other variables that can be used to form the eddy viscosity
  - Spalart-Allmaras (S-A) one-equation model
  - Menter's SST model (two-equation model)

Spalart-Allmaras one-equation model

$$\begin{aligned}\frac{D\tilde{\nu}}{Dt} &= c_{b1}(1-f_{t2})\tilde{S}\tilde{\nu} \\ &+ \frac{1}{\sigma}\left[\nabla\cdot((\nu+\tilde{\nu})\nabla\tilde{\nu}) + c_{b2}(\nabla\tilde{\nu})^2\right] \\ &- \left[c_{w1}f_w - \frac{c_{b1}}{\kappa^2}f_{t2}\right]\left[\frac{\tilde{\nu}}{d}\right]^2 + f_{t1}\Delta U^2\end{aligned}$$

- Full model contains trip terms that enable activation of the model…

$$f_{t1} = c_{t1}g_t \exp\left(-c_{t2}\frac{\omega_t^2}{\Delta U^2}\left[d^2 + g_t^2 d_t^2\right]\right) \qquad g_t = \min\left(0.1, \frac{\Delta U}{\omega_t \Delta x_t}\right)$$

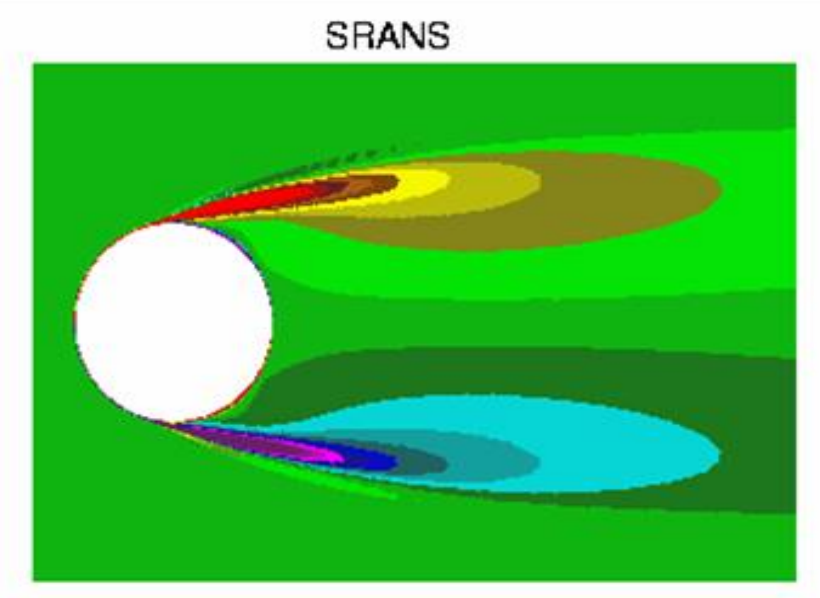
$$f_{t2} = c_{t3}\exp\left(-c_{t4}\chi^2\right)$$

RANS models…

- Where are the problems?
  - Bluff bodies…
    - » Characterized by chaotic vortex shedding
    - » Unless the geometry has sharp edges, separation prediction can be difficult
      - › Even two-dimensional bluff bodies are sufficient to cause simple models to fail, even configurations with sharp corners that set the separation location

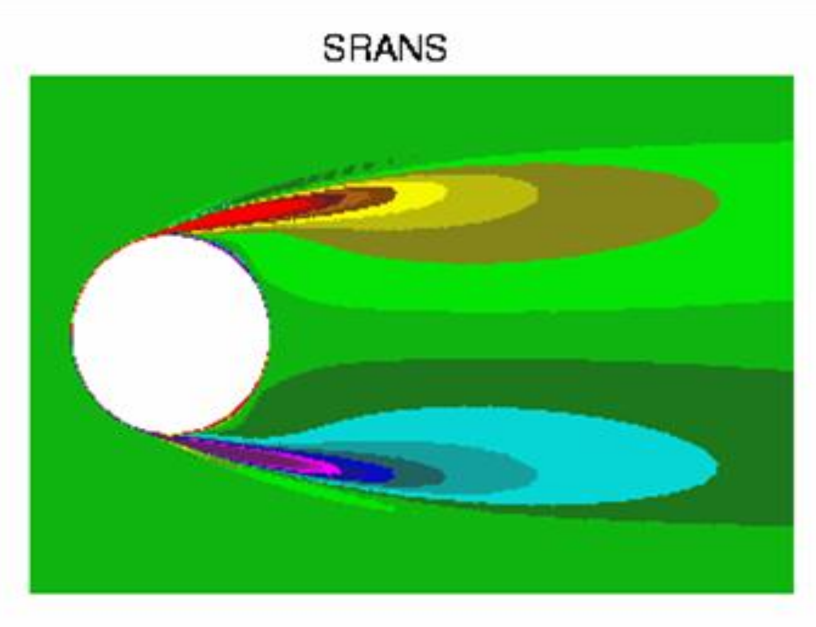
Flow over a cylinder by Strelets group (laminar boundary layer separation)

Drag coefficient is too low compared to measurements, S-A model



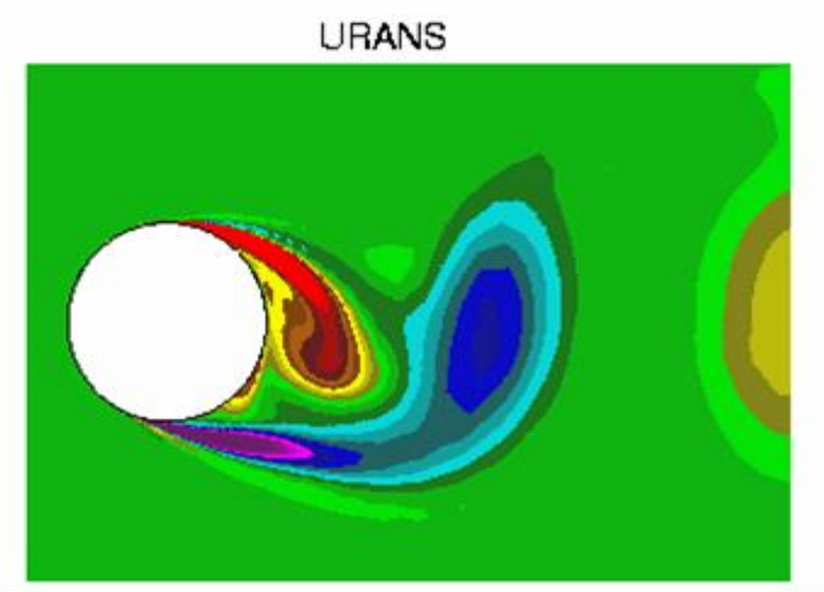
URANS of a cylinder…

Re = 50k, laminar separation, S-A model (Strelets group)



Steady RANS

Drag is too low



Unsteady RANS

Drag is too high

Large Eddy Simulation (LES)

- Time dependent large scale motions are resolved on a grid
  - Small scale turbulence that cannot be resolved is modeled
- The governing equations are filtered…

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u}_i \overline{u}_j) = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\tau_{ij} = \overline{u_i u_j} - \overline{u}_i \overline{u}_j$$

$$\tau_{ij} - \frac{\delta_{ij}}{3}\tau_{kk} = -2\nu_{sgs}\overline{S}_{ij} = -\nu_{sgs}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)$$

- Looks like the RANS equations
  - But there are important differences…

Large Eddy Simulation (LES)

- Subgrid viscosity in LES…

$$\nu_{sgs} = (C_s\Delta)^2|\overline{S}| \qquad |\overline{S}| = (2\overline{S}_{ij}\overline{S}_{ij})^{1/2}$$

- Eddy viscosity in RANS…

$$\nu_t = 0.09\frac{\mathcal{K}^2}{\varepsilon} \qquad \mathcal{K} = \text{kinetic energy} \qquad \varepsilon = \text{dissipation rate}$$

- Length scale in the LES subgrid model is typically coupled to the grid (through the filter width)
- Length scale in the RANS model is a property of the flow and computed from model equations

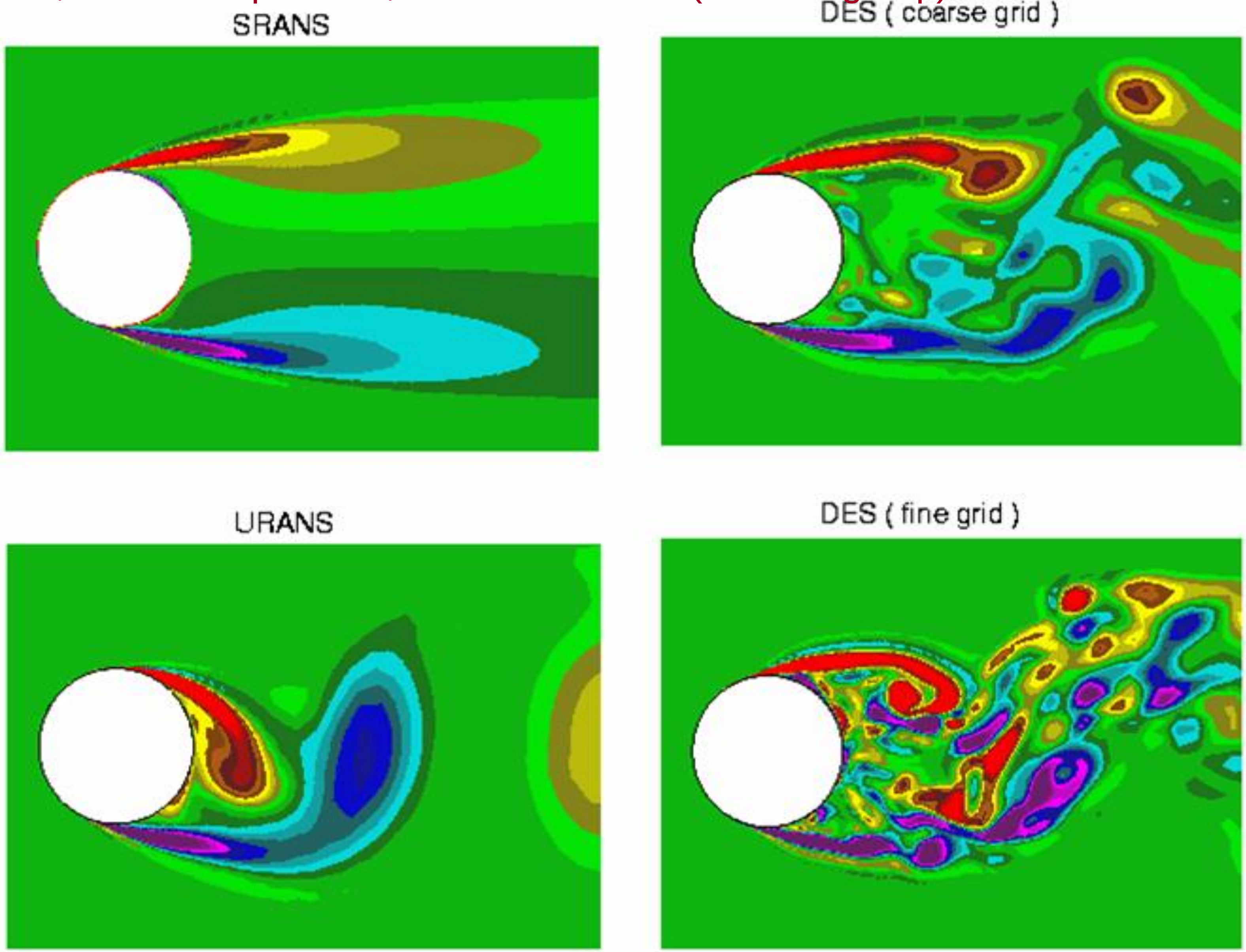
Role of grid refinement is different

Grid convergence in RANS

More physics in LES

Large Eddy Simulation (LES)

Re = 50k, laminar separation, S-A-based DES (Strelets group)



Large Eddy Simulation (LES)

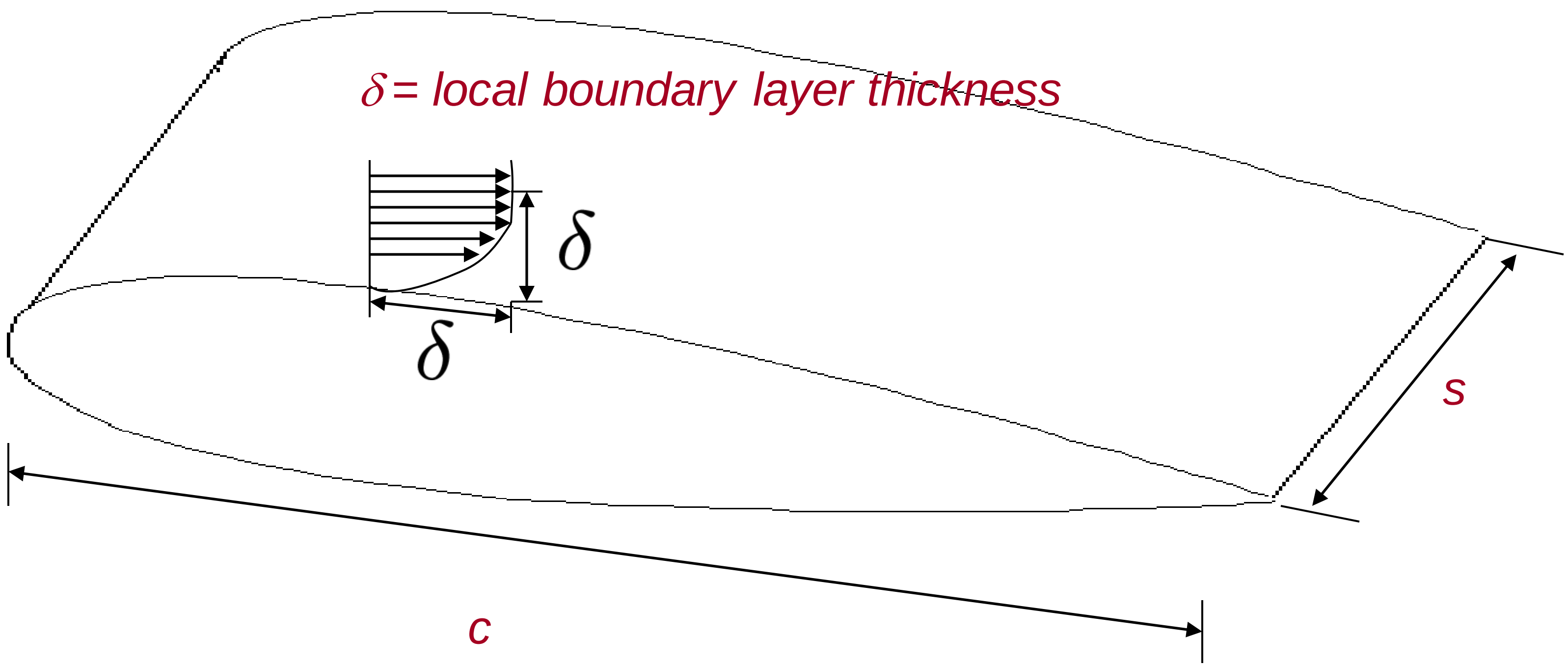
- Very powerful technique…
  - Access to three-dimensional time-dependent description of a flow
  - Relatively simple models possible
  - Predictions less sensitive to modeling errors than RANS

- How much does it cost?
  - (roughly) estimate the grid resolution need to apply LES to prediction of the flow over a section of a wing (Spalart et al. 1997)…
    - » Consider a section 1 m^2 (chord length of a 1 meter, spanwise section 1 meter)
      - › Objective is to estimate the number of cubes of size δ (per side) needed to fill the boundary layer

$$N_{cubes} = \int\int \frac{1}{\delta^2} dA$$

Cost estimate for LES of an airfoil

$$N_{cubes} = \int\int \frac{1}{\delta^2} dA$$



Cost estimate for LES of an airfoil

- Rough estimate for N_{cubes} obtained using a simple correlation for a flat plate boundary layer

$$\delta(x) = 0.37x \left(\frac{U_\infty x}{\nu}\right)^{-0.2}$$

- Consider a chord-based Reynolds number of 2×10^6

$$N_{cubes} = \int \int \frac{1}{\delta^2} dA \approx 9 \times 10^6$$

- Above estimate is the number of cubes of dimension δ needed to fill the boundary layer over the wing

Cost estimate for LES of an airfoil

$$N_{cubes} = \int\int \frac{1}{\delta^2} dA \approx 9 \times 10^6$$

- Above estimate is the number of cubes of dimension δ needed to fill the boundary layer over the wing
- Number of grid points dictated by the resolution per boundary layer thickness
  - Assume the wall-layer is modeled (not resolved)
  - Let N_0 be the number of grid points per boundary layer thickness
    - » N_0: 10 points per boundary layer thickness is minimum
    - » N_0: 15-20 points per boundary layer thickness desirable (Nikitin et al. 2000)

$$N_g = N_0^3 N_{cubes}$$

Cost estimate for LES of an airfoil

$$N_g = N_0^3 N_{cubes}$$

- For $N_0 = 20$…

$$N_g = 7 \times 10^{10}$$

- Timestep that is required coupled to the grid spacing…(so we'll need a lot of timesteps)

- Above estimate assumes the wall-layer is modeled (hopefully accurately)
  - Direct resolution of the wall layer will make the cost higher

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Detached Eddy Simulation (DES)

- Motivation…
  - Desire for a simulation strategy that combines the efficiency of RANS and the fidelity of LES
    - » Circumvent the modeling errors in RANS methods in massively separated flows
    - » Avoid the computational cost of whole-domain LES at high Reynolds numbers

- Proposed in 1997 by Spalart and colleagues
  - Develop a single simulation strategy that exhibits different ("hybrid") behavior

Definition: "A Detached-Eddy Simulation is three-dimensional numerical solution using a single turbulence model, which functions as a sub-grid-scale model in regions where the grid is fine enough for a Large-Eddy Simulation and as a Reynolds-averaged model in regions where it is not." (Travin et al. 2000)

Formulation of S-A DES

- S-A RANS model

$$\frac{D\tilde{\nu}}{Dt} = \underbrace{P_\nu}_{\textit{Production}} - \underbrace{\epsilon_\nu}_{\textit{Destruction}} + \underbrace{\frac{1}{\sigma_\nu}\left[\nabla((\nu+\tilde{\nu})\nabla\tilde{\nu}) + c_{b2}|\nabla\tilde{\nu}|^2\right]}_{\textit{Transport}}$$

