LES Applications in Aerodynamics

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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

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

\[
\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j} - \frac{\overline{u'_i u'_j}}{\partial x_j}
\]

- 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.
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…
  \[ P \approx \varepsilon \]
  \[ P = -u'v' \frac{dU}{dy} \]
  \[ \nu_t P \approx \nu_t \varepsilon \]
  \[ -u'v' = \nu_t \frac{dU}{dy} \]

- Combining the above relations…
  \[ \nu_t \varepsilon \approx \nu_t \left(-u'v' \frac{dU}{dy}\right) = \left(u'v'\right)^2 \]
  \[ \nu_t = \frac{\left(u'v'\right)^2}{\varepsilon} \]
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

\[
\frac{u'v'}{K} \approx C
\]

- We had...

\[
\nu_t = \frac{(u'v')^2}{\varepsilon}
\]

- Now we have...

\[
\nu_t = C^2 \frac{K^2}{\varepsilon}
\]
Important parts of the previous exercise...

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

  \[ \nu_t = \mathcal{U} l_m \]

  \( \mathcal{U} = \) velocity scale \( l_m = \) 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

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

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

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

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

\[
\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial}{\partial x_j} \left( \overline{u_i u_j} \right) = - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}
\]

\[
\tau_{ij} = \overline{u_i u_j} - \overline{u_i} \overline{u_j}
\]

\[
\tau_{ij} - \frac{\delta_{ij}}{3} \tau_{kk} = -2\nu_{sgs} S_{ij} = -\nu_{sgs} \left( \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right)
\]

- Looks like the RANS equations
  - But there are important differences...
Large Eddy Simulation (LES)

- Subgrid viscosity in LES…
  \[ \nu_{sgs} = (C_s \Delta)^2 |\bar{S}| \]
  \[ |\bar{S}| = (2\bar{S}_{ij}\bar{S}_{ij})^{1/2} \]

- Eddy viscosity in RANS…
  \[ \nu_t = 0.09 \frac{\mathcal{K}^2}{\varepsilon} \]
  \[ \mathcal{K} = \text{kinetic energy} \]
  \[ \varepsilon = \text{dissipation rate} \]

- 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 m² (chord length of a 1 meter, spanwise section 1 meter)
      › Objective is to estimate the number of cubes of size $\delta$ (per side) needed to fill the boundary layer

\[
N_{cubes} = \int \int \frac{1}{\delta^2} dA
\]
Cost estimate for LES of an airfoil

\[ N_{\text{cubes}} = \int \int \frac{1}{\delta^2} dA \]

\( \delta = \text{local boundary layer thickness} \)
Cost estimate for LES of an airfoil

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

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

- Consider a chord-based Reynolds number of $2 \times 10^6$

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

- Above estimate is the number of cubes of dimension $\delta$ needed to fill the boundary layer over the wing
Cost estimate for LES of an airfoil

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

- Above estimate is the number of cubes of dimension \( \delta \) 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)

\[ N_g = N_0^3 N_{\text{cubes}} \]
Cost estimate for LES of an airfoil

\[ N_g = N_0^3 N_{cubes} \]

- For \( N_0 = 20 \ldots \)

\[ N_g = 7 \times 10^{10} \]

- 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
Outline

- **Subgrid-scale models**
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- **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**
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

\[
\frac{D\tilde{\nu}}{Dt} = P_\nu - \epsilon_\nu + \frac{1}{\sigma_\nu} \left[ \nabla ((\nu + \tilde{\nu}) \nabla \tilde{\nu}) + c_{b2} |\nabla \tilde{\nu}|^2 \right]
\]

Production \hspace{2cm} \text{Destruction} \hspace{2cm} \text{Transport}

- Production and destruction terms…

\[ P_\nu \propto \tilde{S}\tilde{\nu} \]

\[ \epsilon_\nu \propto \left[ -\frac{\tilde{\nu}}{d} \right]^2 \]

- Replace the length scale…

\[ \text{(wall distance)} \hspace{1cm} d \rightarrow \tilde{d} \]
Formulation of DES…

- Balance the production and destruction terms…

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

- 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 \( \Delta \)
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 \( \Delta \) such that RANS length scale maintained in the boundary layer
    \[ \Delta \equiv \max(\Delta x, \Delta y, \Delta z) \]

