

# Investigation of Grey Area Construction on the performance of Detached Eddy Simulation

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Since its introduction in 1997, the use of Detached Eddy Simulation (DES) and similar hybrid turbulence techniques have become increasingly popular in the field of CFD. However, with increased use some of the limitations of the DES model have become apparent. One of these is the dependence of DES on grid construction, particularly regarding the point of transition between the Reynolds-Averaged Navier-Stokes and Large Eddy Simulation models. To address this, the originators of the DES approach have recently introduced Delayed Detached Eddy Simulation (DDES), which aims to minimize grey area effects. To investigate the grey area effects, the authors are constructing grid which is highly controlled in order to precisely define the grey area region in an unstructured grid. In order to carry out the simulations on these grids the one equation Spalart-Allmaras(SA) based DES and the Menter's Shear Stress Transport(SST) based DES turbulence models are implemented in the in-house CFD code UNCLE and efforts are made to validate and compare the results from these simulations to the results by Travin et al. Preliminary results for the  $Re = 1.4 \times 10^5$  case are presented in this abstract; additional tests will be presented in the final paper.

## Nomenclature

$x$	=	spatial coordinate
$dt$	=	time step
$\rho$	=	density of fluid
$U_{ij}$	=	velocity vector
$d$	=	distance variable in Spalart-Allmaras (SA) turbulence model
$\nu$	=	kinematic viscosity
$\nu_T$	=	turbulent viscosity
$\tilde{l}, \tilde{l}_{k-\omega}$	=	DES length scale
$\Omega_{ij}$	=	rotation tensor
$c_{b1}, c_{b2}, c_{v1}, c_{w1}, c_{w2}, c_{w3}, K, \sigma$	=	SA model closure coefficients
$\chi, f_{v1}, f_{v2}, f_w, g, r, \tilde{\nu}$	=	SA model variables
$S$	=	shear stress tensor
$\tilde{S}$	=	correction to the shear stress tensor
$d_w$	=	distance from the wall
$C_{DES}$	=	model constant for the DES turbulence model
$\delta_x, \delta_y, \delta_z$	=	grid spacing in the x, y and z directions
$k$	=	turbulent kinetic energy in the $k - \omega$ turbulence model

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$\omega$  = dissipation rate  
 $\beta^*$  = compressibility correction to the  $k - \omega$  turbulence model

## I. Introduction

Reynolds Average Navier Stokes (RANS) approach is still the most widely applied simulation technique for turbulent engineering flows. The predictions of RANS models become less accurate for unsteady flow around bodies at high Reynolds number in which turbulent eddies shed and detach from the boundary layer flow<sup>12</sup>. On the other hand Large Eddy Simulation (LES) approach is a popular technique to model massively separated regions. In LES, the larger structures in the turbulent spectrum are resolved and the smaller structures are modeled. But the approach has its limitations in the form of computational cost.

The cost limitation factor for the LES in the attached boundary layers and the inaccuracy of the RANS models in the prediction of massively separated regions led to approaches that combine the advantage of LES in the separated regions and the ability of accurate prediction of the RANS model in the attached boundary layer. This has promoted the formulation of numerous hybrid turbulence models, some of which have been classified as Detached Eddy Simulation (DES). In this approach, the attached boundary layer is treated with RANS turbulence model, larger detached eddies in the separated regions are directly simulated, and smaller eddies in this region are modeled by a LES-like turbulence model.

As has been pointed out elsewhere<sup>4</sup>, the original dependence of the DES model on the grid spacing and grid location has rendered the model results unusually dependent on the grid construction, not just simply on the grid resolution. An additional challenge is presented by unstructured grid codes, as the original form of DES implicitly assumes a dominant 2D grid (airfoil cross-section, for example) and third dimension that can effectively be used to control the point of transition from RANS to LES. Unstructured grids often do not possess this 2D/3D structure, and if the elements are not quadrilateral it may also present some question as to the best way to define the grid spacing. The purpose of this project is focus on the effects of moving the RANS-LES transition point and of alternate definitions of the grid spacing on otherwise similar grids in an unstructured CFD code, starting with the Spalart-Allmaras and Menter SST versions of the DES model.