- Production and destruction terms…

$$P_\nu \propto \tilde{S}\tilde{\nu} \qquad\qquad \epsilon_\nu \propto \left[\frac{\tilde{\nu}}{d}\right]^2$$

- Replace the length scale…

(wall distance) $d \longrightarrow \tilde{d}$

Formulation of DES…

- Balance the production and destruction terms…

$$P_\nu \approx \epsilon_\nu \longrightarrow \tilde{S}\tilde{\nu} = \left[\frac{\tilde{\nu}}{\tilde{d}}\right]^2$$

- Leads to…

$$\tilde{\nu} \propto \tilde{d}^2 \tilde{S}$$

- Smagorinsky eddy viscosity…

$$\nu_{sgs} = (C_s\Delta)^2|\overline{S}|$$

- Can obtain a Smagorinsky eddy viscosity if the length scale is made proportional to Δ

Formulation of DES…

- Prescription of the length scale…

$$\tilde{d} \equiv min(d, C_{DES}\Delta)$$

- High cost of LES arises because of resolution requirements in the boundary layer
  - Prescribe Δ such that RANS length scale maintained in the boundary layer

$$\Delta \equiv \max(\Delta x, \Delta y, \Delta z)$$

- Close to the wall Δ is set by the wall parallel spacings

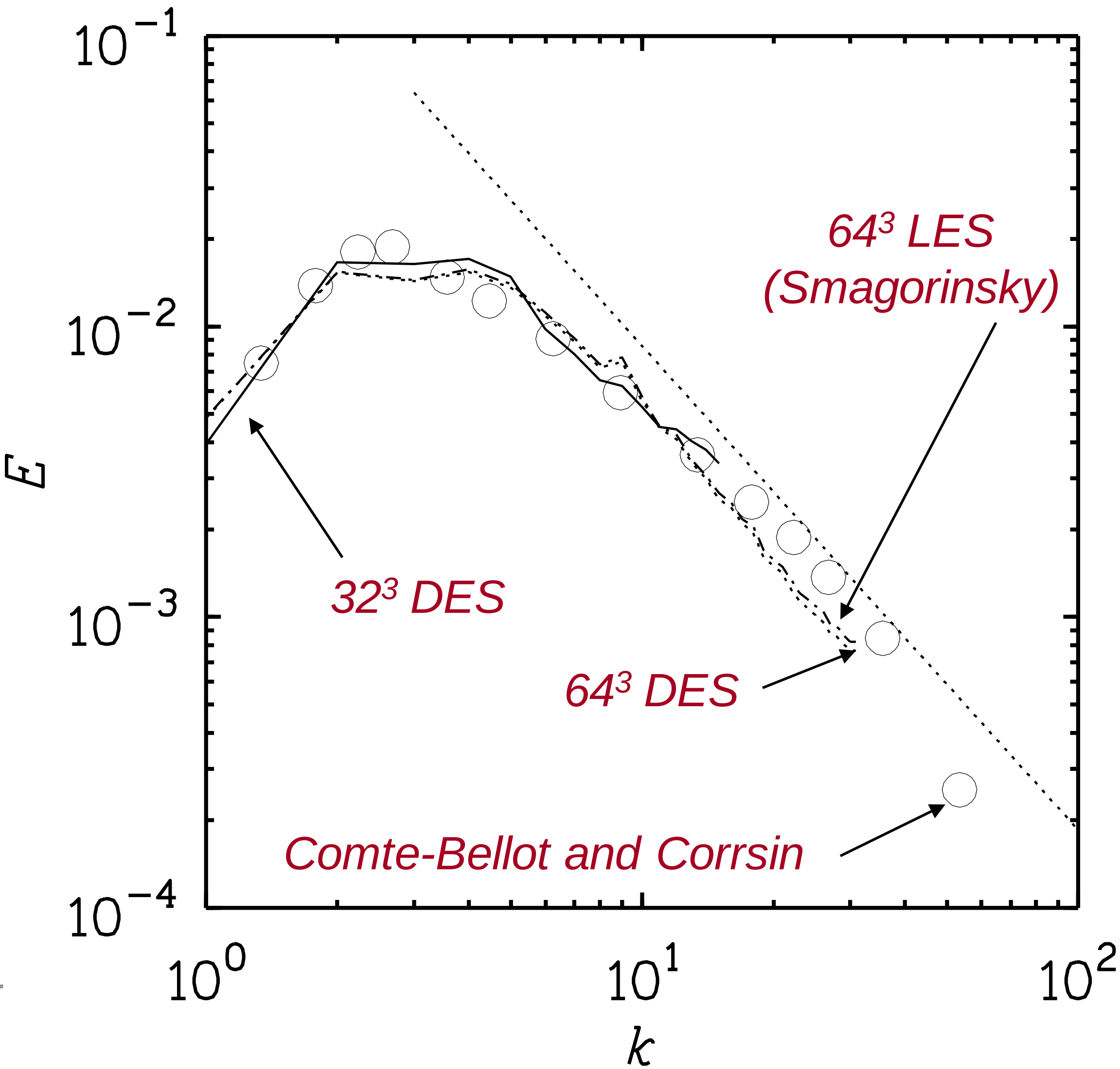
$$d \ll \Delta\,, \quad \tilde{d} = d\,, \quad \text{RANS}$$

- Away from the wall…

$$C_{DES}\Delta < d\,, \quad \tilde{d} = C_{DES}\Delta\,, \quad \text{LES}$$

Calibration of the constant C_{DES}

Decaying isotropic turbulence (Shur et al. 1999)



- Computations for various values of C_{DES}
  - Examined the behavior of the kinetic energy and spectral shape near the cutoff
  - Found scaling of the average eddy viscosity close to $\Delta^{4/3}$

$$\boxed{C_{DES} = 0.65}$$

Aspects of the formulation…

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\tilde{S}\tilde{\nu} + \text{diffusion} - c_{w1} f_w \left[\frac{\tilde{\nu}}{\tilde{d}}\right]^2$$

production *destruction*

$$\tilde{d} = \min(d, C_{DES}\Delta) \qquad \Delta = \max(\Delta_x, \Delta_y, \Delta_z)$$

$$(\Delta_x, \Delta_y, \Delta_z) = \text{grid spacings in each direction}$$

- DES is a *3D unsteady numerical solution using a single turbulence model*
  - Non-zonal
    - » LES in regions where grid density is sufficient
    - » RANS model in other regions
  - Abrupt change in the length scale (discontinuity in the gradient)
  - "RANS Region" and "LES Region" separated by an interface dictated by the grid

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Flow over an airfoil at high angle of attack

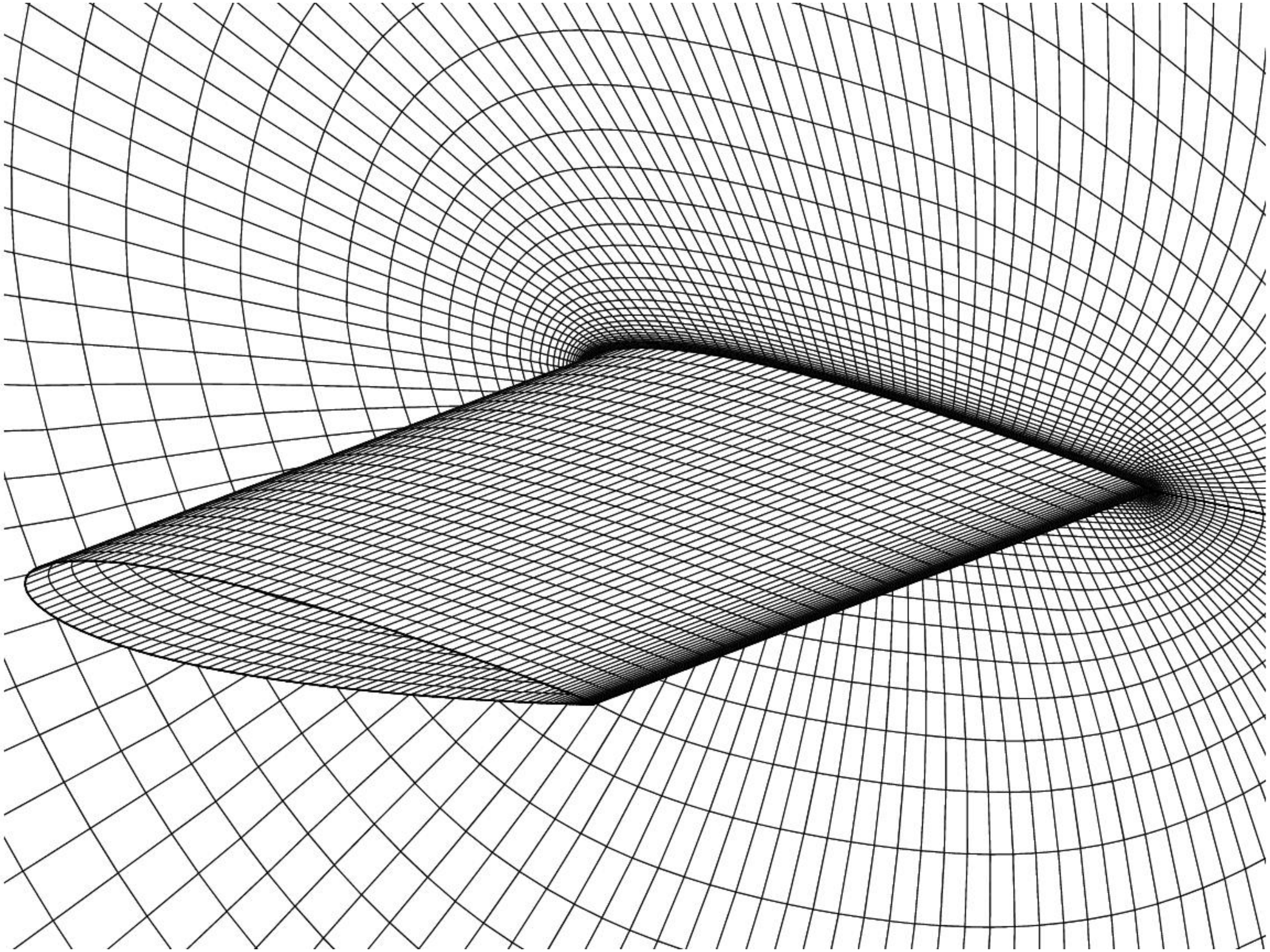
Shur et al. (1999)

- First application of DES following launch of the model in 1997
- Motivation
  - URANS errors of about 40% in drag and lift coefficients
- Flow configuration
  - NACA 0012 airfoil with spanwise extent equal to the chord length
  - Structured 'O' grid with 141 x 65 x 40 grid points in the streamwise, wall-normal and spanwise directions respectively.
  - Fully turbulent predictions
  - RANS-LES interface at 0.026C
    - » Set by the spanwise spacing
  - Reynolds number based on chord length = 10^5

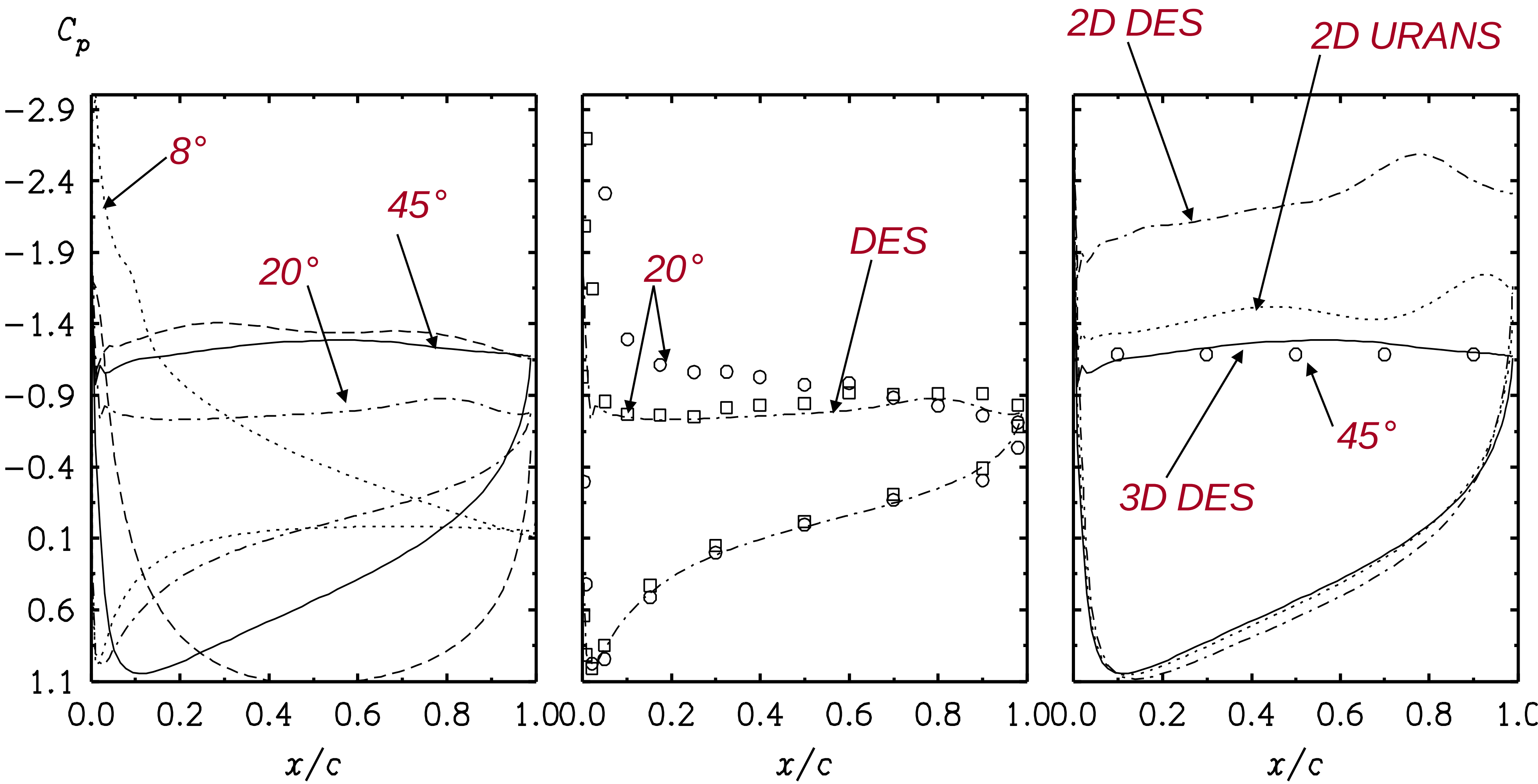
Objectives: would it work?

141 x 65 x 25 grid

Shur et al. (1999)



Pressure coefficient



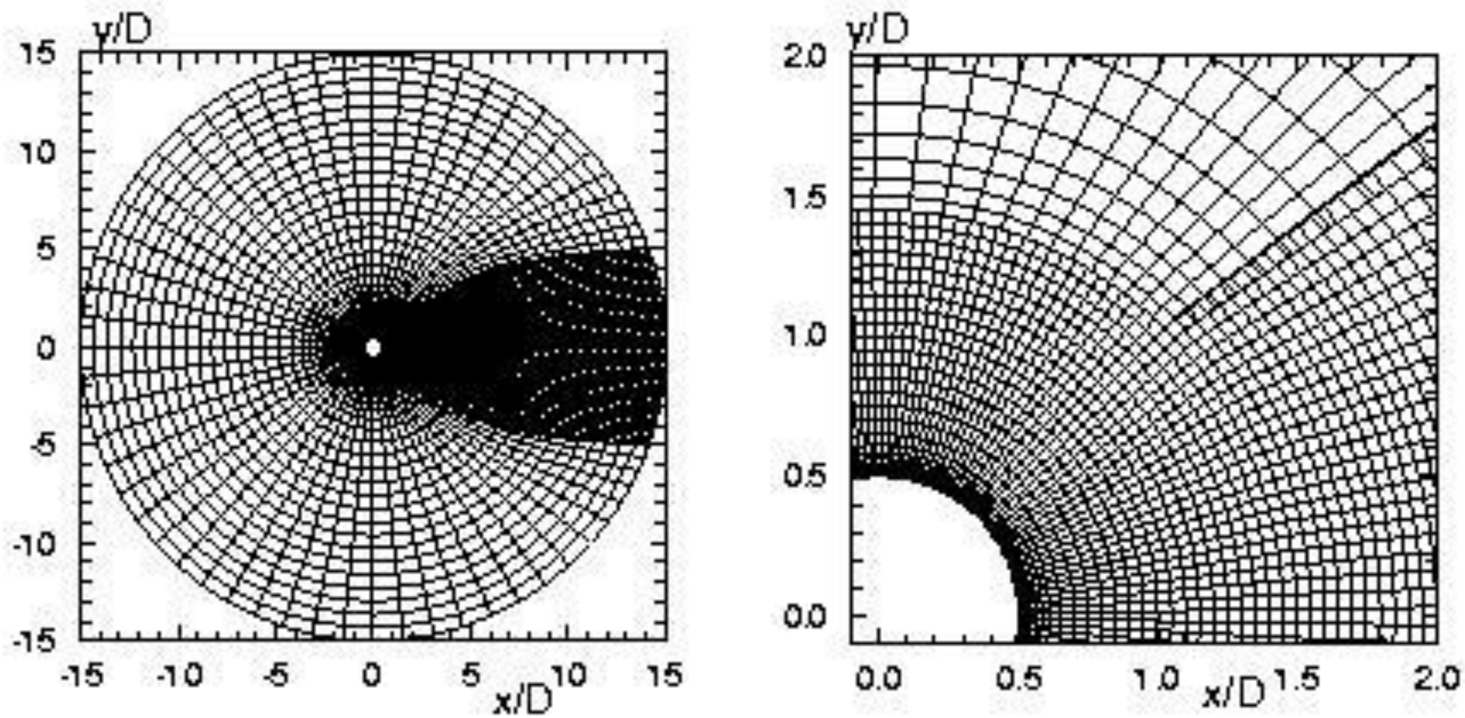
Flow past a circular cylinder

Travin et al. (1999)

- Comprehensive study and assessment of the technique
- Reynolds numbers…
  - 5×10^4, 1.4×10^5 and 3×10^6
- Cylinder known for its drag crisis…
  - Disparity in laminar and turbulent boundary layer separation
    - » Laminar boundary layer separation: turbulence model should remain dormant (mimic'd using tripless approach)
    - » Turbulent boundary layer separation: turbulence model controls separation prediction
- Absence of sharp edges on the surface of the cylinder make it a good test to detect "grey area" failures

Will the generation of three-dimensional structures occur rapidly?

