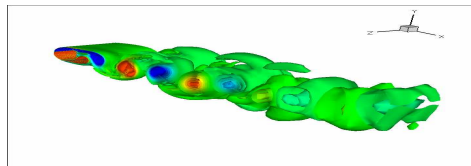

Investigation of the grid spacing calculation effects on the performance of Detached Eddy Simulation

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Outline

- Turbulence modeling approaches
- Hybrid turbulence models
- Implementation of turbulence models in unstructured grid code
- Current results
- Conclusions
- Future work

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Turbulence Modeling Approaches

- Direct Numerical Simulation (DNS)
- Large Eddy Simulation (LES)
- Reynolds-Averaged Navier-Stokes (RANS)
- Hybrid Turbulence Models
 - Detached Eddy Simulation
 - Scale-Adaptive Simulation
 - Delayed-Detached Eddy Simulation

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Evolution of Hybrid Turbulence Models

- 1997 - DES formulation by Spalart *et al* based on Spalart-Allmaras one-equation turbulence model
- 2002 - DES based on Menter's SST model
- 2003 - Scale-Adaptive Simulation by Menter
- 2006 - Delayed-Detached Eddy Simulation by Spalart *et al*

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S-A based Detached Eddy Simulation

Spalart-Allmaras one-equation turbulence model

$$\frac{\partial \tilde{v}}{\partial t} + U_j \frac{\partial \tilde{v}}{\partial x_j} = c_{b1} \tilde{S} \tilde{v} - c_{w1} f_w \left(\frac{\tilde{v}}{d_w} \right)^2 + \frac{1}{\sigma} \frac{\partial}{\partial x_k} \left[(v + \tilde{v}) \frac{\partial \tilde{v}}{\partial x_k} \right] + \frac{c_{b2}}{\sigma} \frac{\partial \tilde{v}}{\partial x_k} \frac{\partial \tilde{v}}{\partial x_k}$$

modified for DES

In SA based DES model d_w is replaced by the new length scale

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

$$\Delta = \max(\delta_x, \delta_y, \delta_z)$$

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SST based Detached Eddy Simulation

Menter's two-equation Shear Stress Transport turbulence model

$$\frac{D\rho k}{Dt} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \frac{\beta^* \rho \omega k}{\text{modified for DES}} + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_{k2} \mu_t) \frac{\partial k}{\partial x_j} \right]$$

$$\frac{D\rho \omega}{Dt} = \frac{\gamma_2}{v_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta_2 \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_{\omega 2} \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2\rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$

In SST based DES model

$$\tilde{l} = \min(l_{k-\omega}, C_{DES} \Delta)$$

$$l_{k-\omega} = k^{1/2} / (\beta^* \omega) \quad \Rightarrow \quad \omega = k^{1/2} / \beta^* l_{k-\omega}$$

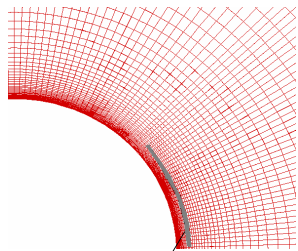
$$\Delta = \max(\delta_x, \delta_y, \delta_z)$$

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Grid construction issues with DES



$$d_w \sim C_{DES} \Delta$$

- The grey area region may shift with the increase in number of grid points in the spanwise direction
- DES may behave incorrectly in the regions of thick boundary layers and shallow separation regions
- Additional issues with unstructured grid, in using the conventional grid spacing definition

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Delayed-Detached Eddy Simulation

Length scale in DES model is replaced by the modified length scale

$$\frac{\partial \bar{v}}{\partial t} + U_j \frac{\partial \bar{v}}{\partial x_j} = c_{v1} \tilde{S} \bar{v} - c_{v1} f_w \left(\frac{\bar{v}}{\tilde{d}} \right)^2 + \frac{1}{\sigma} \frac{\partial}{\partial x_k} \left[(v + \bar{v}) \frac{\partial \bar{v}}{\partial x_k} \right] + \frac{c_{v2}}{\sigma} \frac{\partial \bar{v}}{\partial x_k} \frac{\partial \bar{v}}{\partial x_k}$$

