Turbulence and CFD models: Theory and applications

Roadmap to Lecture 10

1. ~~SRS simulations – Scale-resolving simulations~~
2. ~~LES equations – Filtered Navier-Stokes equations~~
3. **Subgrid-scale models for LES**
4. DES models
5. A few mesh resolution guidelines and rough estimates for LES/DES simulations
6. Final remarks on LES/DES turbulence models

LES sub-grid scale models

- As for RANS models, in LES there are many different models to approximate the apparent stress tensor introduced into the governing equations, or the sub-grid scale stress tensor τ^{SGS}.
- Just to name a few models:
  - Smagorinsky, Smagorinsky-Lilly, dynamic Smagorinsky-Lilly, Deardoff, WALE, Germano dynamic model, Algebraic WMLES S-Omega Model Formulation, one equation kinetic energy transport (standard and dynamic).
- As for RANS, the sub-grid scale models are based on the Boussinesq hypothesis.
- Most of the models are algebraic (or zero equations).
  - Meaning that they do not use additional equations to model the stress tensor.

LES sub-grid scale models – The Smagorinsky model

- Let us introduce the Smagorinsky model [1],

$$\tau^{SGS} = -2\nu_{SGS}\overline{\mathbf{S}}$$

- Where $\overline{\mathbf{S}}$ is the strain-rate tensor, and ν_{SGS} is the subgrid-scale eddy viscosity.
- As for RANS models, our task is to somehow compute the turbulent viscosity, or ν_{SGS} in LES simulations.

[1] J. Smagorinsky. General circulation experiments with primitive equations. I. The basic experiment, Monthly Weather Review, Vol. 91, pp. 99-164, 1963.

LES sub-grid scale models – The Smagorinsky model

- In the Smagorinsky model, the sub-grid scale stress tensor is modeled as follows,

$$\tau^{SGS} = -2\nu_{SGS}\overline{\mathbf{S}}$$

- Where $\overline{\mathbf{S}}$ is the resolved strain-rate tensor,

$$\overline{\mathbf{S}} = \frac{1}{2}\left(\nabla\overline{\mathbf{u}} + \nabla\overline{\mathbf{u}}^{\mathrm{T}}\right)$$

- And ν_{SGS} is the subgrid-scale eddy viscosity,

$$\nu_{SGS} = \left(C_S\Delta\right)^2 \left|\overline{\mathbf{S}}\right|$$

LES sub-grid scale models – The Smagorinsky model

- In the subgrid-scale eddy viscosity relation,
  - Δ is the filter width (proportional the grid spacing),
  - C_s is the Smagorinsky constant (or coefficient),
  - and $|\overline{\mathbf{S}}|$ is defined as,

$$|\overline{\mathbf{S}}| = \left(\overline{\mathbf{S}} : \overline{\mathbf{S}}\right)^{1/2}$$

- The filter width Δ is usually computed as follows,

$$(\Delta_x \Delta_y \Delta_z)^{1/3} = \text{Cell volume}^{1/3}$$

- Obviously, the filter width approximation is accurate for uniform hexahedral cell.
- Depending on the cell shape there are different formulations available.

LES sub-grid scale models – The Smagorinsky model

- Notice that the subgrid-scale eddy viscosity relation resembles a mixing length formulation (refer to Prandtl mixing length formulation),

$$\nu_{SGS} = (C_S \Delta)^2 \left| \overline{\mathbf{S}} \right|$$

- In this equation, $C_S \Delta$ can be seen as the mixing length scale.
- The Smagorinsky model can be further improved by adding a damping function to let the turbulent viscosity exponentially damp to zero close to the walls,

$$\nu_{SGS} = \left[C_S \Delta \underbrace{\left(1 - e^{y^+/25} \right)}_{\text{Van Driest damping function}} \right]^2 \left| \overline{\mathbf{S}} \right|$$