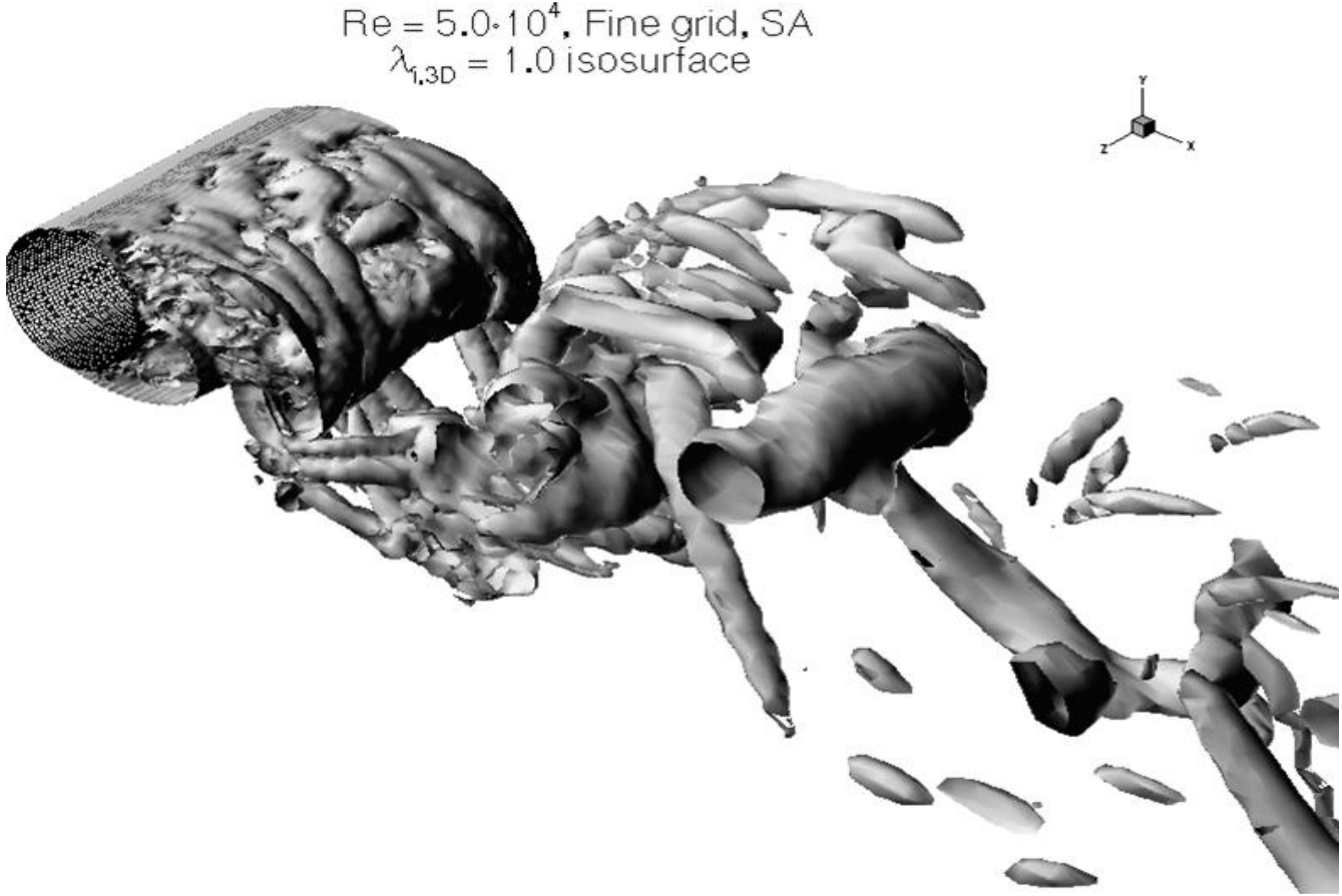
Domain



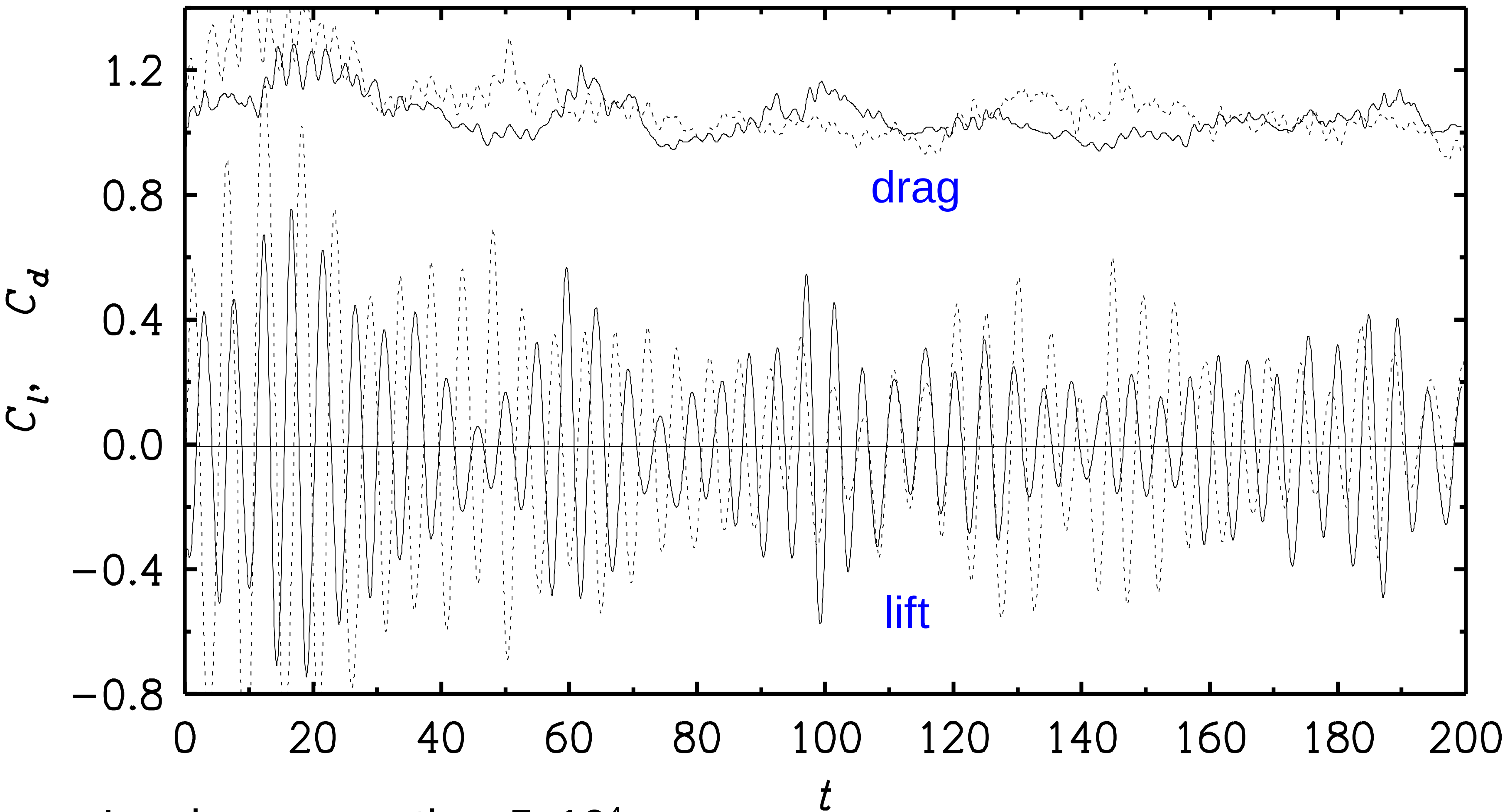
Multiblock grids (Inner block 150 x 36, wake block 74 x 36, outer block 59 x 30. The three blocks meet near x=1.06, y=1.03

- Grid refinement by a factor of √2 in each direction
- Spanwise extent = 2D

Laminar separation – vorticity isosurfaces



Laminar separation – time dependent forces

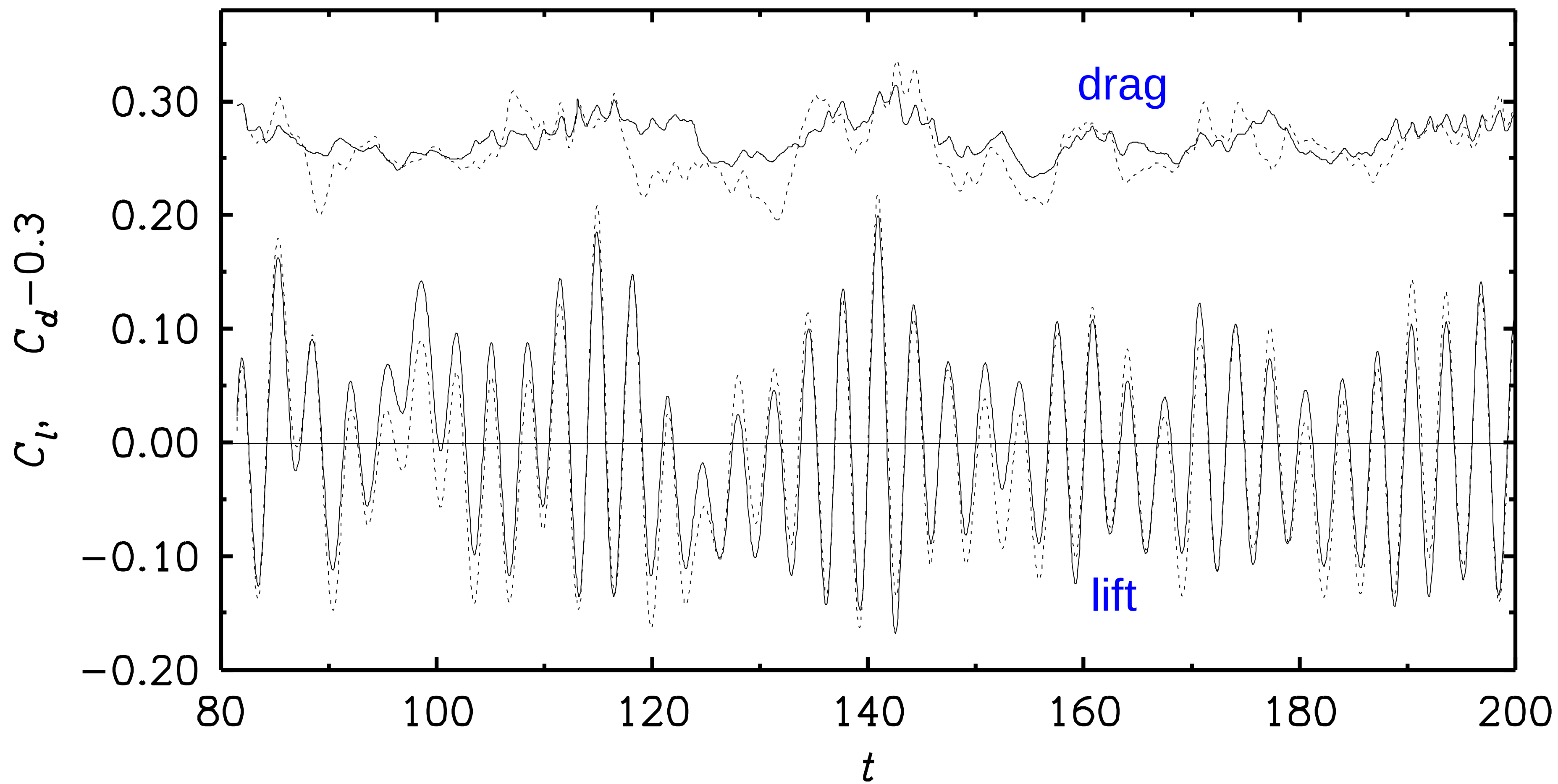


—— Laminar separation, 5×10^4

---- Laminar separation, 1.4×10^5

Very long simulation times!

Turbulent separation – time dependent forces



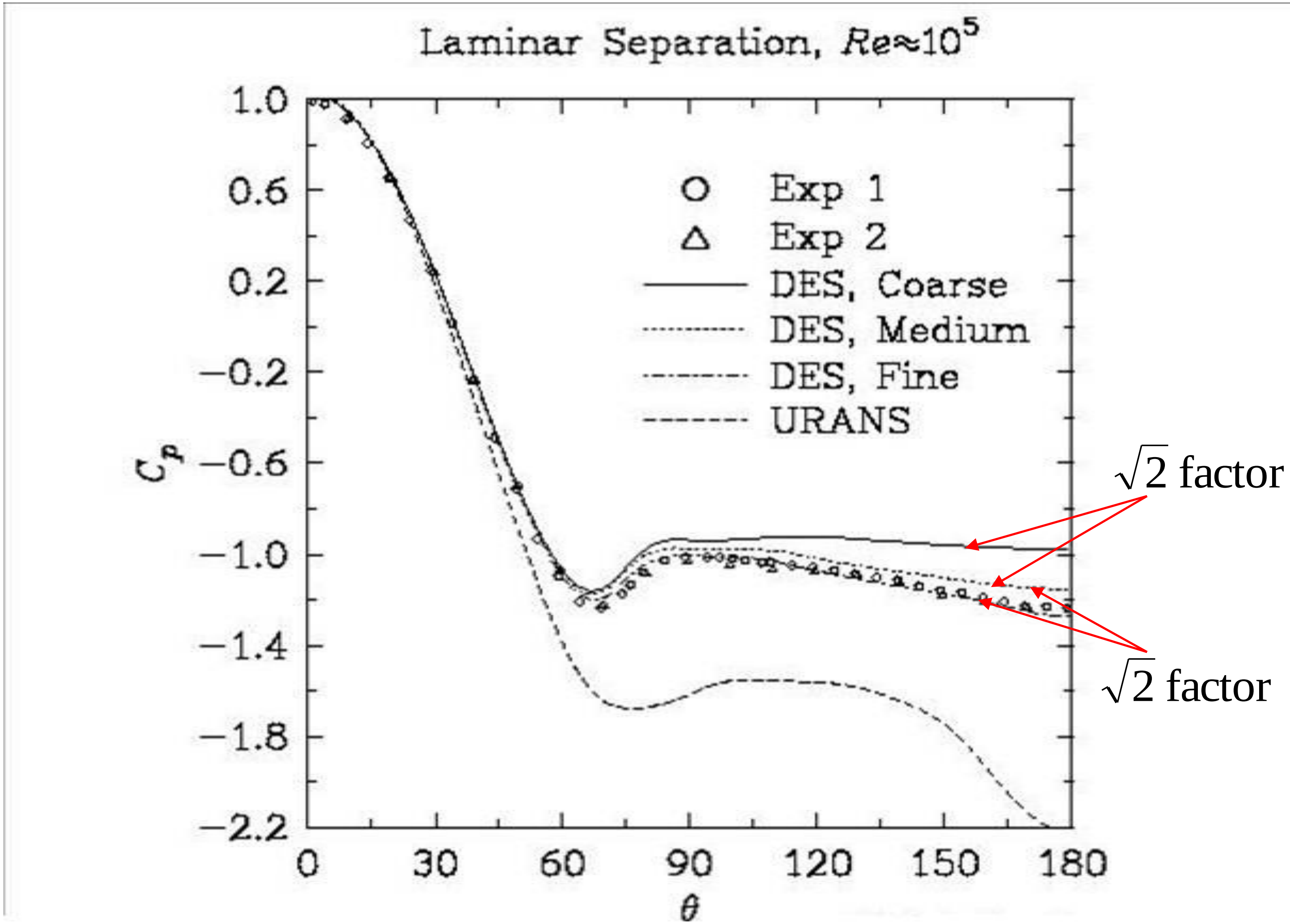
----- spanwise averaged

- - - unaveraged

Turbulent separation, Re=1.4 x 10^5,

118 x 105 x 30 grid

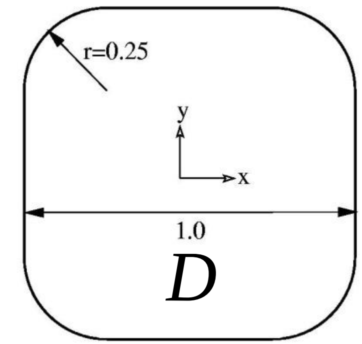
Laminar separation – pressure coefficient



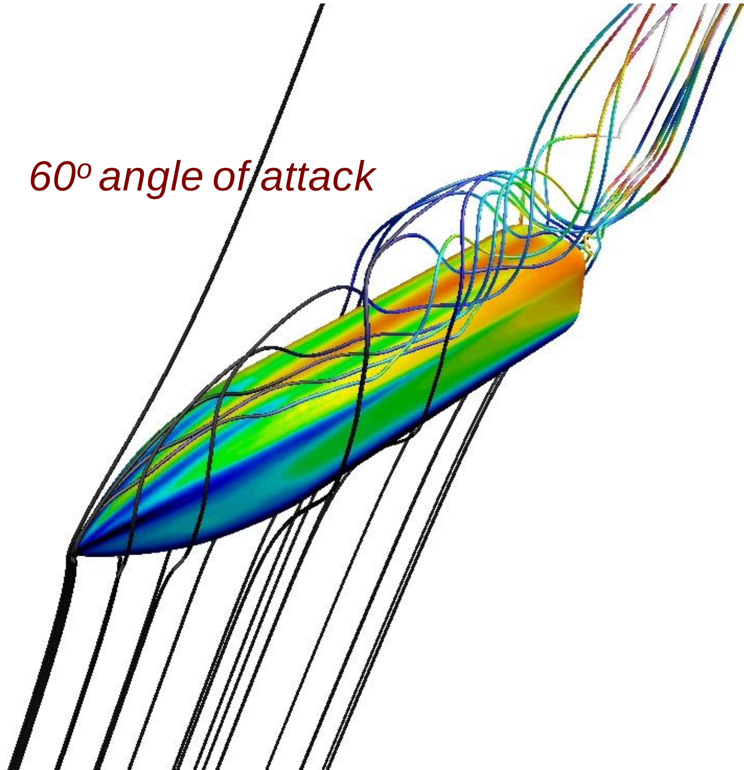
Aircraft forebody

- Rectangular ogive forebody
  - Aft section length = 4D
    - » Cross-section: square with rounded corners, corner radius = D/4
  - Forebody length = 2D
  - Angle of attack: 60^{o} and 90^{o}

forebody cross section



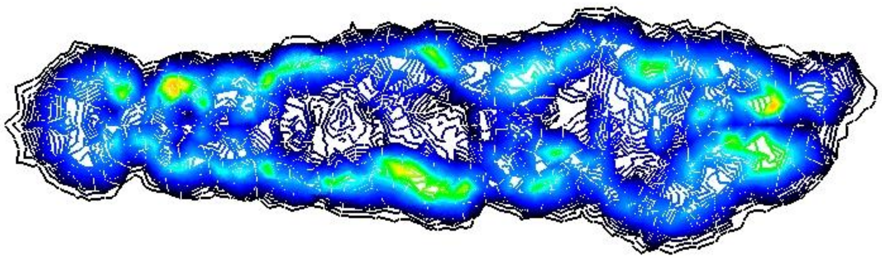
- Simulation details (Viswanathan, Squires and Forsythe 2006)
  - Grid sizes from 2.1 x 10^{6} cells to 8.75 x 10^{6} cells
    - » Unstructured (generated using VGRIDns, Pirzadeh 1996)
  - *Re* = 2.21 x 10^{6}, Mach number = 0.21