## II. Flow algorithm and Flow solver

The simulations will be conducted using the in-house code UNCLE<sup>14</sup> (written by Dr P. G. Huang at the Univ. of Kentucky). Currently, the DES version of both the one equation Spalart Allmaras model<sup>3</sup> and the Shear Stress Transport model<sup>6</sup> are implemented in the code. A brief description of the code and the two DES models follows.

### A. UNCLE

UNCLE is an in-house CFD code at the University of Kentucky, written by Dr. George Huang, designed to meet the challenges of physical problems with complex geometries, complicated boundary conditions on parallel computers while maintaining high computational efficiency.<sup>15</sup> The laminar form of the code was validated by Dr. Chen Hua at University of Kentucky using various challenging test cases.<sup>14</sup> It is a two/three-dimensional, finite-volume, unstructured incompressible Navier-Stokes solver for steady and unsteady flow fields. It is highly flexible in terms of grid geometry as it can handle volumes of various types such as triangular, quadrilateral, tetrahedral and hexahedral. METIS<sup>17</sup>, a program based on multilevel 26 graph partitioning schemes, is used for grid partitioning. The parallel construction of code is done using message passing interface (MPI) protocols. UNCLE relies on a cell-centered pressure-based method that is based on the SIMPLE algorithm with second order accuracy in both time and space. A second order upwind scheme is adopted to compute the advection terms and a second order central difference scheme is used for computing the diffusion terms. A collocated grid system with the Rhie and Chow momentum interpolation method<sup>18</sup> is employed to avoid the checkerboard solution of the pressure based scheme. Fluxes on the volume faces are determined through interpolation of cell-centered values. The time discretization is second-order fully implicit scheme.

## B. Detached Eddy Simulation (DES) based on Spalart Allmaras (SA) Model

The one equation Spalart-Allmaras (SA) model is a transportation equation for the turbulent viscosity. The equation is formulated using the empiricism and the arguments of dimensional analysis, Galilean invariance and selective dependence on the molecular viscosity.<sup>3</sup> This turbulence model is local and hence is compatible with both the structured and unstructured grids. The insensitivity of this model to the free stream helps to obtain a stable solution.

The standard form of the SA model in terms of the eddy viscosity, which includes eight closure coefficients and three closure functions, along with the SA based Detached Eddy Simulation turbulence model is implemented in the in-house code, UNCLE. The solution to the governing differential equation is currently treated in the same manner as the momentum equations. The length of the scale of RANS SA model is the distance to the closest wall,  $d_w$ . The modification consists in substituting for  $d$  in the loss term a new length scale,  $\tilde{l}$ . The definition of  $\tilde{l}$  is given by,

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

where  $C_{DES}$  is the new adjustable model constant and is typically set to 0.65. In the original formulation,  $\Delta$  is based on the largest dimension of the local grid cell, which is given by,

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

For wall bounded separated flows, the above formula results in a model that functions as a RANS SA model in the attached boundary layer and as a subgrid scale in the rest of the flow which includes the separated regions and near the wake. Once the field point is away from the attached boundary layer the model becomes explicitly grid dependent, and the model performs as a subgrid scale version of the SA model.

## C. Detached Eddy Simulation (DES) based on Shear Stress Transport (SST) Model

Menter's models were two-equation eddy viscosity turbulence models with emphasis on the engineering perspective. The basic problem of two equation models is the prediction of the separation in the adverse pressure gradient flows which is still unsolved. The Menter SST model is based on combining elements of two other two-equation models.<sup>6</sup> The idea is to retain the accurate formulation of the  $k$ - $\omega$  model in the near wall region and to that add the advantage of the  $k$ - $\epsilon$  model in the outer part of the boundary layer.

DES model can be obtained from a RANS model by appropriate change in the length scale which is explicitly or implicitly involved in any RANS turbulence model. In case of Menter, the modification is applied to the  $k$ - $\omega$  model. In the Menter SST model the length scale in terms of  $k$  and  $\omega$  is given by