LES sub-grid scale models – The Smagorinsky model

- The Smagorinsky model is the oldest LES model, but because of its simplicity it is widely used.
- It is not a particularly good choice for wall-bounded flows, but for flows far from solid boundaries it can be quite adequate.
- In the Smagorinsky model, the value of the constant (or coefficient) C_s is of the order $\mathcal{O}(10^{-1})$.
- The values found in the literature can range from 0.1 to 0.4.
- Many of the drawbacks of the Smagorinsky model are due to the fact that the value of this constant (or coefficient) can depend on the flow conditions.
- To overcome the drawbacks of the Smagorinsky model, more refined models have been developed.
    - Models with wall damping functions, dynamic models, one equation models and so on.

LES sub-grid scale models – Dynamic Smagorinsky model

- One of the largest deficiencies of the Smagorinsky model is that the coefficient C_s needs to be calibrated.
- Germano et al. [1] and Lilly [2], conceived a procedure in which the Smagorinsky model constant is dynamically computed based on the information provided by the resolved scales of motion.
- The concept of the dynamic procedure is to apply a second filter (called the test filter) to the equations of motion.
- The new filter width is usually equal to twice the grid filter width.
    - Both filters produce a resolved flow field.
- The difference between the two resolved fields is the contribution of the small scales whose size is in between the grid filter and the test filter.
- The information related to these scales is used to compute the model constant,

$$C_s\left(\mathbf{x}, t\right)$$

[1] M. Germano, U. Piomelli, P. Moin, W. H. Cabot. Dynamic Subgrid-Scale Eddy Viscosity Model. In Summer Workshop. Center for Turbulence Research, Stanford, CA. 1996.
[2] D. K. Lilly. A Proposed Modification of the Germano Subgrid-Scale Closure Model. Physics of Fluids. 4. 633–635. 1992.

LES sub-grid scale models – Dynamic Smagorinsky model

- In the dynamic Smagorinsky model, the subgrid-scale eddy viscosity is computed as follows,

$$\nu_{SGS} = C_s\left(\mathbf{x}, t\right)\Delta^2\left|\overline{\mathbf{S}}\right|$$

- The use of the second filter leads to the so-called subtest-scale stresses,

$$\tau_{ij}^{ST} = \widehat{\overline{u_i u_j}} - \hat{\bar{u}}_i \hat{\bar{u}}_j$$

- The subtest-scale stresses are related to the SGS stresses via the Germano identity [1] as follows,

$$\hat{L}_{ij} = \tau_{ij}^{ST} - \hat{\tau}_{ij}^{SGS} = \widehat{\bar{u}_i \bar{u}_j} - \widehat{\bar{u}}_i \widehat{\bar{u}}_j$$

- Where $\hat{L}_{ij}$ denotes the Leonard stresses associated with the test filter.
- It represents the contribution to the Reynolds stresses by the scales whose length is contained between the filter width Δ and the test filter width $\hat{\Delta} = 2\Delta$.

[1] M. Germano. Turbulence: the filtering approach. J. Fluid Mech. Vol. 238. 1992

LES sub-grid scale models – Dynamic Smagorinsky model

- If we express the subtest-scale stresses and SGS stresses using the eddy viscosity approach, we obtain,

$$\hat{L}_{ij} - \frac{\delta_{ij}}{3} L_{kk} = -2 C_s M_{ij}$$

- Where

$$M_{ij} = \hat{\Delta}^2 \left| \hat{\bar{S}} \right| \hat{\bar{S}}_{ij} - \widehat{\left[\Delta^2 \left| \bar{S} \right| \bar{S}_{ij} \right]}$$

- At this point, C_s can be computed using the least-squares minimization proposed by Lilly [1],

$$C_s\left(\mathbf{x}, t\right) = -\frac{1}{2} \frac{L_{ij} M_{ij}}{M_{ij}^2}$$

[1] D. K. Lilly. A Proposed Modification of the Germano Subgrid-Scale Closure Model. Physics of Fluids. 4. 633–635. 1992.