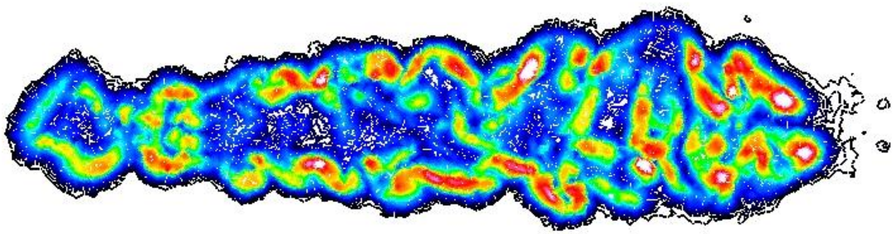
60^{o} angle of attack

Role of grid refinement and turbulence model

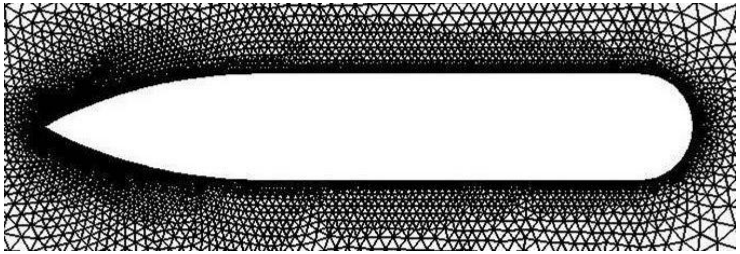
vorticity contours in the wake, y/D = 1.0, 90± angle of attack

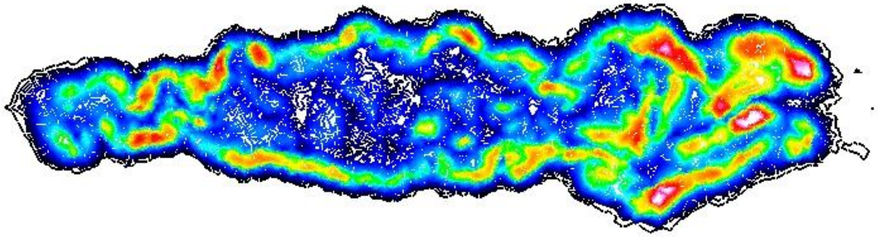


DES – coarse grid (2.1x10^6 cells)

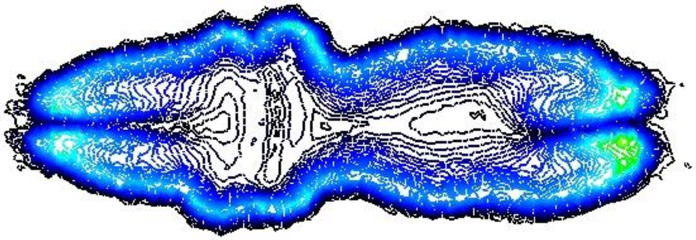


DES – fine grid (8.8x10^6 cells)



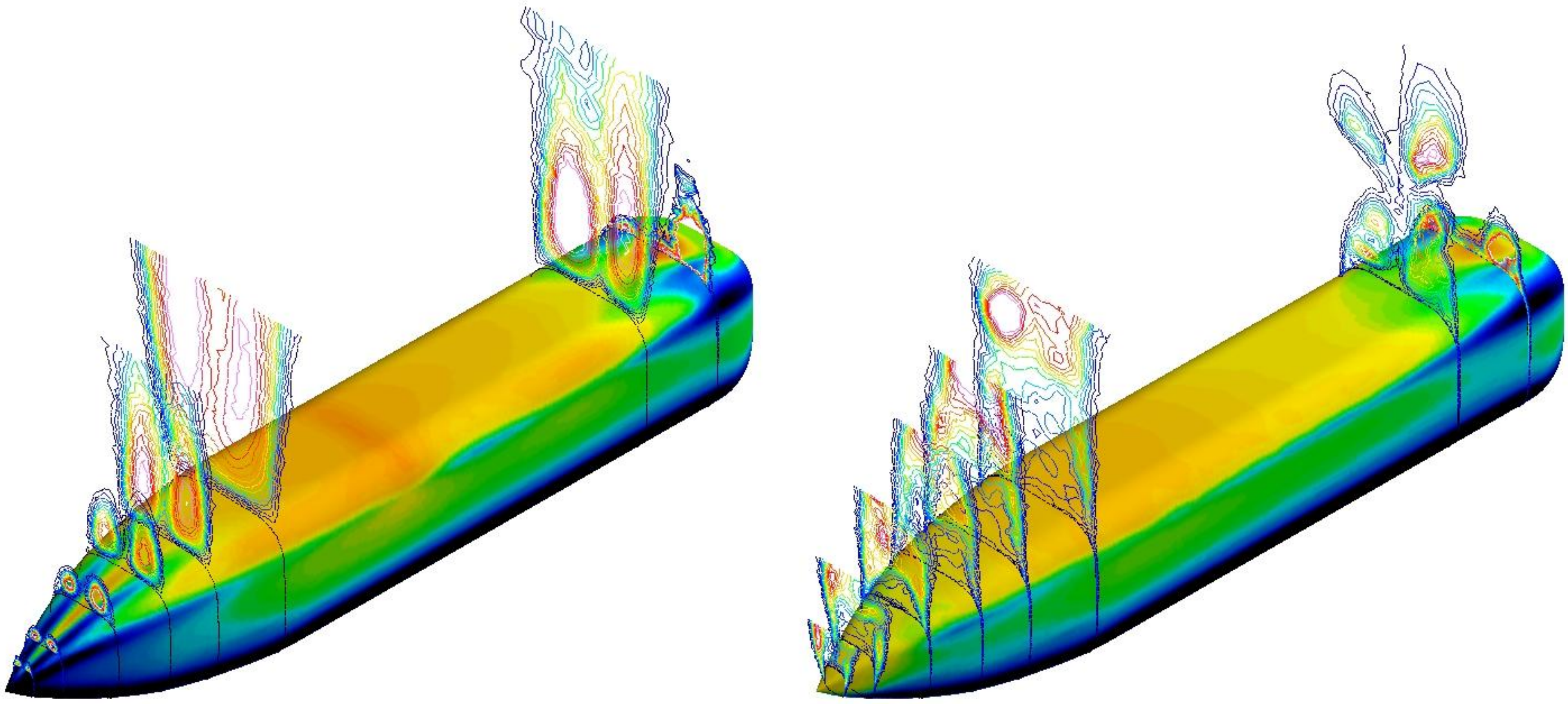


DES – baseline grid (6.5x10^6 cells)



RANS – baseline grid (6.5x10^6 cells)

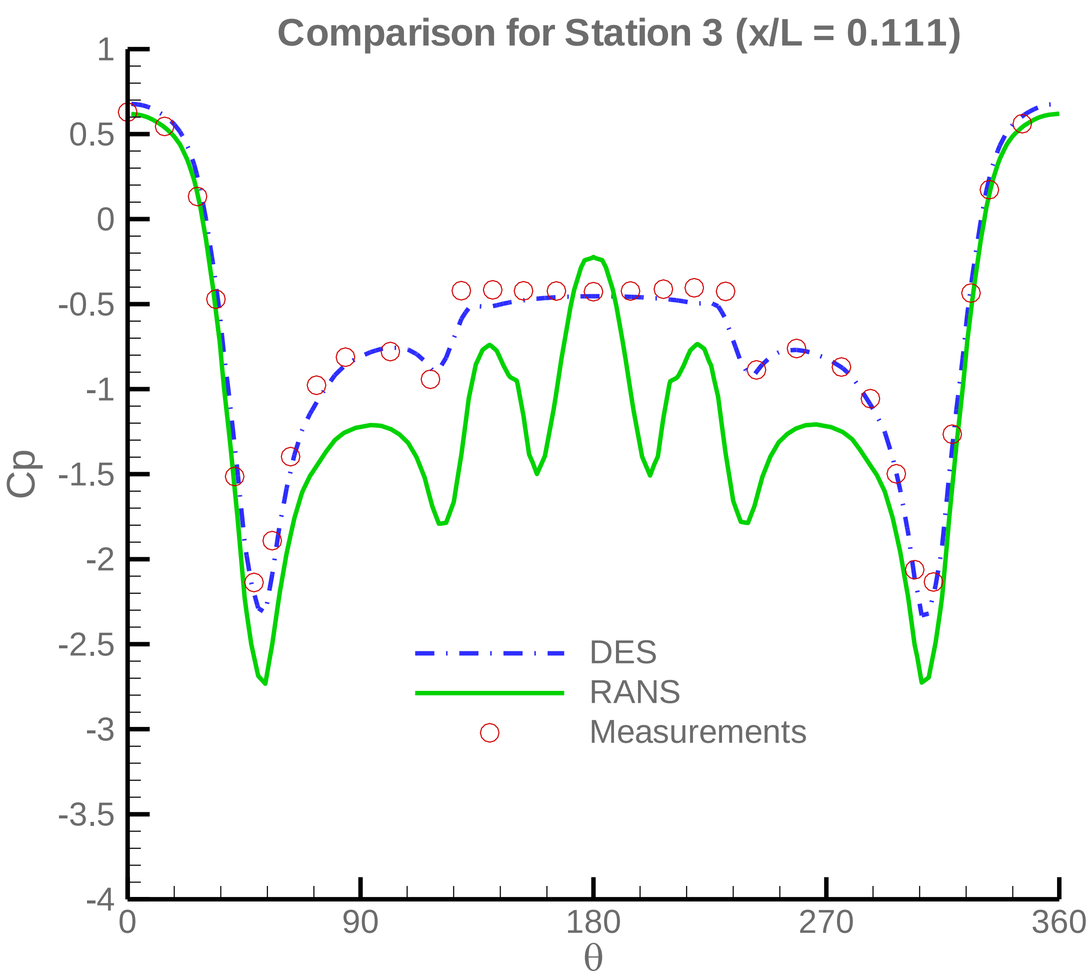
Planar cuts of eddy viscosity, $\alpha = 90^o$

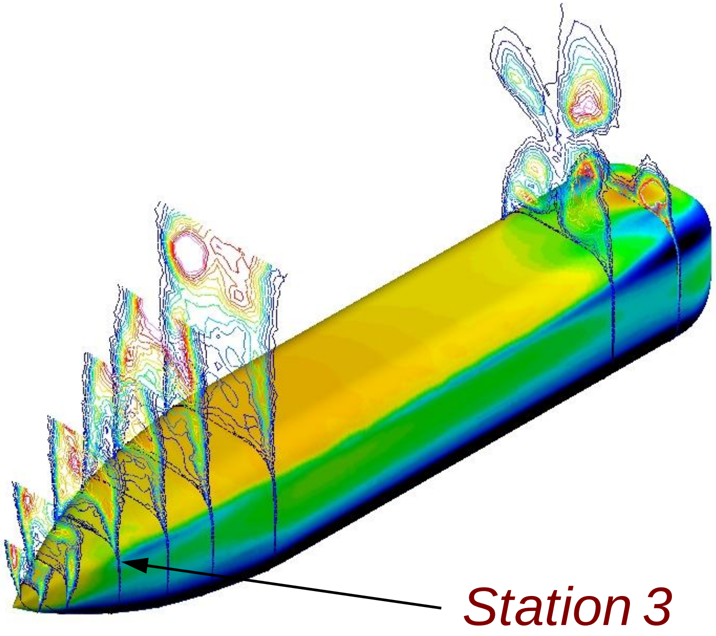


S-A RANS *DES*

surface colored by pressure

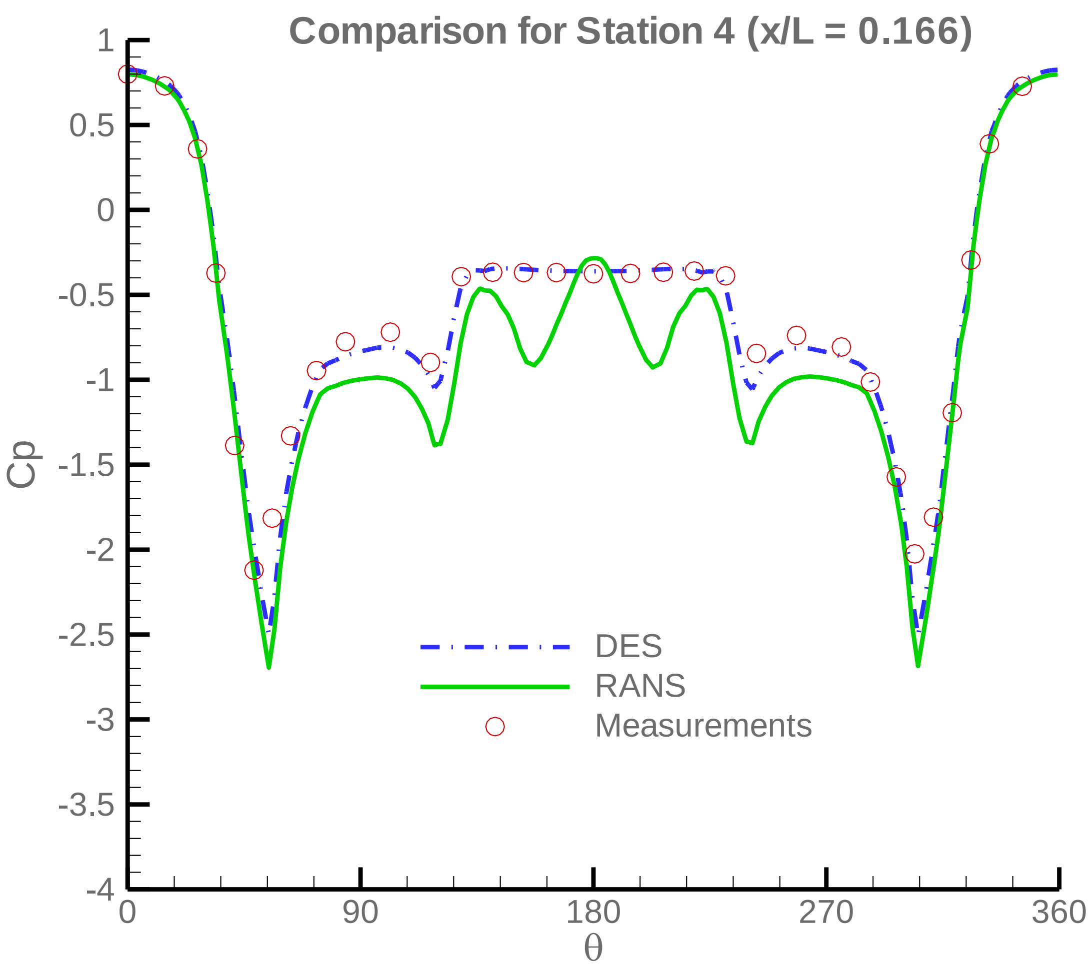
Azimuthal Pressure Distribution

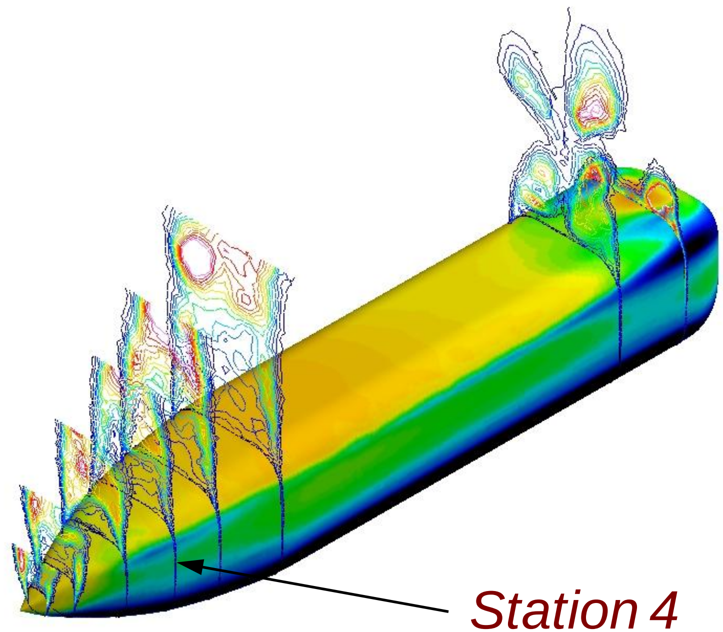




Viswanathan, Squires and Forsythe (2006)