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

Modifying the dissipative term of the  $k$  - transport equation, the loss term becomes,

$$D_{RANS}^k = \rho \beta^* k \omega = \rho k^{3/2} / l_{k-\omega}$$

Replacing  $l_{k-\omega}$  with the DES length scale  $\tilde{l}$  yields

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

where  $C_{DES}$  and  $\Delta$  are defined as with the SA-DES model. Substituting this in the above equation we get,

$$D_{DES}^k = \rho k^{3/2} / \tilde{l}$$

While the conventional definition of  $\Delta$  is the same for both models, CFD solvers on unstructured grids do not necessarily have a simple means to compute the maximum grid distance. An alternate formulation is to use the cube root of the volume to define the value of  $\Delta$ , or

$$\Delta = (\delta_x \delta_y \delta_z)^{1/3}$$

which for a hexahedral style element is clearly different than the maximum distance unless the volume is approximately cubical. Another formulation that we have considered is a combination of the two conditions,

$$\Delta = \max(\sqrt[3]{\delta_x \delta_y \delta_z}, \delta_z)$$

Properly, each of these different volume implementations potentially requires a recalibration of the  $C_{DES}$  parameter based on homogeneous turbulence decay. However, a purpose of this paper is to consider the differences in the results if these different formulations are used without any adjustment of  $C_{DES}$ .

#### D. Cluster Architecture

The 3D simulations in this paper to date have been carried out on the Kentucky Fluid Cluster 5 (KFC5). KFC5 is a 64-bit architecture, constructed of 47 AMD64 2.08 GHz processors linked by a single Gigabit (1 GB/s) switch. Each node has 512 MB of RAM and each processor has a L2 cache of 512 KB. The server is separate from the nodes and plays no direct role in the iterative computation. KFC5 is housed at the University of Kentucky.<sup>15</sup> Additional simulations will be conducted on KFC6a and KFC6b, two clusters that will be constructed in November, 2006. These clusters will each have 23 nodes; one set based on the Intel 6400 duo processor, the other on the AMD 4600 dual core processor. Both will have 1 GB RAM per node. Based on preliminary tests, we expect a performance improvement of 20-30% on KFC6 versus KFC5.

The METIS code is used for the domain decomposition so that an excellent load balancing between the subgrids on each node can be achieved. Any unstructured grid can be partitioned into an integer number of zones using METIS without losing load balance.

### III. Test Case and Grid Construction Issues

#### A. Description of the grid

A three dimensional circular cylinder is used as the test case for the validation of SA based DES hybrid turbulence model. An initial grid with 660,000 grid points has been used with 200 grid points spaced uniformly in the circumferential direction, 110 in the radial direction, and 30 in the spanwise direction spaced uniformly. The radius  $r/D = 0.5$  is used for the validation purpose to compare with the appropriate test cases. A snap shot of the grid in the XY plane is presented in Figure 1. It is an unstructured grid and hexahedral cells are used. The grid runs from -15.0 to +15.0 in the x and y directions and 0.0 to +2.0 in the z-direction. Periodicity is applied for the first grid plane and the last grid plane in the spanwise direction. No slip conditions are applied to the surface of the cylinder and the inlet velocity is set to  $U = 1.0$ . For convenience the grid is extended to a square on the outside boundaries.

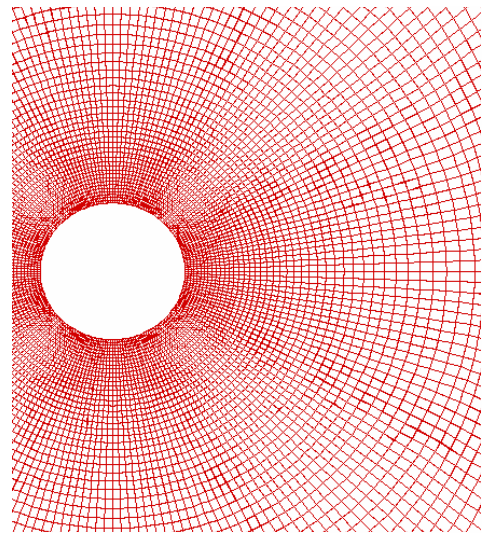
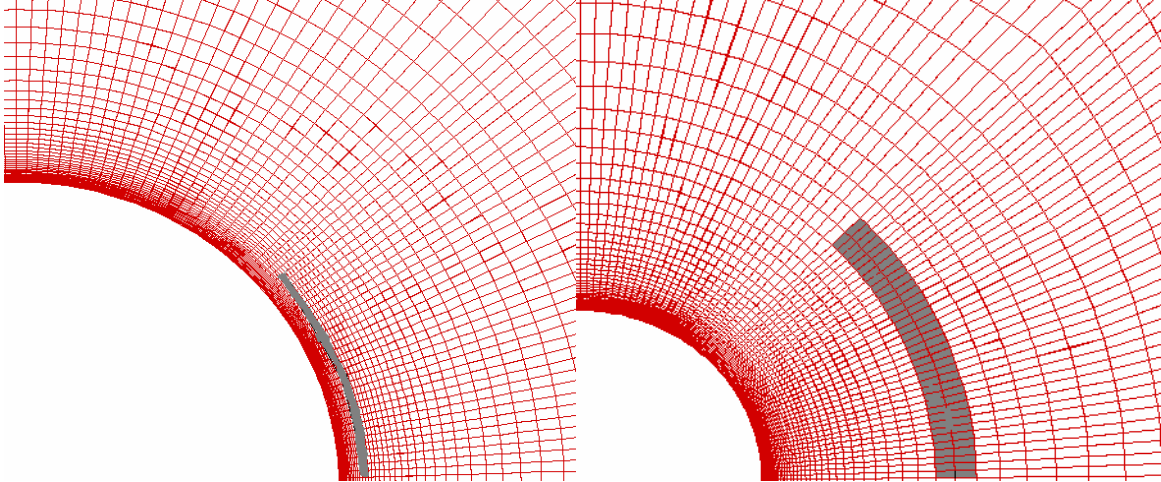