□□□□□□□□
modified DES

$$\tilde{d} \equiv d - f_d \max(0, d - C_{DES} \Delta)$$

$$f_d \equiv 1 - \tanh\left([8r_d]^3\right)$$

$$r_d \equiv \frac{V_t + V}{\sqrt{U_{i,j} U_{i,j}} \kappa^2 d^2}$$

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Scale-Adaptive Simulation

Menter's Scale-Adaptive Simulation hybrid turbulence model

$$\frac{\partial(\rho v_i)}{\partial t} + \frac{\partial(\rho U_j v_i)}{\partial x_j} = c_1 \mu_t S - c_2 \rho \left(\frac{v_i}{L_{vK-SAS}} \right)^2 + \frac{\partial}{\partial x_j} \left(\frac{\mu_t}{\sigma} \frac{\partial v_i}{\partial x_j} \right)$$

$$L_{vK-SAS} = \frac{\left| \frac{\partial U_i}{\partial x_j} \frac{\partial U_i}{\partial x_j} \right|}{\left| \frac{\partial^2 U_i}{\partial x_m^2} \frac{\partial^2 U_i}{\partial x_n^2} \right|}$$

For better LES decay rates

$$\tilde{L}_{vK-SAS} = \max(L_{vK-SAS}, C_{SAS} \tilde{\Delta})$$

$$\tilde{\Delta} = \min(\Delta x, \Delta y, \Delta z)$$

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Project

- Project objectives
 - the shift in the grey area region with changing grids
 - the shift in the grey area region with changing method of calculation of the grid spacing
 - the change in solution with varying methods of grid spacing evaluation
- Current status
 - implementation of hybrid turbulence models SA-DES and SAS in unstructured grid code UNCLE
 - validation of the implemented models

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Unstructured Grid Code (UNCLE)

UNCLE (originally written by Dr P. George Huang)

- three-dimensional, unstructured, incompressible Navier-Stokes solver
- cell-centered pressure based SIMPLE algorithm
- second order upwind scheme for advection terms
- second order central difference scheme for diffusion terms
- second order fully implicit scheme for time discretization

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Test Cases

- Two-dimensional flat plate
- Two-dimensional circular cylinder
- Three-dimensional circular cylinder

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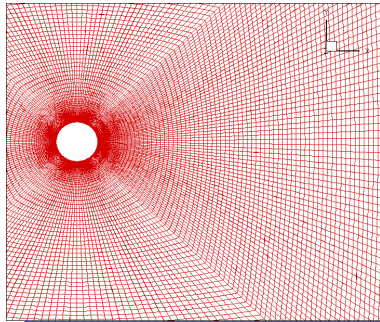
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Three-dimensional Circular Cylinder

Flow over a three-dimensional circular cylinder

	Test case-1	Test case-2	Test case-3
Reynolds number	3900	13400	140000
Grid points	1.2M	1M	660,000
y^+ - initial grid spacing	2×10^{-3}	5×10^{-5}	1×10^{-4}
Grid spacing definition	$\Delta = (\sqrt{\delta x \delta y \delta z}, \delta z)$	$\Delta = (\sqrt{\delta x \delta y \delta z}, \delta z)$	$\Delta = (\sqrt{\delta x \delta y \delta z}, \delta z)$



Initial value: $\tilde{v} = 5v$

BC: wall $\tilde{v} = 0$

inlet $\tilde{v} = 5v$

outflow $\partial \tilde{v} / \partial x_i = 0$

spanwise is periodic

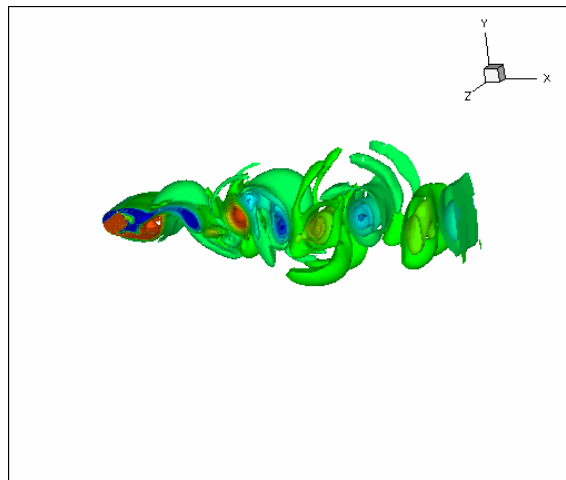
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Three-dimensional Circular Cylinder