Azimuthal Pressure Distribution





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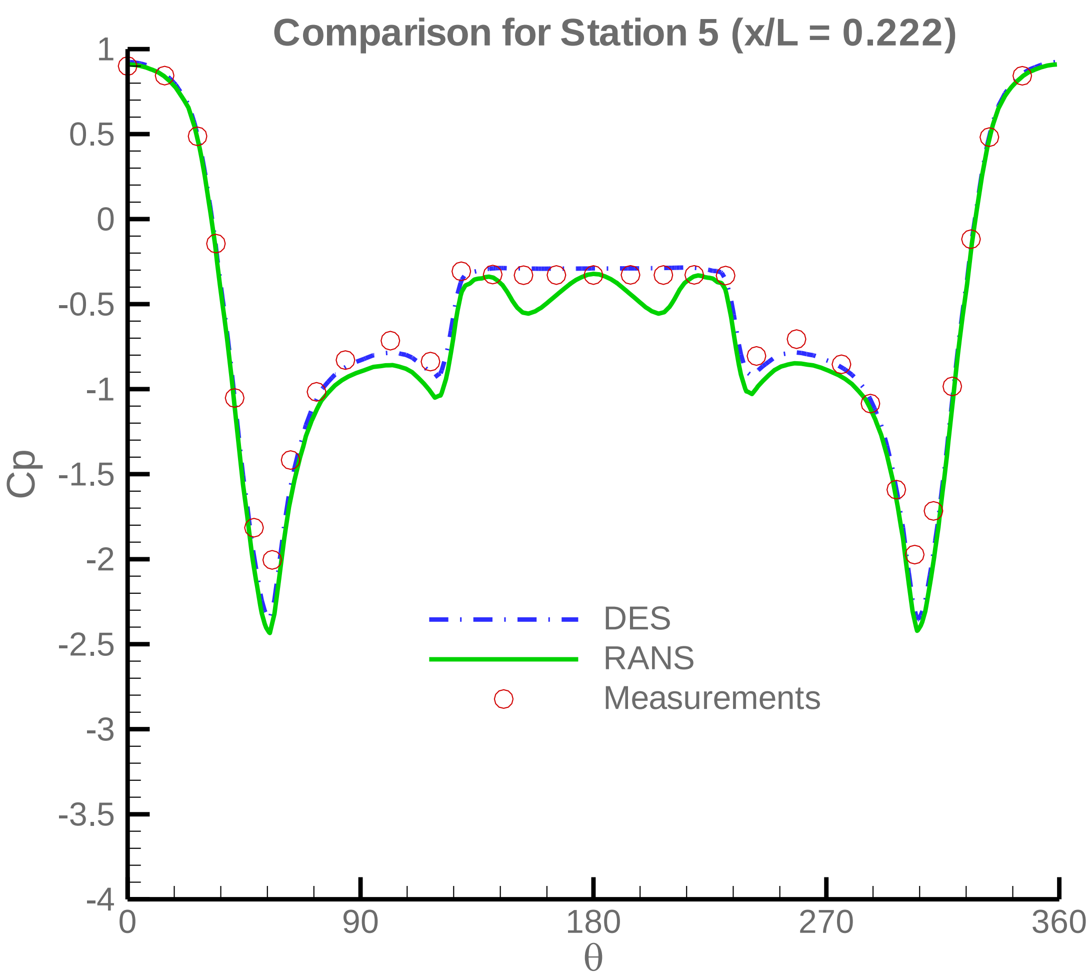

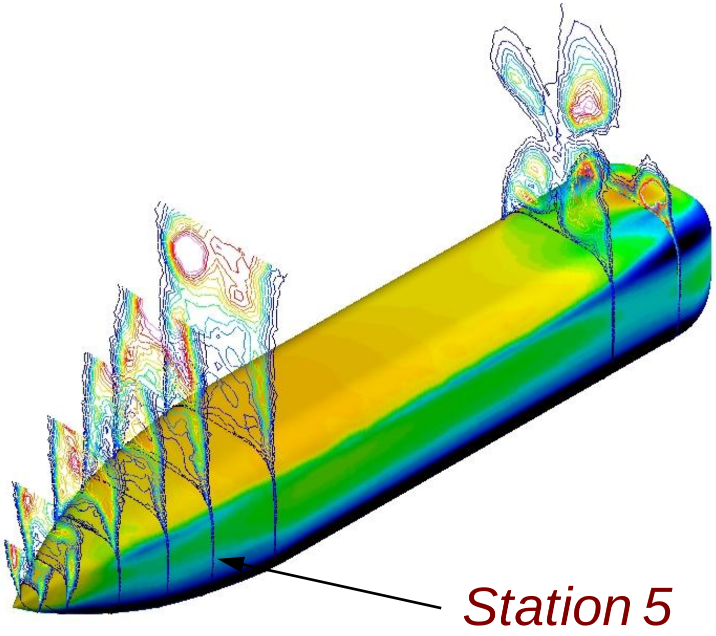

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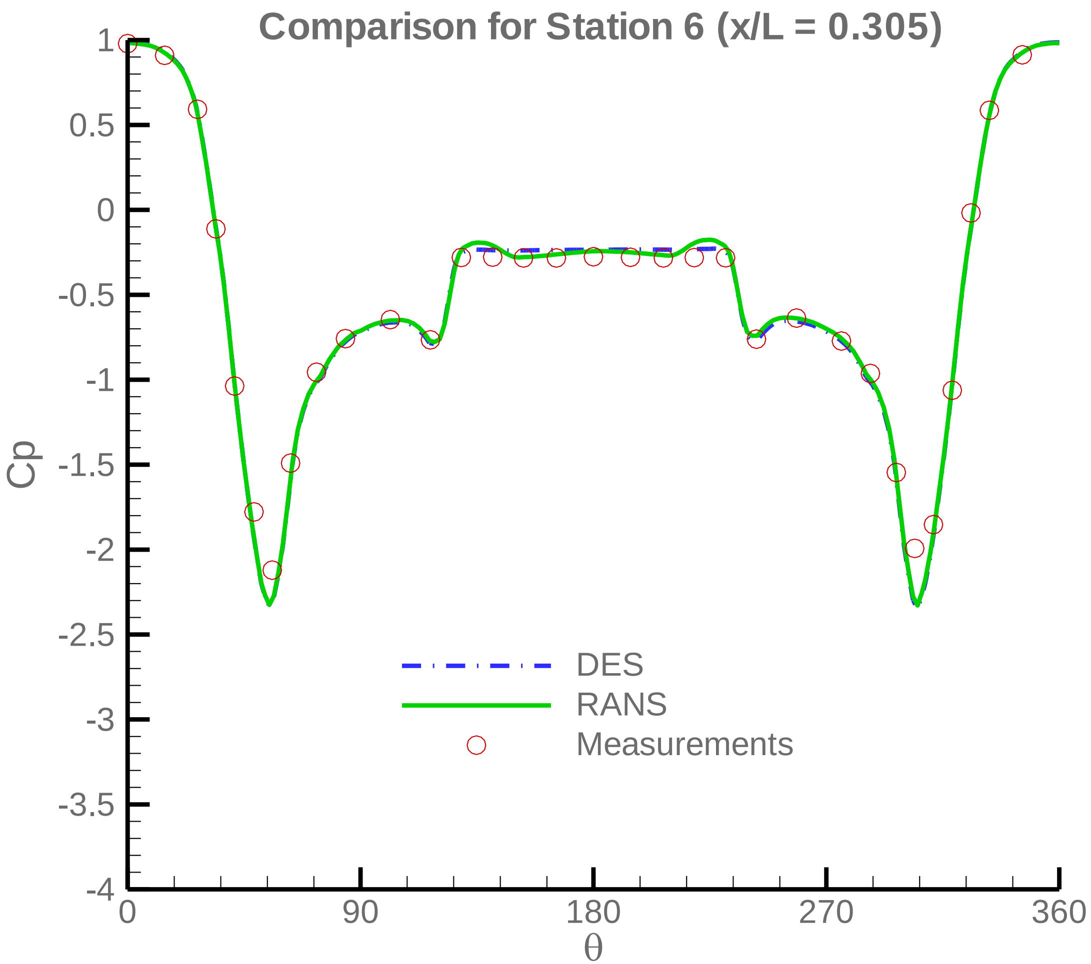
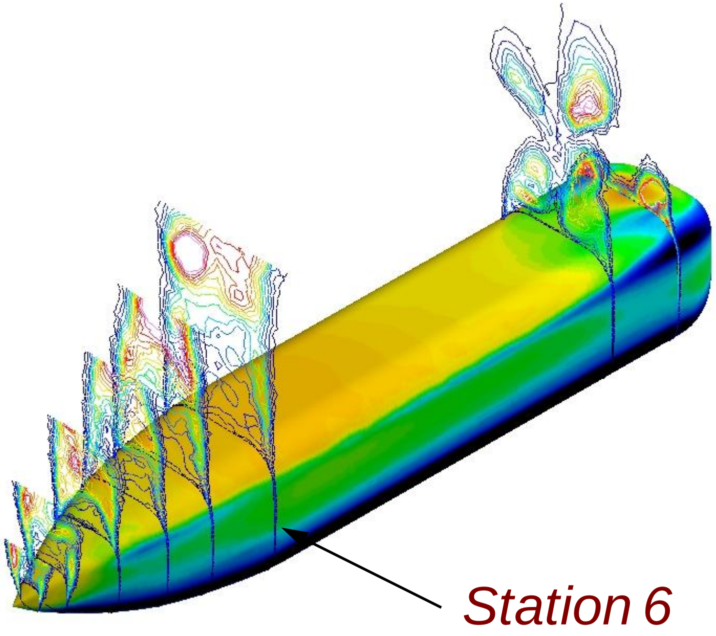
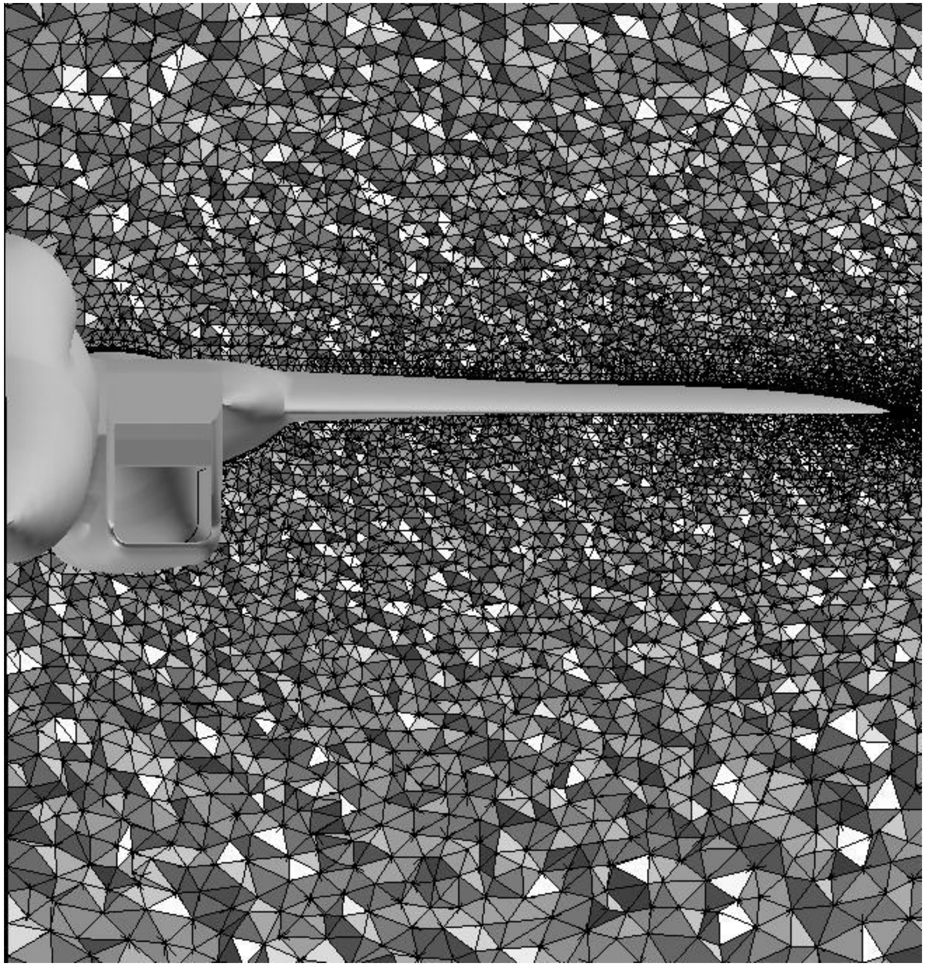


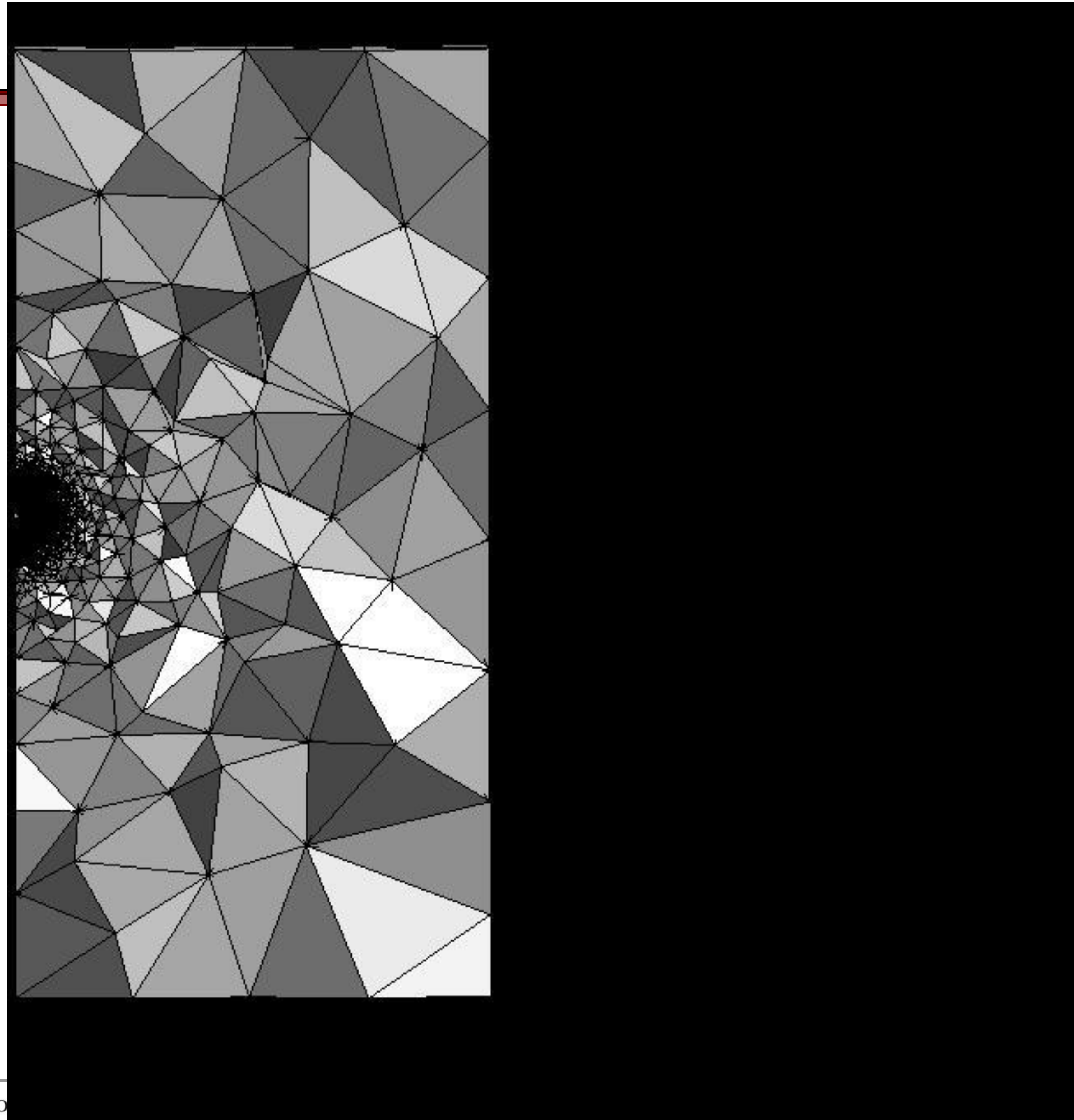


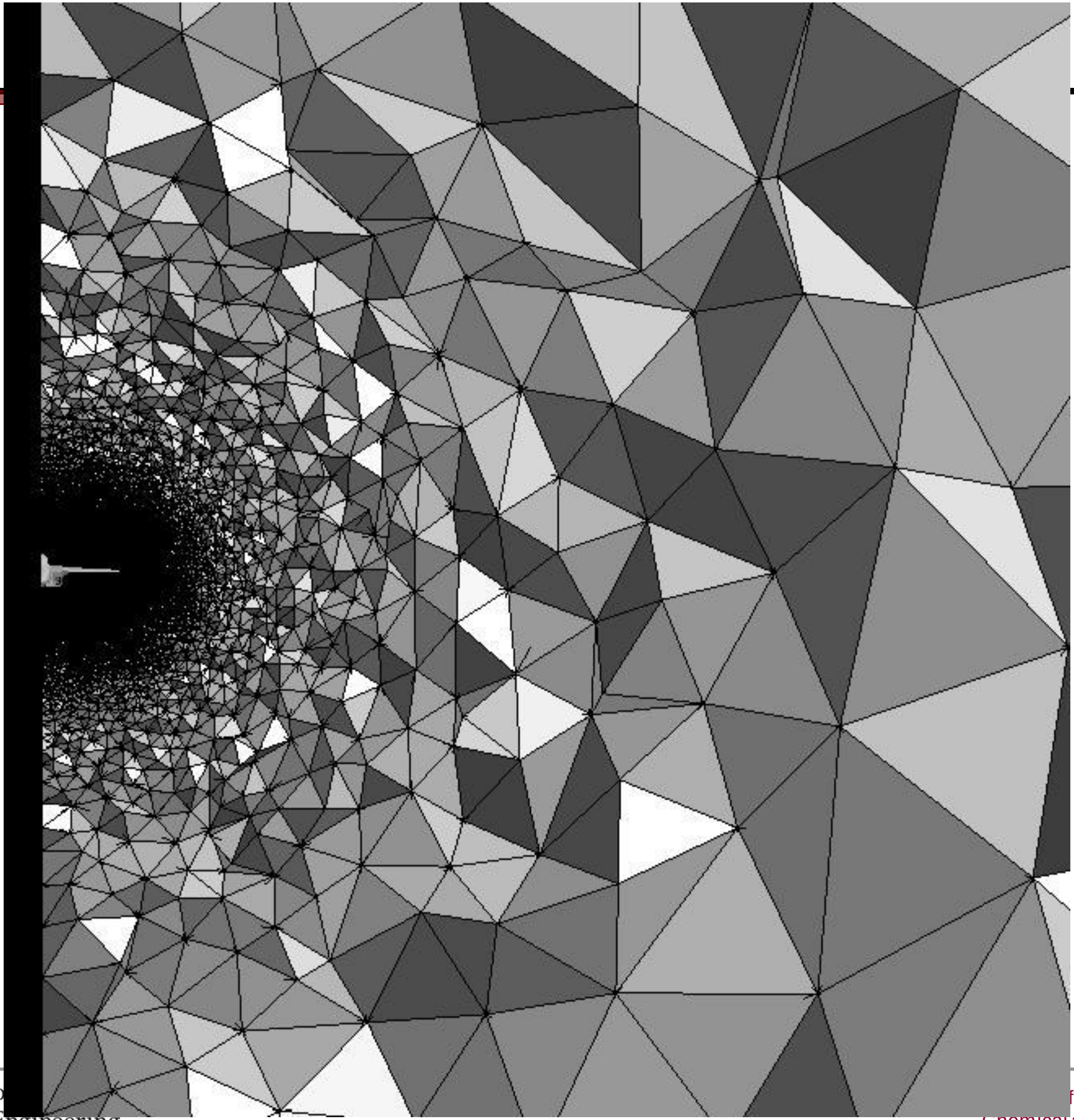
Viswanathan, Squires and Forsythe (2006)