Figure-1: Snapshot of the grid.

#### B. Grid Construction issues with DES

Detached Eddy Simulation is the hybrid turbulence model proposed to use the Reynolds Averaged Navier Stokes turbulence model the thin boundary layers and the Large Eddy Simulation turbulence model in the regions of massive separation.<sup>4</sup> The DES turbulence model can exhibit incorrect behavior in the thick boundary layers and the shallow separation region which is titled as a ‘grey area’ region. When the grid spacing parallel to the wall is less than the boundary layer thickness, the LES turbulence model takes over as the length scale is fine enough for the DES to switch into a LES mode from RANS mode; however, as the grid spacing is partially inside the boundary layer and the resolved Reynolds stresses in LES mode do not completely replace the modeled Reynolds stresses from the RANS mode. This leads to the depletion of the stresses which in turn leads to the reduction in the skin friction computations leading to a premature separation.

An additional issue that arises with unstructured grids is the definition of the grid spacing. For the hexahedral grid shown, the conventional definition of  $\Delta$  can be applied in a fairly direct fashion, but more complicated cell volumes (such as tetrahedral or combined hexahedral-tetrahedral) do not have that luxury. If other means of defining the grid spacing are used, the region of RANS-LES transition can shift significantly (Figure 2). This has implications for both the location of the grey area and the magnitude of the dissipation term in the LES region.



**Figure-2 Grey area region in the 3D circular cylinder, Grid Spacing computed from**  
**(a)  $\Delta = \max(\sqrt[3]{\delta_x \delta_y \delta_z}, \delta_z)$  (b)  $\Delta = \max(\delta_x, \delta_y, \delta_z)$**

Figure 2 presents the variation of the transition region from RANS mode to the LES mode with varying methods of computing the length scale for the DES model. In figure 2(a) the grid spacing delta is computed from cube root of the volume of the local grid cell which is used in the UNCLE code and the presented results corresponds to this computation of the DES length scale. In figure 2(b) the grid spacing delta is computed from the actual calculation of the individual grid spacing in the x, y and z directions and taking the maximum of those three values. The transition region is computed to a radial distance of 0.5375 in the first case and where as in the latter case the grey region is moved to 1.0311 in the radial direction. We can observe the variation of the grey area region with the change in the method of computing the length scale. This problem is subjected to further work in future and more simulations would be carried out to study the influence of the calculations of the length scale in moving grey are region.

### C. Test Case: Three Dimensional Circular Cylinder

The three dimensional circular cylinder is considered as the test case to investigate the grey area and grid construction issues. The first step in the investigation is the implementation and validation of the SA based DES model against the benchmark results. Results from the paper of Travin et al<sup>1</sup> and the referenced experiments within that paper are considered for the validation. The grid construction and the initial conditions are replicated from the Travin et al definitions. The triplex version of the SA model is used with the implementation of the DES model and  $\tilde{\nu}$  is initiated to 5 times the molecular viscosity for the “turbulent” cases.