LES sub-grid scale models – The WALE model

- An alternative to the Smagorinsky model is the Wall-Adaptive Local Eddy (WALE) viscosity model [1].
- This model is designed to overcome many of the deficiencies of the Smagorinsky model without adding significant new complexities.
- In this model, subgrid-scale eddy viscosity is computed as follows,

$$\nu_{SGS} = (C_W \Delta)^2 \frac{\left(S_{ij}^d S_{ij}^d\right)^{3/2}}{\left(\bar{S}_{ij}\bar{S}_{ij}\right)^{5/2} + \left(S_{ij}^d S_{ij}^d\right)^{5/4}}$$

- Where S_{ij}^d (filtered velocity gradient tensor) is defined as follows,

$$S_{ij}^d = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_k}\frac{\partial \bar{u}_k}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_k}\frac{\partial \bar{u}_k}{\partial x_i}\right) - \frac{1}{3}\delta_{ij}\frac{\partial \bar{u}_k}{\partial x_l}\frac{\partial \bar{u}_l}{\partial x_k}$$

- And C_W is the model coefficient, which values can go anywhere between 0.3 to 0.6.

[1] F. Nicoud, F. Ducros. Subgrid-scale stress modelling based on the square of the velocity gradient tensor. Flow, Turb. Combustion, 62. 1999.

Final remarks

- A very good alternative to the Smagorinsky model is the WALE model.
- The WALE model (Wall-Adaptive Local Eddy Viscosity model), overcomes many of the drawbacks of the Smagorinsky model and retains its simplicity.
- The WALE model predicts accurately the flow near the walls. It also predicts transition.
- But again, the model constants (or coefficients) can depend on the flow conditions.
- Dynamic models where the Smagorinsky coefficient is dynamically computed in function of space and time offer superior performance, but at a slightly higher computational cost.
- Some more advanced LES models introduce some transport effects by solving an equation for k and using double filtering to find out more information about the sub-grid scales (as dynamic models).
    - Clearly, this model are more expensive than the algebraic models.

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DES models

- An alternative to LES models, is the use of Detached-Eddy simulation (DES) models.
- Detached-Eddy Simulation (DES) is a hybrid technique first proposed by Spalart et al. [1] for prediction of turbulent flows at high Reynolds numbers (refer also to [2,3]).
- The development of this technique was motivated by estimates which indicate that the computational costs of applying Large-Eddy Simulation (LES) to complete configurations such as an airplane, submarine, or road vehicle are prohibitive.
- The high cost of LES when applied to complete configurations at high Reynolds numbers arises because of the resolution required in the boundary layers, an issue that remains even with fully successful wall-layer modeling.
- In Detached-Eddy Simulation (DES), the aim is to combine the most favorable aspects of the two techniques, *i.e.*, application of RANS models for predicting the attached boundary layers and LES for resolution of time-dependent, three-dimensional large eddies.
- The cost scaling of the method is then favorable since LES is not applied to resolution of the relatively smaller-structures that cover the boundary layer.

[1] P. Spalart, W. Jou, M. Stretlets, S. Allmaras. Comments on the Feasibility of LES for Wings and on the Hybrid RANS/LES Approach. AFOSR Conf. 1997.
[2] P. Spalart. Strategies for turbulence modelling and simulations. International Journal of Heat and Fluid Flow 21 (2000).
[3] K. D. Squires. Detached-eddy simulation: Current status and perspectives. Direct and Large-Eddy Simulation V. ERCOFTAC Series, vol 9. Springer, 2004.