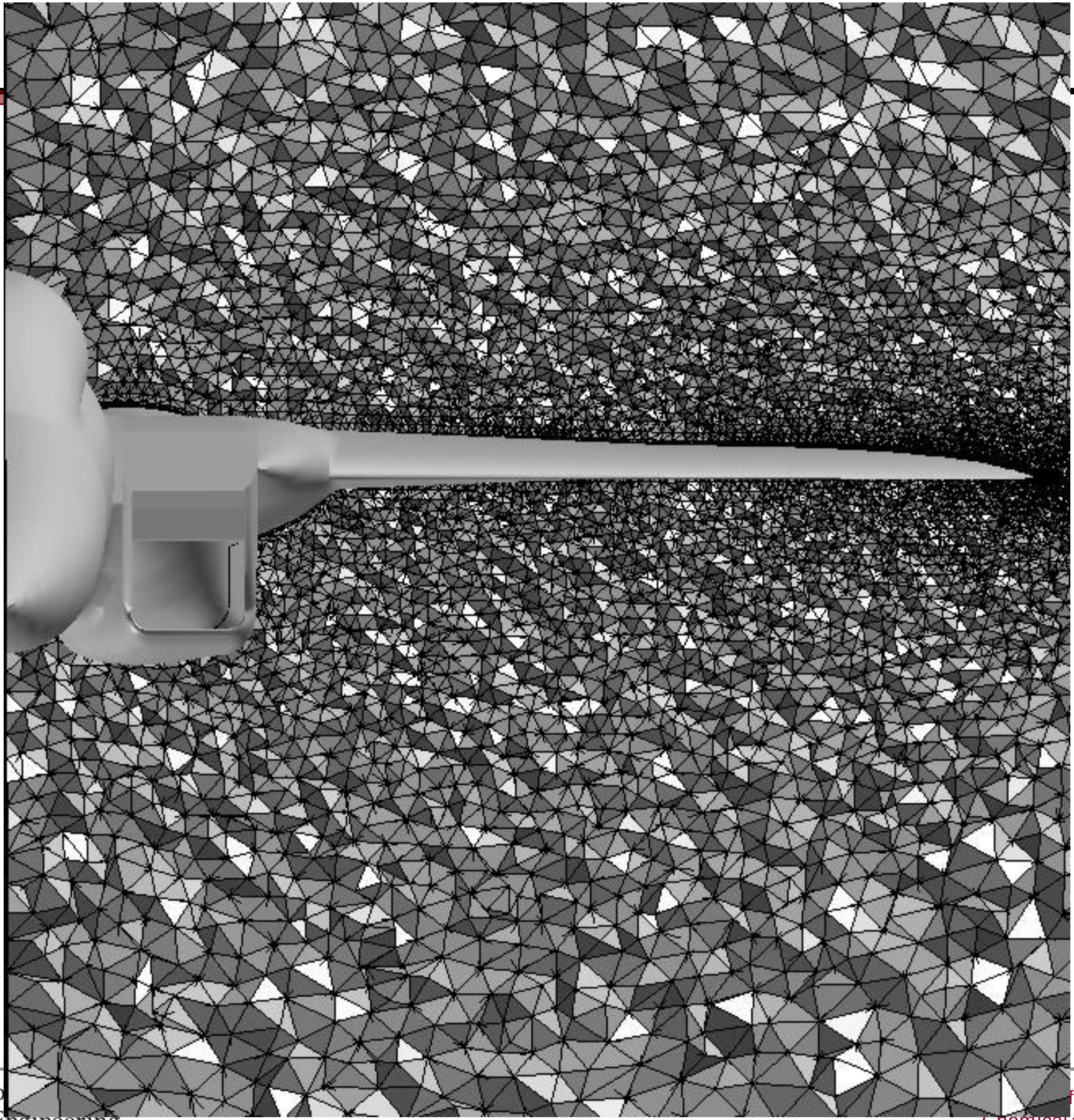
F-15E at 65 Degrees Angle of Attack

- Re = 13.6 x 10^6, M = 0.3
- Stability and control database provided by Boeing Military Aircraft for assessing DES predictions
  - Data at 65^o and 74^o AOA
- Simulation details (Forsythe et al. 2003)
  - Unstructured grids
    - » 4 x 10^6, 6 x 10^6, 10 x 10^6 cells
    - » Resolved wall layer
  - Timestep variation of 0.01, 0.02, and 0.04 (dimensionless using chord and freestream speed)

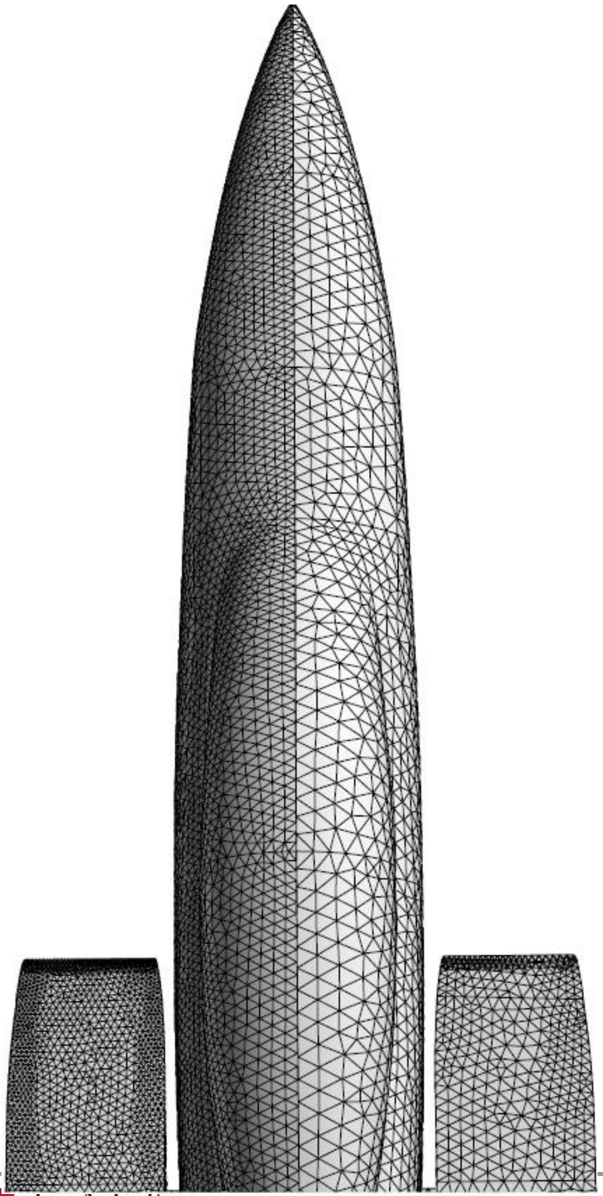




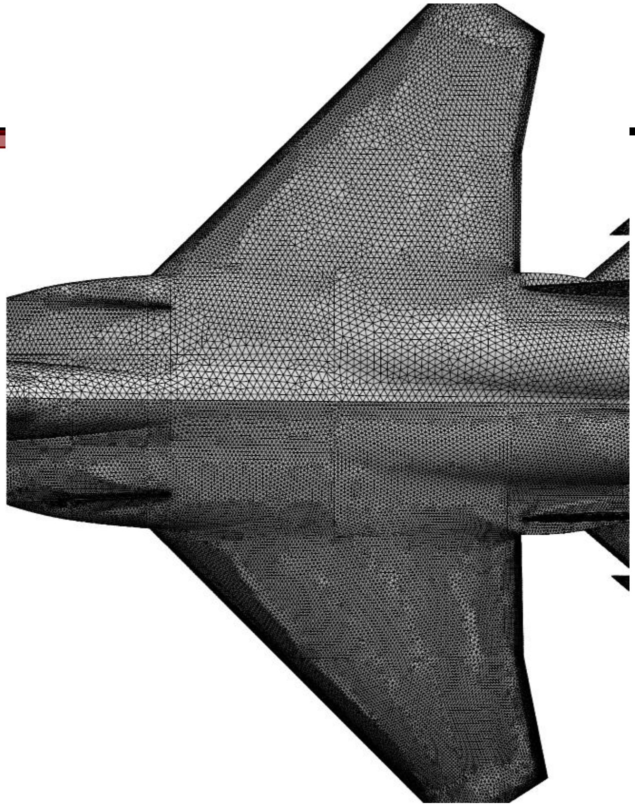




Surface grids



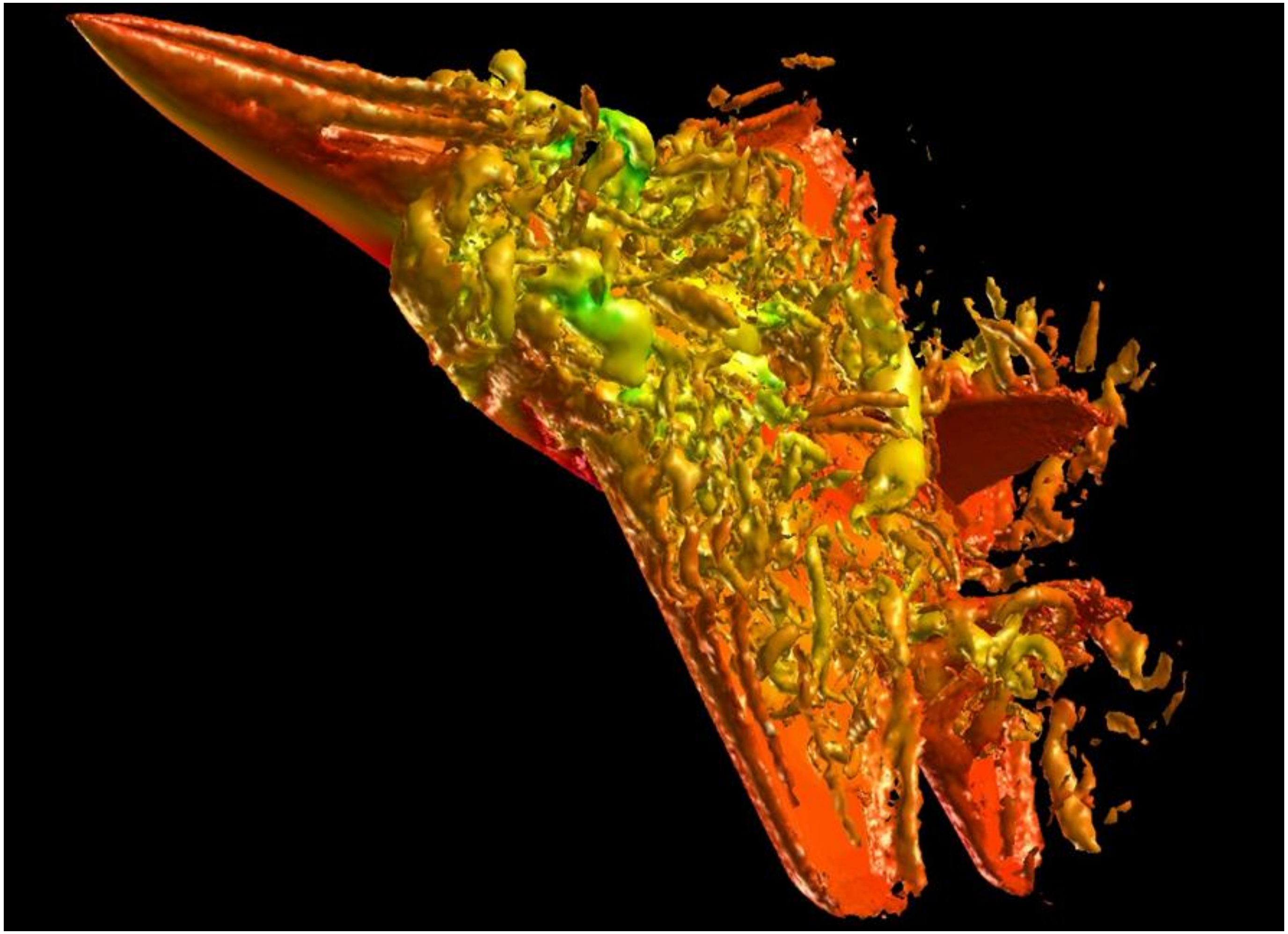
Forebody



Wing

Tail

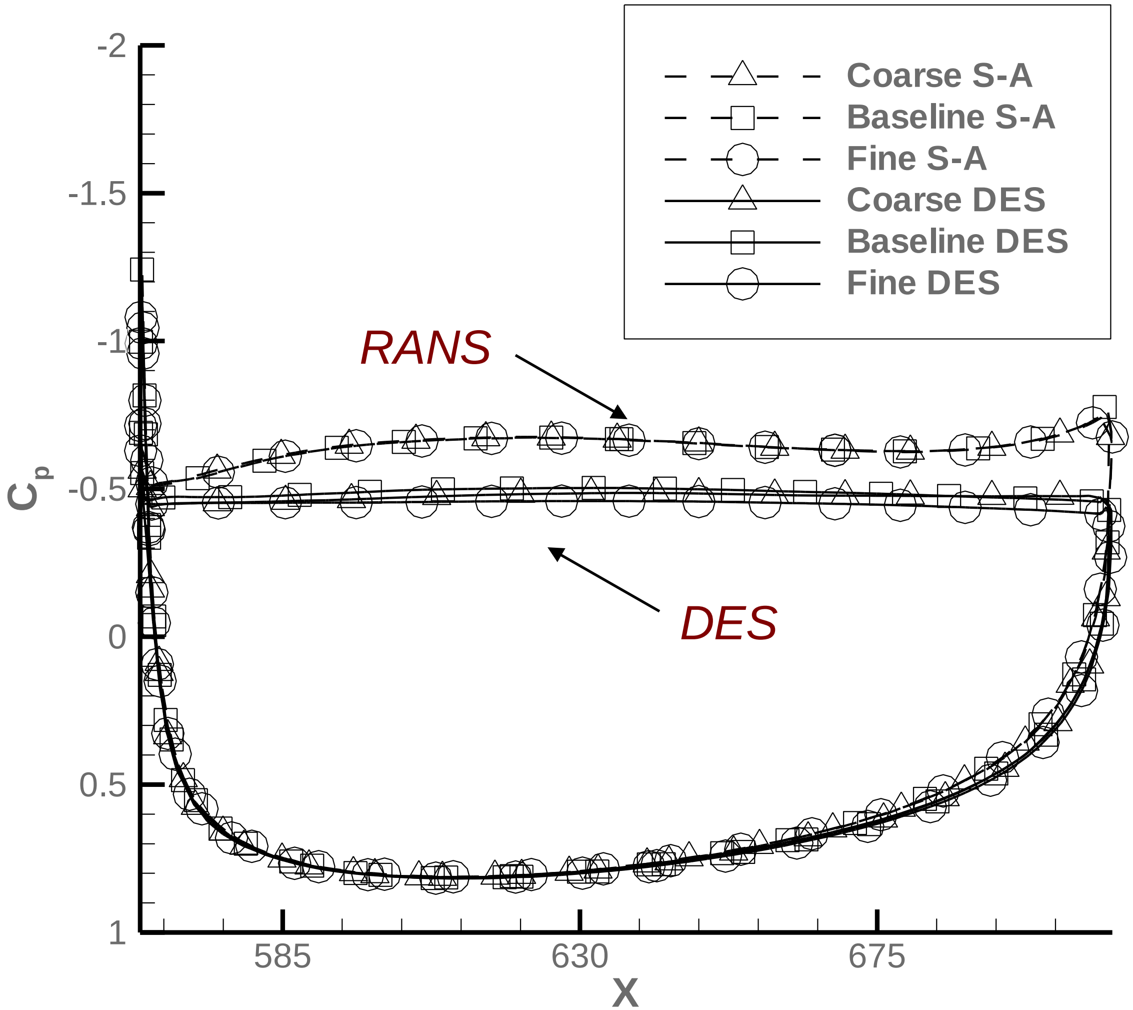
Instantaneous vorticity field



F-15E at 65^o angle of attack

Forsythe, Squires, Wurtzler and Spalart (2004)

Influence of mesh and model on wing pressure coefficient

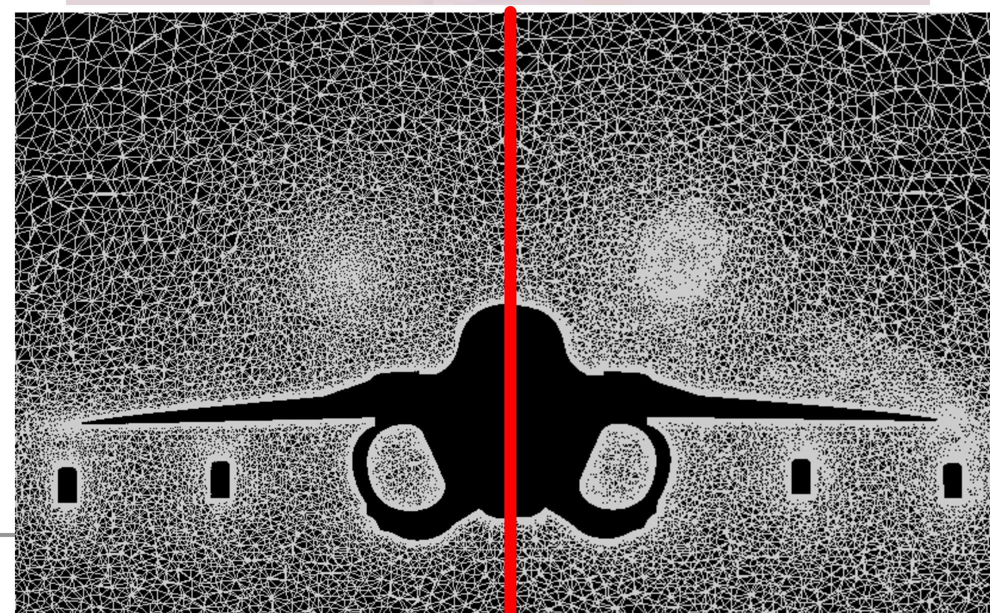


F-15E at 65° angle of attack

Forsythe, Squires, Wurtzler and Spalart (2004)