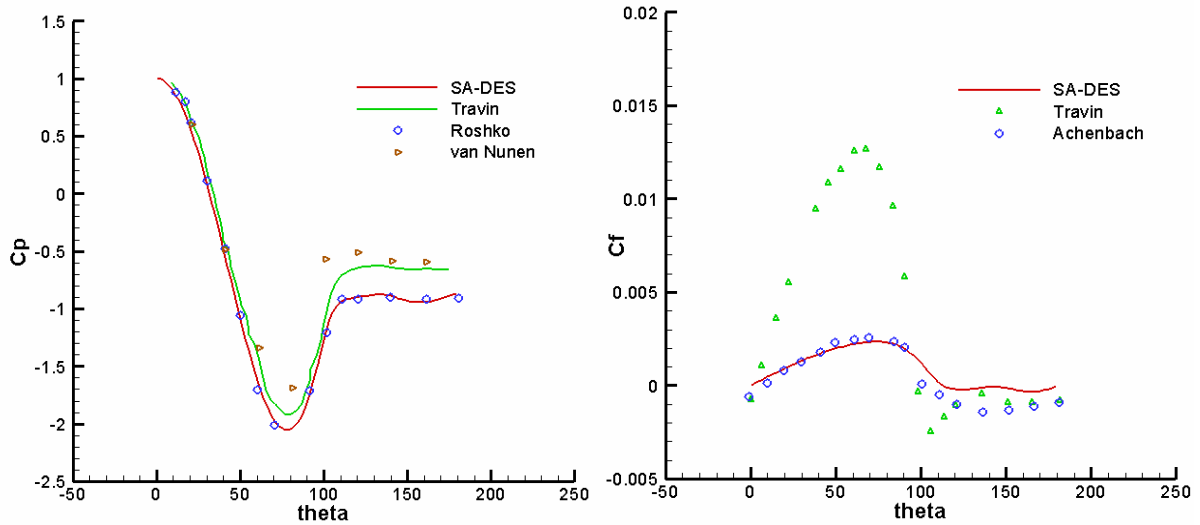


Figure-3 (a) Cylinder Pressure Coefficient and (b) Skin Friction Coefficient for  $Re = 1.4 \times 10^5$

Figure 3 shows the pressure coefficient and the skin friction coefficient from the model at a Reynolds number of 140,000 along with the experimental results from van Nunen<sup>9</sup> and Roshko<sup>8</sup> and the simulations from Travin et al. The computations of the coefficient of pressure are well in agreement with the experimental results from Roshko<sup>8</sup> (for  $Re = 8.5 \times 10^6$ ), however the lower values in the wake region compared to the Travin et al results may be due to differences in the grid construction. More grid points are being added in the wake region for a better result and these simulations are currently in process. Coming to the skin friction coefficient curve the values are well in agreement with experimental results<sup>10</sup>. The wavy pattern in the wake region is likely a grid refinement issue again which is being rectified for the next simulation. Longer integration periods may also be necessary for obtaining average values (the integration has covered over 150 non-dimensional ( $t = D/U$ ) time units, but the average has only been taken over the last eight oscillation cycles for these preliminary results).

#### IV. Summary and Future Work

The SA and SST based DES hybrid turbulence model are implemented in the in-house unstructured CFD code UNCLE to study issues related to grid construction. The validation of the turbulence models is being carried out and a few preliminary results are presented in this abstract. In the final paper, further simulations will be carried out to compare different choices in the definition of the grid spacing and different stretching of the grid to move the location of the grey area. The goal of the final paper is not to focus on grid refinement per se, but on how the stretching and grid spacing definitions can affect the results on a reasonably dense and well-constructed grid. Multiple cases following Travin et al will be considered.

Plans are also to implement the improvised hybrid turbulence model version of the DES proposed by the originators of the DES, Delayed Detached Eddy Simulation (DDES)<sup>4</sup>, and the Scale-Adaptive Simulation (SAS) model<sup>5</sup> of Menter. Both of these models are designed to address some of the grid construction issues, which will be a useful comparison to the putatively more grid-dependent SA-DES and SST-DES models. The ability to investigate these two models in depth in the final paper will depend on the availability of computer power to devote these computations.

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