DES models

- DES models [1], are hybrid between RANS and LES.
- In DES, RANS models are used close to the walls, and in the far field LES models are used.
- The near wall turbulence is not explicitly computed, but fully modeled.
- The mesh resolution requirements are equivalent to those of RANS/URANS.
- These models work particularly well for detached flows and external aerodynamics.
- Refrain from using DES models with internal flows.
- When using DES models, it is recommended to resolve the boundary layer as we use RANS models in this region.
- It is possible to use more stretching in the stream-wise and span-wise direction than with LES because it is not necessary to resolve eddies located in the wall region.
- In DES, it is critical to analyze the location of the LES/RANS interface. The goal is to be in RANS mode in the wall regions and in LES mode in the free flow.
- With DES we can use larger CFL numbers in comparison to LES.

[1] P. Spalart, W. Jou, M. Stretlets, S. Allmaras. Comments on the Feasibility of LES for Wings and on the Hybrid RANS/LES Approach. AFOSR Conf. 1997.

DES models

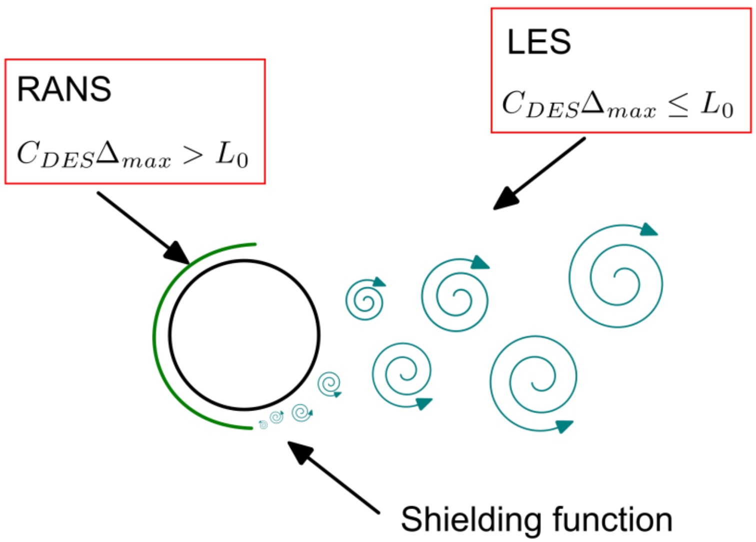
- DES models formulations are relative simple and can be built on top of any RANS model (usually Spalart-Allmaras or $k-\omega$ SST).
- In DES models the switch between RANS and LES is based on a criterion similar to,

$$C_{DES}\Delta_{max} > L_0 \rightarrow \text{RANS}$$
$$C_{DES}\Delta_{max} \leq L_0 \rightarrow \text{LES}$$

where

$$L_0 = \frac{k^{1.5}}{\epsilon} = \frac{k^{0.5}}{0.09\,\omega}$$

- In the previous equations, Δ_{max} is the maximum edge length of the local cell.



A shielding function can be used to avoid the resolved structures from entering into the boundary layer regions. This is referred to as delayed DES or DDES.