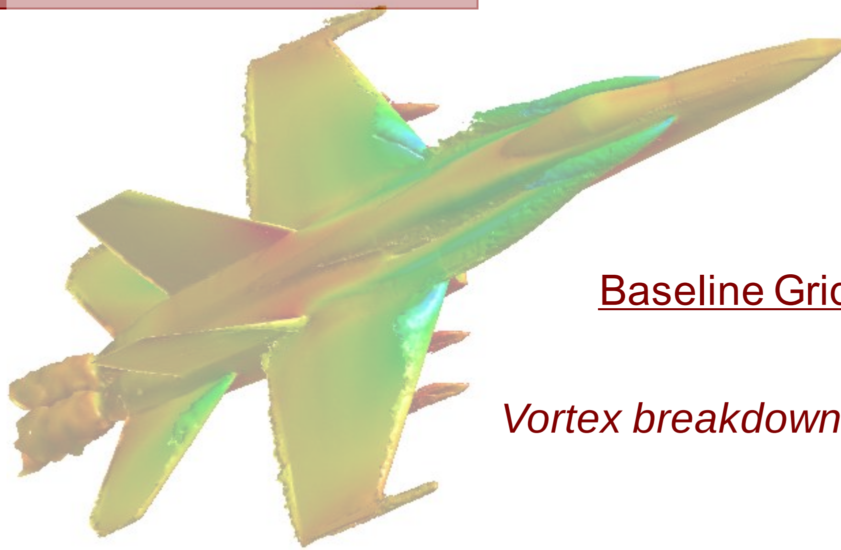
Applications – F-18C at 30 Degrees Angle of Attack

- Re = 13.9 x 10^6, M = 0.28
  - Leading Edge Extension used to increase lift, twin tails canted for increased maneuverability
    - » Tail buffet at large incidence due to vortex breakdown
- Simulation details
  - Baseline mesh of 5.9 x 10^6 cells
  - Adaptive Mesh Refinement (Pirzadeh 2000)
    - » Solution-based adaption to 6.2 x 10^6 cells
  - Comparison of DES to S-A RANS/URANS



Morton, Steenman, Cummings and Forsythe (2003)

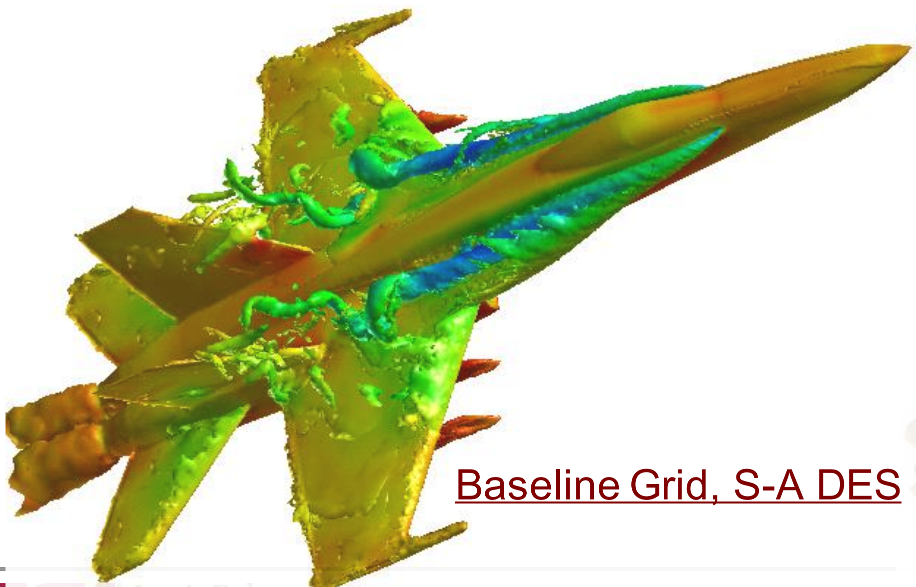
Vorticity Isosurface



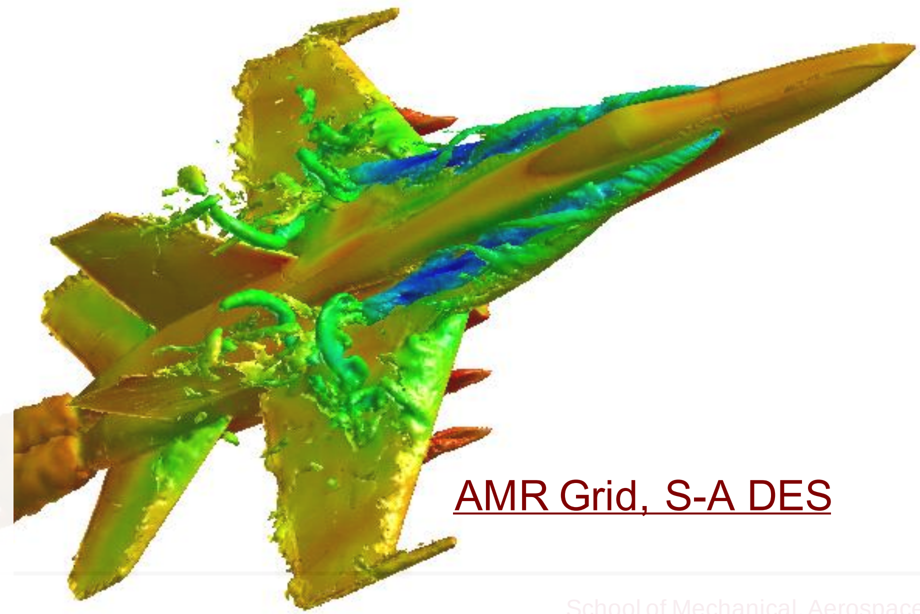
Baseline Grid – S-A RANS

Vortex breakdown not predicted by RANS

Morton, Steenman, Cummings and Forsythe (2004)

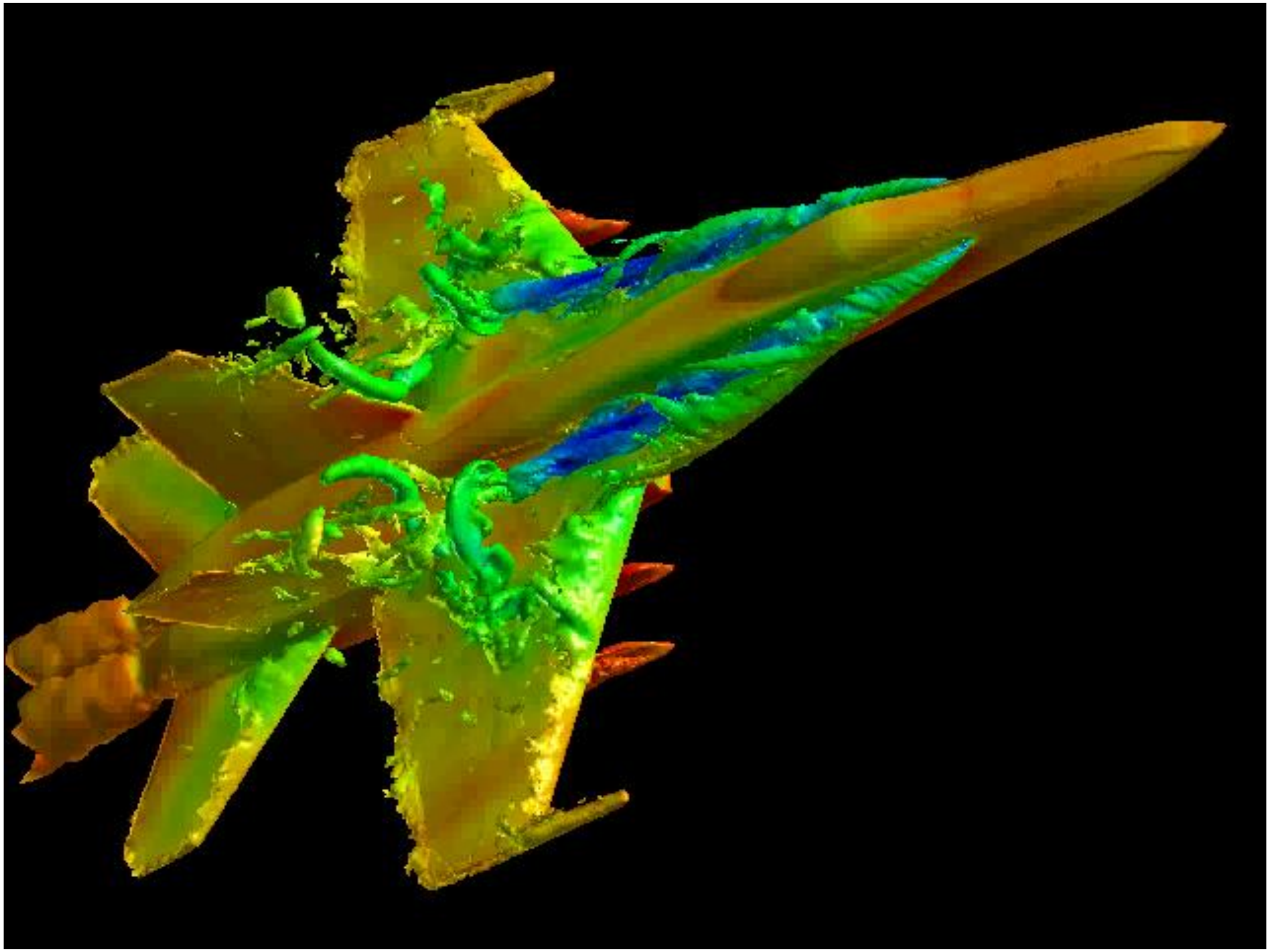


Baseline Grid, S-A DES



AMR Grid, S-A DES

Instantaneous Vorticity Field



F-18C at 30^o angle of attack

Morton, Steenman, Cummings and Forsythe (2004)

Streamwise LEX vortex breakdown position

Flight test and tunnel test measurements from NASA TM-101734

Configuration differences compared to <u>NASA F-18 HARV:</u>

- Flaps set to 0±, 0±, 0±
- Diverter slot included

DES prediction without diverter slot

Presence of diverter slot influences breakdown location

Morton, Steenman, Cummings and Forsythe (2004)

	$Re_{\bar{c}}$	Model scale, percent	Fluid medium	Ref.
● Flight	8 to 13 x 10^6		Air	18
❑ DTRC	1.75 x 10^6	6	Air	4,18
() BART	1.60 x 106	3	Air	18
Δ LSWT	3.60 x 10^5	12	Air	18
◸ FVF	1.26 x 10^4	3	Water	18

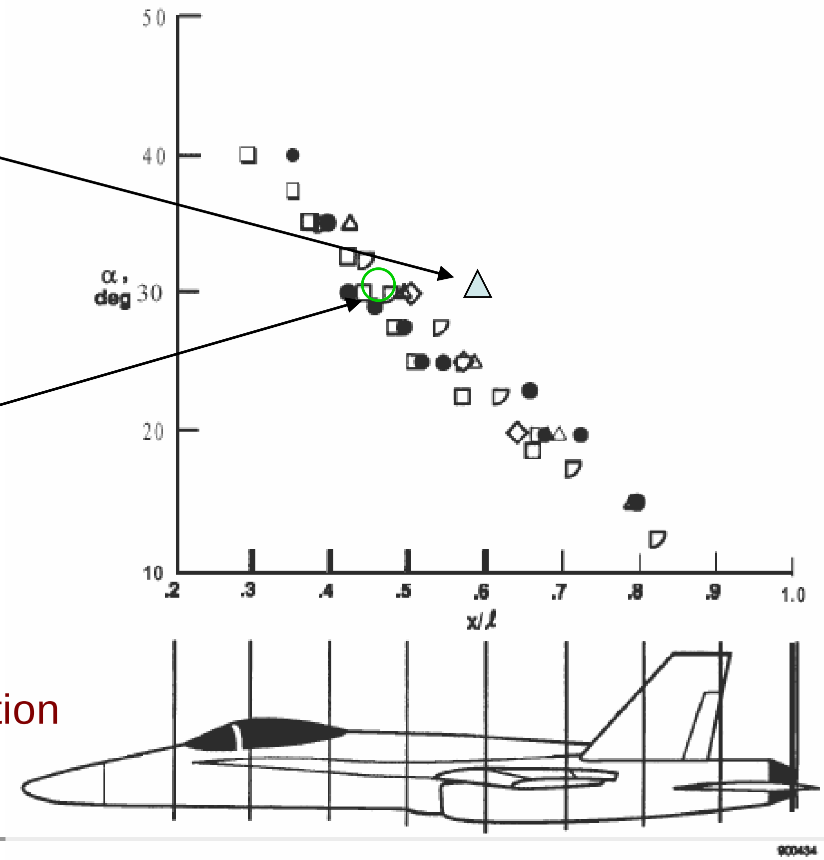


Figure from NASA TM-101734

Outline

- Subgrid-scale models
  - Length scales in LES subgrid models vs. length scales in RANS models
    - » Reminder of a key difference between the techniques
- Challenges for whole-domain LES in aerodynamics applications
  - Resolving the boundary layer at high Reynolds numbers
- Formulation of hybrid RANS-LES models
  - Detached Eddy Simulation
- Applications
  - Massively separated flows - from simple geometries to complex geometries
- Improvements and newer developments

Original formulation of DES ("DES97")

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\tilde{S}\tilde{\nu} + \text{diffusion} - c_{w1}f_w\left[\frac{\tilde{\nu}}{\tilde{d}}\right]^2$$

production *destruction*

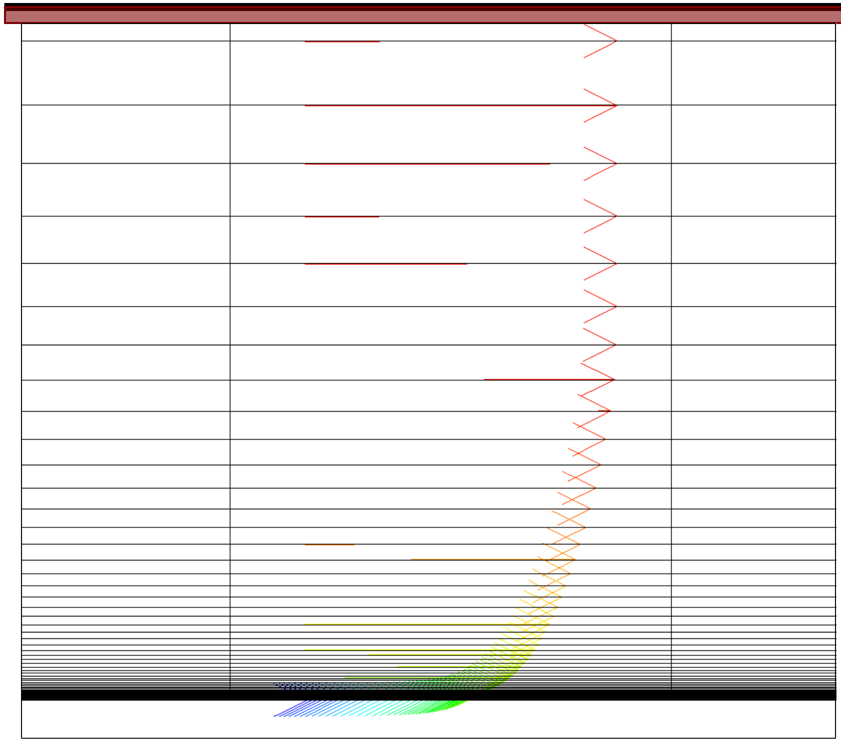
$$\tilde{d} = \min(d_w, C_{DES}\Delta)$$

- Turbulent stress in the RANS region is completely modeled
- Modeled Reynolds stress decreases in the LES region
  - Resolved Reynolds stress (due to resolved velocity fluctuations) is intended to dominate the total stress in the LES Region
- Location where $d_w = C_{DES}\Delta$ dictates the location of the interface

Background…

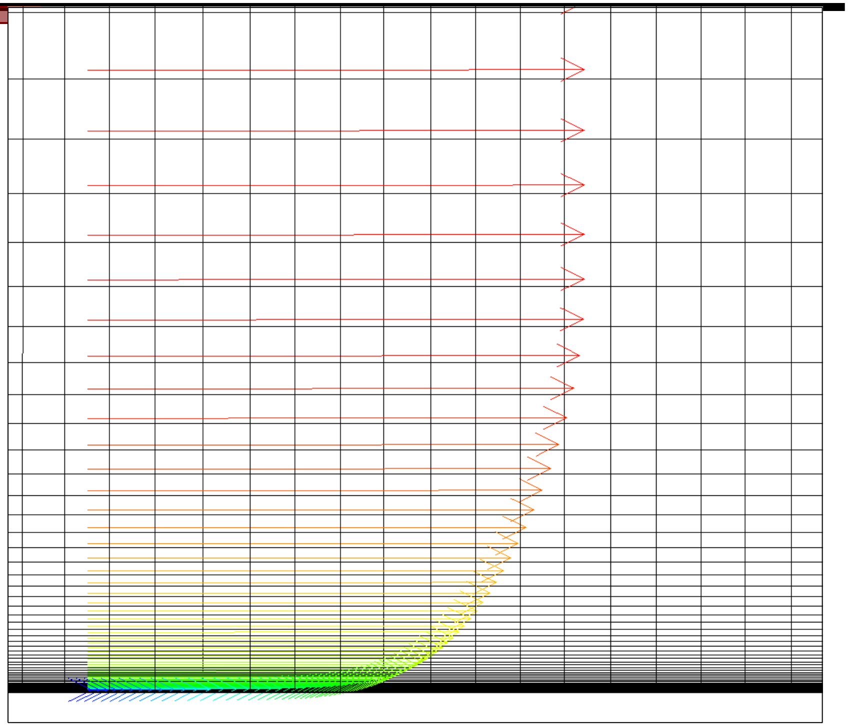
- Reduction of model length scale lowers the eddy viscosity
  - Lowers modeled Reynolds stress
  - Requires an increase in resolved Reynolds stress
    - » Generation of three-dimensional structure ("eddy content") in a separating shear layer
      - › Straightforward in massive separations
      - › What about other flow regimes?
- Issues…
  - Grid spacing fine enough to reduce model length scale and identify "LES region" within the domain
    - » Resolved Reynolds stresses derived from 3D structure have not yet replaced modeled stress
      - › Results from insufficient grid resolution and/or
      - › Delay in generation of resolved stress by instabilities in the flow
    - » Initiated in boundary layers