- Close to the wall \( \Delta \) 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 $\Delta^{4/3}$

\[ C_{DES} = 0.65 \]
Aspects of the formulation...

\[
\frac{D\tilde{\nu}}{Dt} = c_b \tilde{S}\tilde{\nu} + \text{diffusion} - c_w f_w \left[\frac{\tilde{\nu}}{\tilde{d}}\right]^2
\]

- Production
- Destruction

\[
\tilde{d} = \min(d, C_{DES} \Delta) \quad \Delta = \max(\Delta_x, \Delta_y, \Delta_z)
\]

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

- DES is a \textit{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

\[ C_p \]

\begin{align*}
\text{8°} & & \text{20°} & & \text{45°} \\
\text{2D DES} & & \text{2D URANS} & & \text{3D DES}
\end{align*}
Flow past a circular cylinder

Travin et al. (1999)

- Comprehensive study and assessment of the technique
- Reynolds numbers…
  - $5 \times 10^4$, $1.4 \times 10^5$ and $3 \times 10^6$
- 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?
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 $\sqrt{2}$ in each direction
- Spanwise extent = 2D
Laminar separation – vorticity isosurfaces

Re = 5.0 \cdot 10^4, Fine grid, SA
\lambda_{1,3D} = 1.0 isosurface
Laminar separation – time dependent forces

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

![Graph showing laminar separation with pressure coefficient and factors]
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° and 90°

- Simulation details (Viswanathan, Squires and Forsythe 2006)
  - Grid sizes from $2.1 \times 10^6$ cells to $8.75 \times 10^6$ cells
    » Unstructured (generated using VGRIDns, Pirzadeh 1996)
  - $Re = 2.21 \times 10^6$, Mach number = 0.21
Role of grid refinement and turbulence model

vorticity contours in the wake, \( y/D = 1.0 \), \( 90^\pm \) 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, $\alpha = 90^\circ$

S-A RANS

surface colored by pressure

DES
Azimuthal Pressure Distribution

Comparison for Station 3 (x/L = 0.111)

Viswanathan, Squires and Forsythe (2006)
Azimuthal Pressure Distribution

Comparison for Station 4 (x/L = 0.166)

Viswanathan, Squires and Forsythe (2006)
Azimuthal Pressure Distribution

Comparison for Station 5 \((x/L = 0.222)\)

- DES
- RANS
- Measurements

Viswanathan, Squires and Forsythe (2006)
Azimuthal Pressure Distribution

Comparison for Station 6 (x/L = 0.305)

Viswanathan, Squires and Forsythe (2006)
F-15E at 65 Degrees Angle of Attack

- \( \text{Re} = 13.6 \times 10^6, \ M = 0.3 \)
- 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 \times 10^6, 6 \times 10^6, 10 \times 10^6 cells
    - Resolved wall layer
  - Timestep variation of 0.01, 0.02, and 0.04 (dimensionless using chord and freestream speed)
Surface grids
Instantaneous vorticity field

F-15E at 65° 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

Baseline Grid, S-A DES

AMR Grid, S-A DES

Morton, Steenman, Cummings and Forsythe (2004)
Instantaneous Vorticity Field

F-18C at 30° 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 NASA F-18 HARV:

- Flaps set to $0^\pm$, $0^\pm$, $0^\pm$
- Diverter slot included

Presence of diverter slot influences breakdown location

Morton, Steenman, Cummings and Forsythe (2004)
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Original formulation of DES (“DES97”)

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

- 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

![Diagram showing the role of the mesh in flow separation](attachment:diagram.png)
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

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

- Use of $r_d$ in a function that “shields” the boundary layer:

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

  - “C” and “n” control thickness and sharpness of $f_d$
    - Optimized values $C = 8$, $n = 3$
Delayed Detached Eddy Simulation

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

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

- Limits:

  \[ f_d = 0 \rightarrow \text{RANS} \quad f_d = 1 \rightarrow \text{DES97} \]

- 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 $2\pi\delta \times 2\delta \times \pi\delta$
    - 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

\[ u^+ = 2.43 \times \log(y^+) + 5.2 \]
Length scale and eddy viscosity

DDES and DES97 on the coarse grid

\[ \tilde{d}/d \]

\[ \nu_t/\nu \]

\[ \text{DDES} \]

\[ \text{DES97} \]
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