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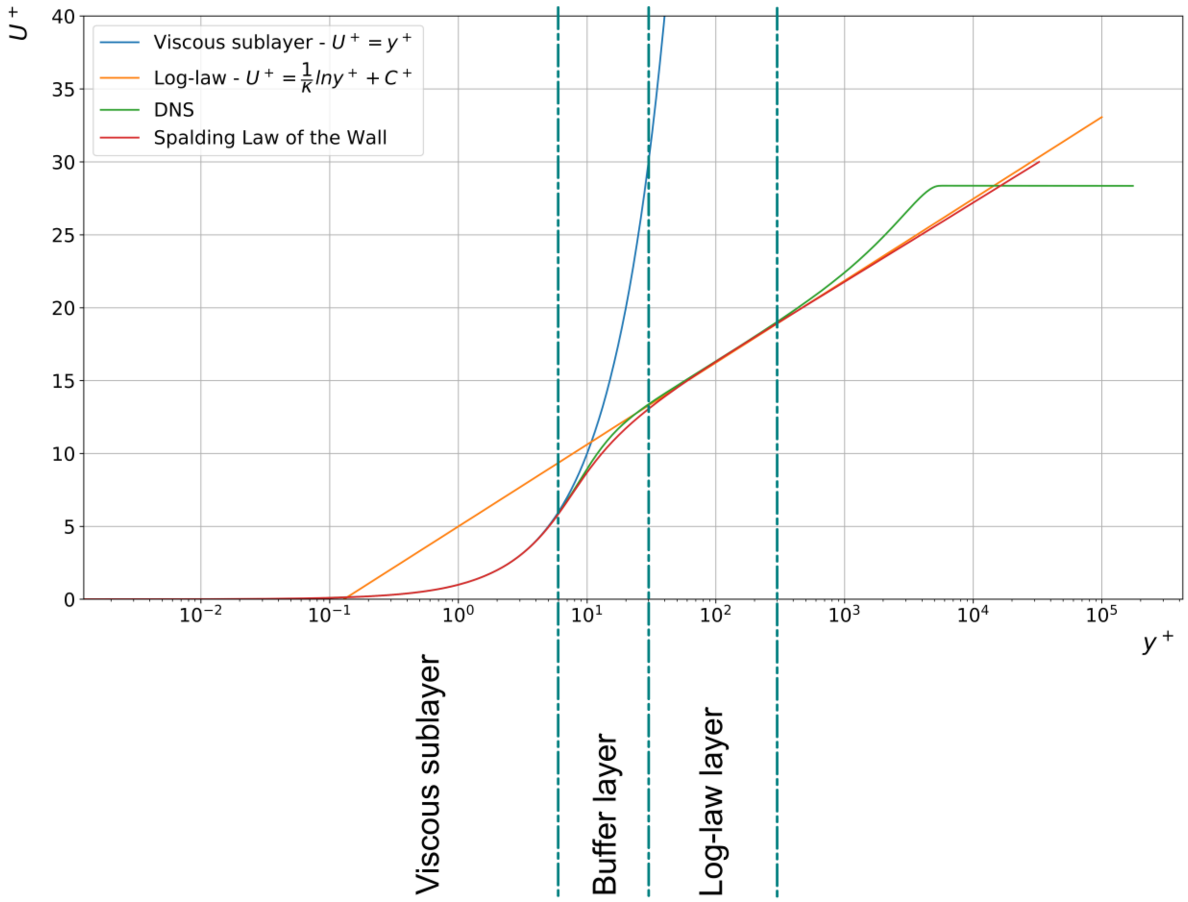
Turbulence near the wall - Law of the wall



$$y^+ = \frac{\rho \times U_\tau \times y}{\mu} = \frac{U_\tau \times y}{\nu}$$

$$U_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

$$u^+ = \frac{U}{U_\tau}$$

Where y is the distance normal to the wall, U_τ is the shear velocity, and u^+ relates the mean velocity to the shear velocity

- y^+ or wall distance units is a very important concept when dealing with turbulence modeling.
- Remember this definition as we are going to use it a lot.

y^+ wall distance units normal to the wall

- We never know a priori the y^+ value (because we do not know the friction velocity).
- What we usually do is to run the simulation for a few time-steps or iterations, and then we get an estimate of the y^+ value.
- After determining where we are in the boundary layer (viscous sub-layer, buffer layer or log-law layer), we take the mesh as a good one or we modify it if is deemed necessary.
- It is an iterative process and it can be very time consuming, as it might require remeshing and rerunning the simulation.
- Have in mind that it is quite difficult to get a uniform y^+ value at the walls.
- Try to get a y^+ <u>mean</u> value as close as possible to your target.
- Also, check that you do not get very high maximum values of y^+ (more than a 1000)
- Values up to 300 are fine. Values larger that 300 and up to a 1000 are acceptable is they do not covert a large surface (no more than 10% of the total wall area), or they are not located in critical zones.
- Use common sense when accessing y^+ value.