The iso-surface of the vorticity magnitude at $Re=3900$



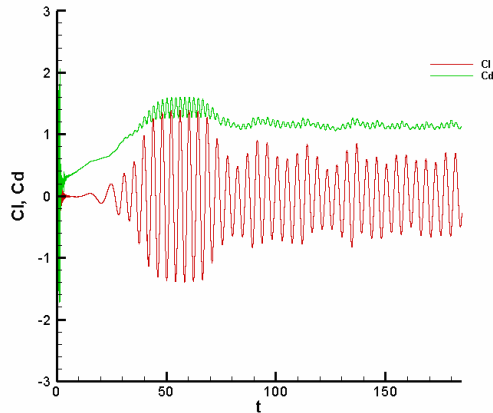
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Three-dimensional Circular Cylinder

The lift-drag plot at $Re=3900$



	$\overline{C_d}$
Experiment	0.99 ± 0.05
Present	1.19383

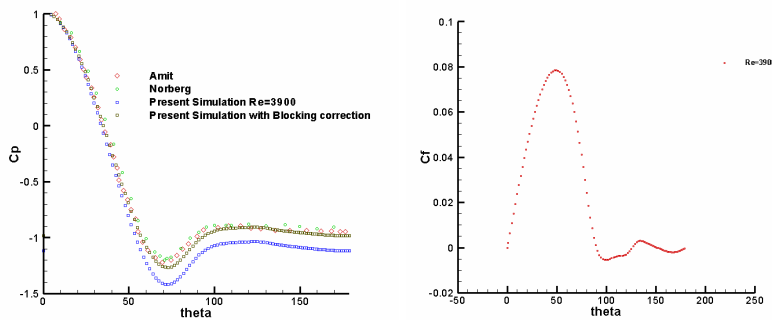
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Three-dimensional Circular Cylinder

Pressure distribution on the surface of the cylinder and the skin friction coefficient plot at $Re=3900$



Blocking correction $c_{pc} = 1 - (1 - c_p) / (1 + \epsilon)^2$

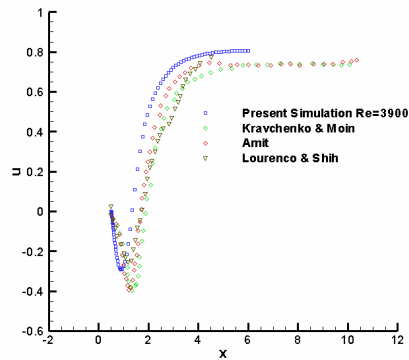
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Three-dimensional Circular Cylinder

Centerline velocity plot at $Re=3900$



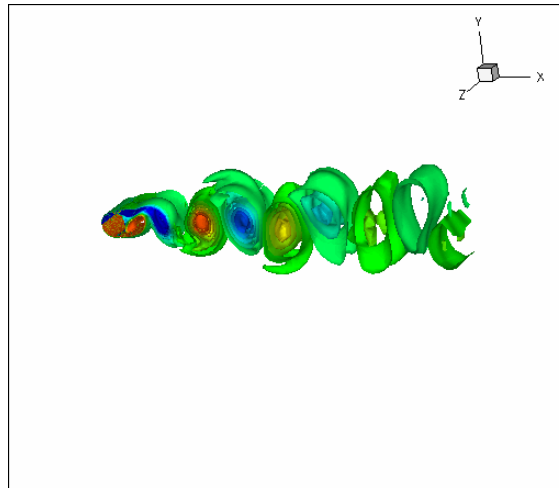
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Three-dimensional Circular Cylinder

The iso-surface of the vorticity magnitude at $Re=13400$



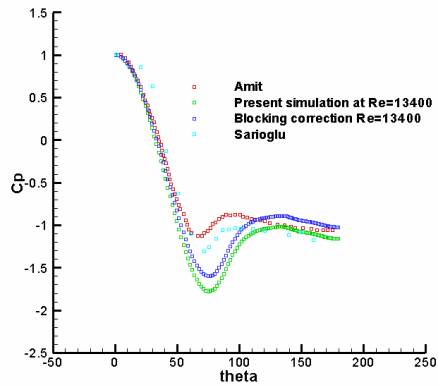
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Three-dimensional Circular Cylinder