Types of grids…



Type I grid - Typical of RANS and DES with a thin boundary layer

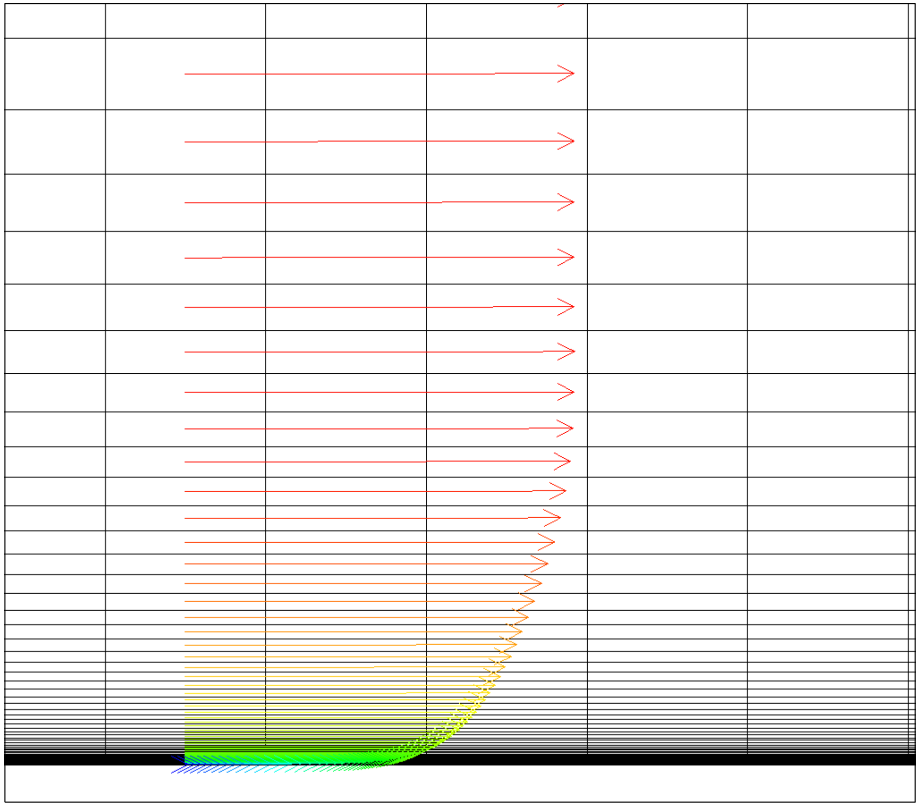
Wall-parallel grid spacings are comparable to the boundary layer thickness



Type III grid – capable of wall-modeled LES

Wall-parallel grid spacings are a fraction of the boundary layer thickness

Types of grids…

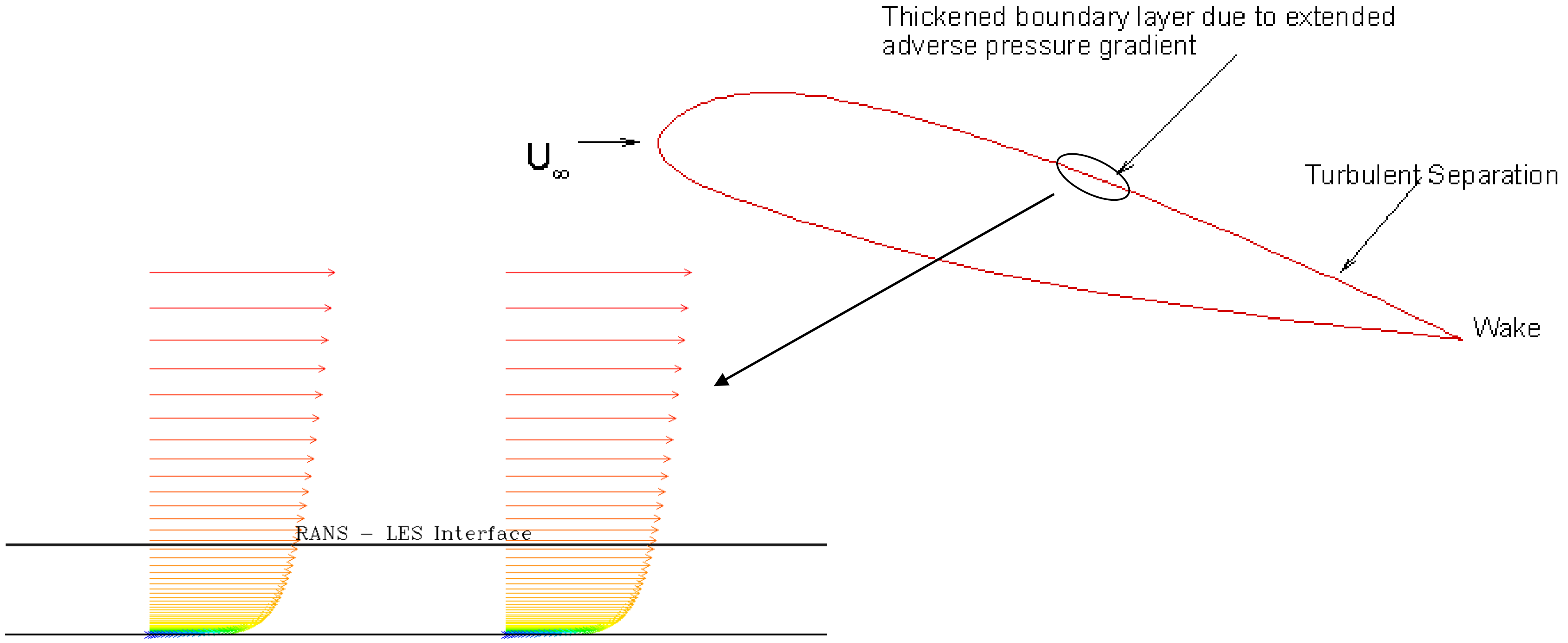


Type II grid – Ambiguous

Wall-parallel grid spacings are fine enough to locate the RANS-LES interface within the boundary layer though insufficient to resolve turbulent fluctuations

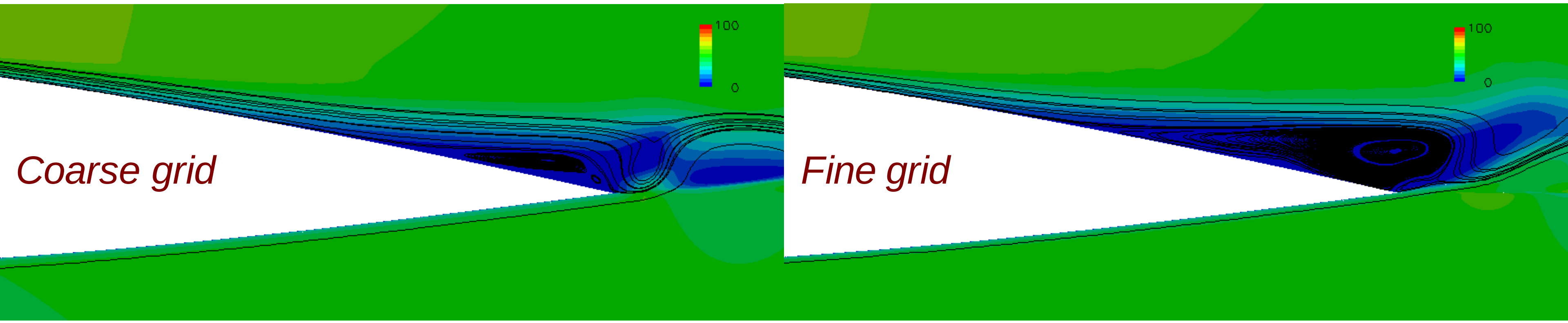
Role of the mesh

- Grid spacing fine enough to activate the “LES region” in the boundary layer
  - RANS eddy viscosity will be reduced, lower modeled stress
  - Resolved Reynolds stresses derived from 3D structure may not have yet replaced modeled stress
    - » Results from insufficient grid resolution and/or thickened boundary layer



Need to address "ambiguous grids"

DES97 prediction of streamlines over an Aerospatiale-A airfoil at 13.3 degrees angle of attack, Re = 2 x 10^6



- Example of an "*ambiguous grid*"
  - Can result in separation induced by the grid
- For applications in attached boundary layers
  - Preferable to over-ride length scale switch and maintain RANS behavior regardless the boundary layer grid density

Objective is formulation of DES that is resistant to ambiguous grids

Modification of the DES length scale

- Incorporation of information from the solution field into the length scale $\tilde{d}$
  - Similar idea to F_2 used by Menter and Kuntz (2004) in SST-DES

$$r_d = \frac{\nu_t + \nu}{S_d \kappa^2 d_w^2}$$

$\nu_t =$ eddy viscosity $\quad S_d =$ velocity gradients $\quad d_w =$ wall distance

- Use of r_d in a function that "shields" the boundary layer:

$$f_d = 1 - \tanh\left[(C r_d)^n\right]$$

  - "C" and "n" control thickness and sharpness of f_a
    - » Optimized values C = 8, n = 3

DES formulation resistant to ambiguous grids

Delayed Detached Eddy Simulation

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\tilde{S}\tilde{\nu} + \text{diffusion} - c_{w1} f_w \left[\frac{\tilde{\nu}}{\tilde{\tilde{d}}}\right]^2$$

$$\tilde{d} = d_w - f_d \max\{d_w - C_{DES}\Delta, 0\}$$

- Limits:

$$f_d = 0 \rightarrow \text{RANS} \qquad\qquad f_d = 1 \rightarrow \text{DES97}$$

- DDES obtained for most other RANS models by multiplying by f_d the term that constitutes the difference between RANS and DES

Spalart, Deck, Shur, Squires, Strelets, Travin (2006)

DDES response as wall-modeled LES

- Application to fully-developed channel flow
  - $Re_\tau = 5000$, domain $2\pi\delta$ x 2δ x $\pi\delta$
    - » Coarse grid…

$$\Delta_x = \Delta_z = 0.10\delta\,, \quad 65 \times 75 \times 33 \text{ points}$$

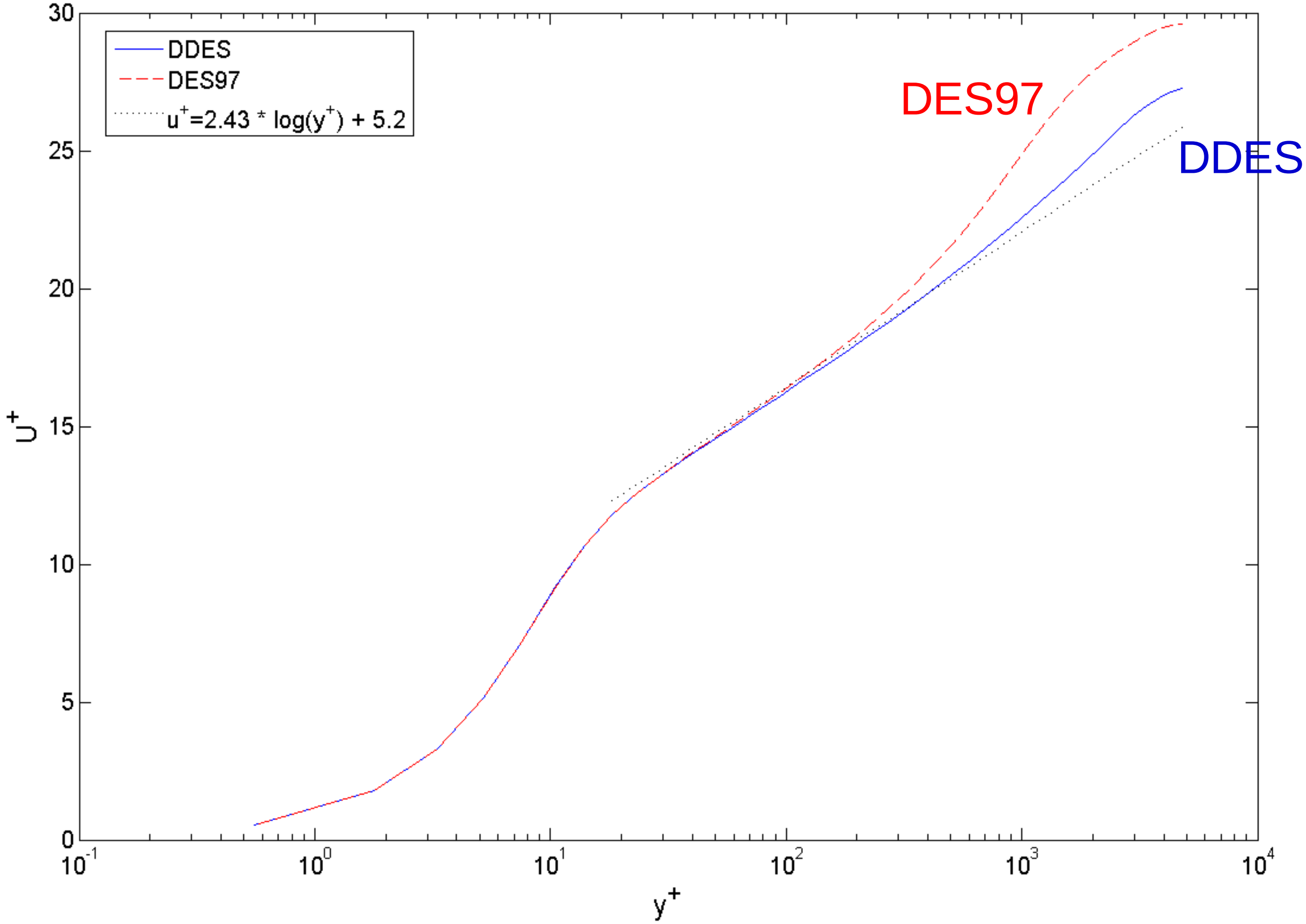
    - » Fine grid…

$$\Delta_x = \Delta_z = 0.05\delta\,, \quad 129 \times 129 \times 65 \text{ points}$$

  - Aims…
    - » Comparison to DES97
    - » Assess the response of the technique to the grid

Mean velocity: DDES and DES97

Coarse grid

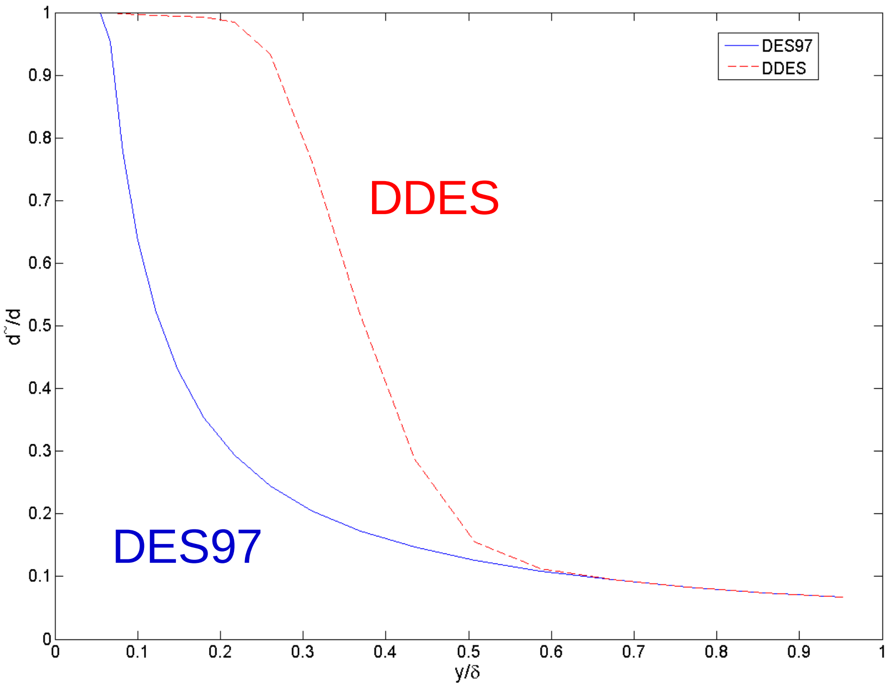


Lower skin friction error than in DES97

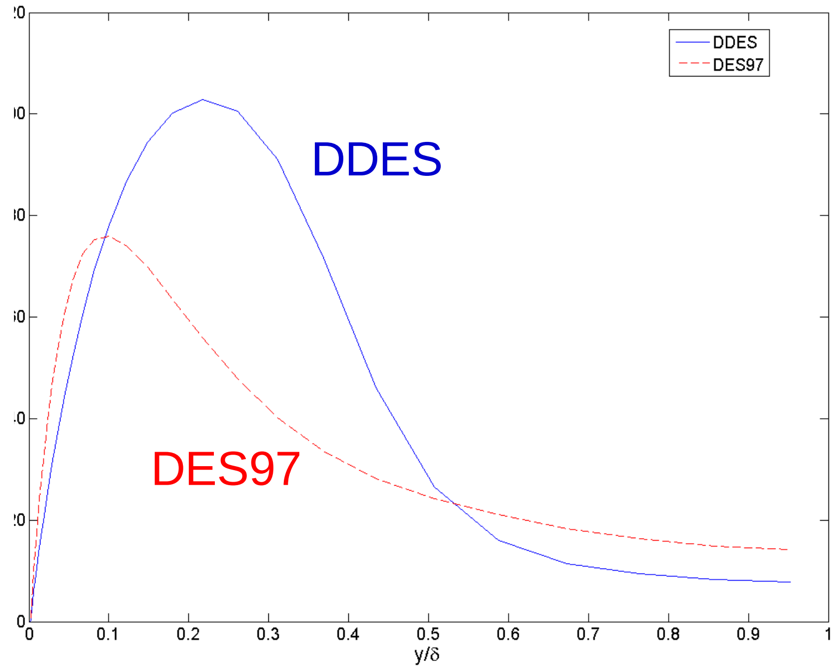
Length scale and eddy viscosity

DDES and DES97 on the coarse grid

$$\tilde{d}/d$$



$$\nu_t/\nu$$



Summary

- DDES version addresses interface errors
  - Incorporates information from the solution field into the length scale definition
    - » Solution field (eddy viscosity) determines the length scale along with the grid spacing and wall distance
  - DDES has become DES as the standard for natural applications and other applications where wall modeling is not the objective