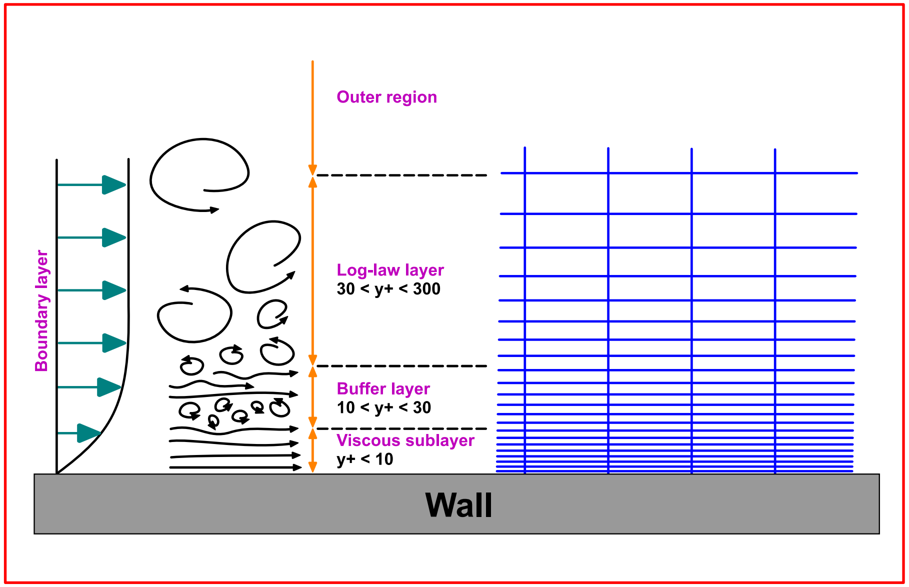
Estimating normal wall distance

- At meshing time, to estimate the normal wall distance to the first cell center, we use the well know y^+ definition,

$$y^+ = \frac{\rho \times U_\tau \times y}{\mu} = \frac{U_\tau \times y}{\nu}$$

- Where we set a target y^+ value and then we isolate the quantity y (normal wall distance to the first center). This will be distance that we will use when generating the boundary layer mesh.

- So if you choose a low y^+, you will have a mesh that is clustered towards the wall. And if you choose a large y^+ value, you will have a coarse mesh towards the walls.



Estimation of y^+

- At meshing time, to estimate the normal distance from the wall to the first cell center, we use the well-known y^+ definition,

$$y^+ = \frac{\rho \times U_\tau \times y}{\mu} = \frac{U_\tau \times y}{\nu}$$

- The problem is that at meshing time we do not know the value of the shear velocity,

$$U_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

- So, how do we get an initial estimate of this quantity?

Estimation of y^+

- At meshing time, to estimate the normal distance from the wall to the first cell center, you can proceed as follows,

1. $$Re = \frac{\rho \times U \times L}{\mu}$$

Compute the Reynolds number using the characteristic length of the problem.

2. $$C_f = 0.058 \times Re^{-0.2}$$

Compute the friction coefficient using any of the correlations available in the literature. There are many correlations available that range from pipes to flat plates, for smooth and rough surfaces.

This correlation corresponds to a smooth flat plate case, ideal for external aerodynamics.

3. $$\tau_w = \frac{1}{2} \times C_f \times \rho \times U_\infty^2$$

Compute the wall shear stresses using the friction coefficient computed in the previous step.