Pressure distribution at the surface of the cylinder at $Re=13400$



Blocking correction $c_{pc} = 1 - (1 - c_p) / (1 + \epsilon)^2$

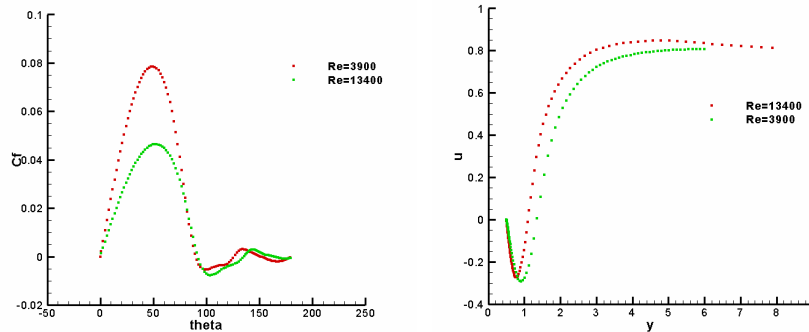
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Three-dimensional Circular Cylinder

Skin friction coefficient plot and centerline velocity plot at $Re=13400$



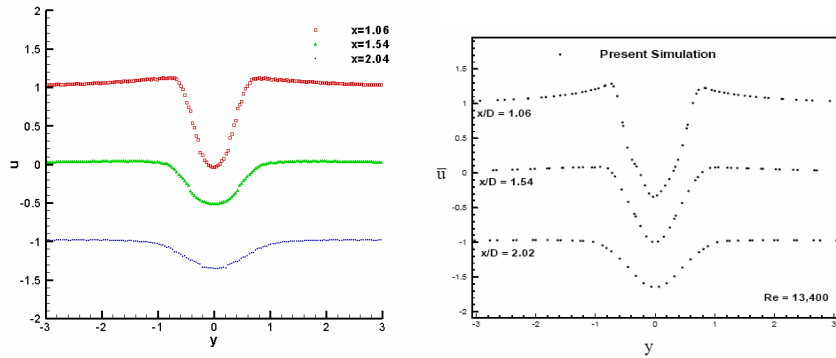
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Three-dimensional Circular Cylinder

Velocity profiles in the streamwise direction at $Re=13400$



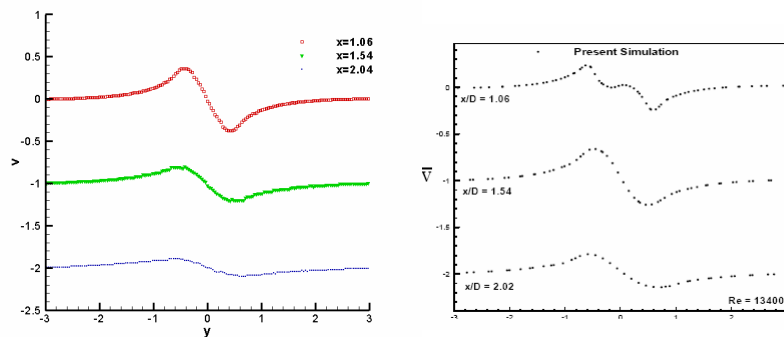
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Three-dimensional Circular Cylinder

Velocity profiles in the cross-flow direction at $Re=13400$



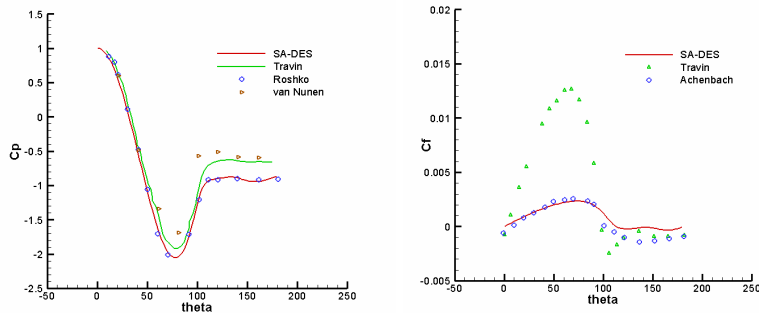
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Three-dimensional Circular Cylinder

Pressure distribution at the surface of the cylinder and the skin friction coefficient plot at $Re=140000$



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Possible Sources of Errors

- Expanding outer boundaries
- Finer grid resolution in the wake region
- Finer grid resolution in the z -direction
- Longer integration over time intervals

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Conclusions

- The DES hybrid turbulence model is implemented and is being validated in the unstructured grid code, UNCLE.
- Results have been presented for three different turbulent Reynolds numbers using SA-DES
- One possible definition of the grid spacing has been used

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Future Work

- Simulate SA-DES cases with improved grids
- Simulate SAS and SST-DES cases
- Need to observe the transition of the grey area region with the change in the method of evaluating the grid spacing
- Implement DDES hybrid turbulence model in UNCLE for comparison between DES and DDES models

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THE END

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