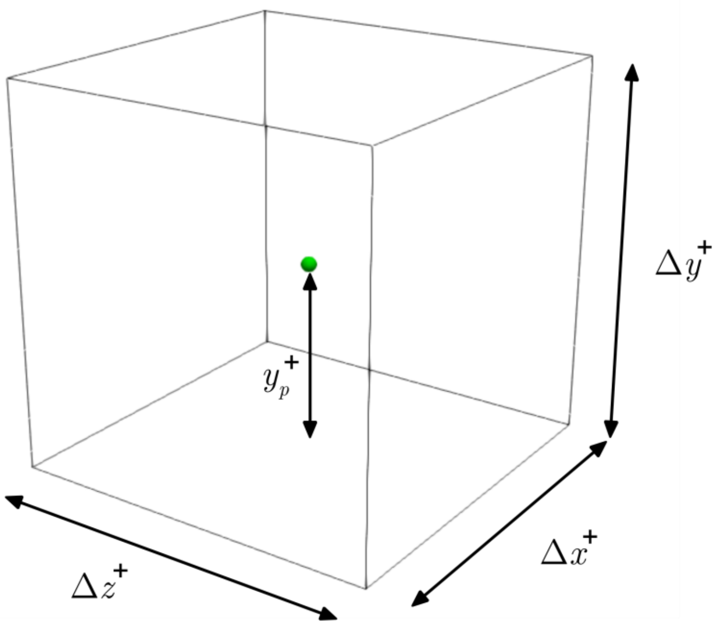
4. $$U_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

Compute the shear velocity using the wall shear stresses computed in the previous step.

5. $$y = \frac{\mu \times y^+}{\rho \times U_\tau}$$

Set a target y^+ value and solve for y using the flow properties and previous estimates.

Wall distance units x⁺ – y⁺ – z⁺



- Similar to y^+, the wall distance units can be computed in the stream-wise (Δx^+) and span-wise (Δz^+) directions.
- The wall distance units in the stream-wise and span-wise directions can be computed as follows:

$$\Delta x^+ = \frac{U_\tau \Delta x}{\nu} \qquad \Delta z^+ = \frac{U_\tau \Delta z}{\nu}$$

- And recall that y^+ is computed at the cell center, therefore:

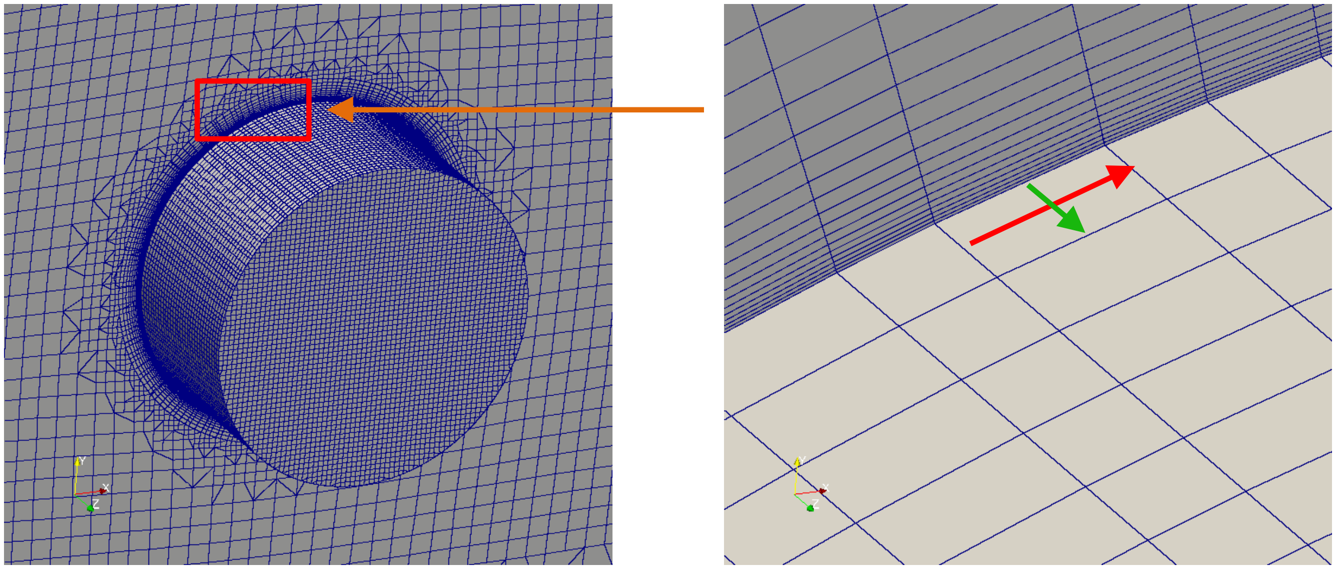
$$\Delta y^+ = 2 \times y^+$$

$$(\Delta x^+, \Delta y^+, \Delta z^+) = \left(\frac{x}{l_\tau}, \frac{y}{l_\tau}, \frac{z}{l_\tau}\right)$$

where $l_\tau = \frac{\nu}{U_\tau}$

Viscous length

Wall distance units and some rough estimates



- Similar to y^+, the wall distance units can be computed in the span-wise (Δz^+) and stream-wise (Δx^+) directions.
- Typical requirements for LES are (these are approximations based on different references):

$$\Delta x^+ < 50, \ \Delta z^+ < 50 \quad \text{for} \quad y^+ < 6$$

Wall resolving

$$\Delta x^+ < 4\Delta y^+, \ \Delta z^+ < 4\Delta y^+ \quad \text{for} \quad 30 \leq y^+ \leq 300$$

Wall modeling

Wall distance units and some rough estimates

- Some guidelines specific to DES meshes:
  - The mesh requirements are very similar to those of RANS meshes.
  - It is extremely important to resolve well the integral length scales.
- Some guidelines specific to LES meshes:
  - When it comes to LES meshes, it is recommended to use wall functions. Otherwise the meshing requirements are similar to those of DNS.
  - Recommended wall distance units values are,

$$\Delta x^+ < 50, \; \Delta z^+ < 50 \quad \text{for} \quad y^+ < 6$$

Wall resolving

$$\Delta x^+ < 4\Delta y^+, \; \Delta z^+ < 4\Delta y^+ \quad \text{for} \quad 30 \leq y^+ \leq 300$$

Wall modeling

- If you are doing DNS simulations, the requirements for wall distance units in all directions are in the order of 1.
- You might b able to go as high as 10 for Δx^+ and Δz^+.

LES wall functions

- As we have already mentioned, it is highly recommended to use wall functions with LES simulations.
- In LES simulations, it is imperative to use y^+ insensitive wall functions.
- That is, formulations that cover viscous sublayer, buffer region, and log-law region.
- This can be achieved by using a blending function between the viscous sublayer and the log-law layer [1].
- Kader [1] proposed the following blending function to obtain a y^+ insensitive formulation,

$$u^+ = e^{\Gamma} u^+_{lam} + e^{1/\Gamma} u^+_{turb}$$

$$\Gamma = -\frac{a\left(y^+\right)^4}{1+by^+} \qquad a = 0.01 \qquad b = 5$$

- This formula guarantees the correct asymptotic behavior for large and small values of y^+ and reasonable representation of velocity profiles in the cases where y^+ falls inside the buffer region.

[1] B. Kader. Temperature and Concentration Profiles in Fully Turbulent Boundary Layers. 1981.

LES wall functions

- Another y^+ insensitive wall function is the Spalding's law [1].
- This is maybe the most known *"universal"* velocity profile, which is essentially a fit of the laminar, buffer and logarithmic regions of the boundary layer,

$$y^+ = u^+ + \frac{1}{E}\left[e^{\kappa u^+} - 1 - \kappa u^+ - \frac{1}{2}\left(\kappa u^+\right)^2 - \frac{1}{6}\left(\kappa u^+\right)^3\right]$$

where $E = 9.1$ and $\kappa = 0.42$ are constants and,

$$y^+ = \frac{y_p u_\tau}{\nu} \qquad u^+ = \frac{u_p}{u_\tau}$$

The sub-index p indicates the cell center next to the wall

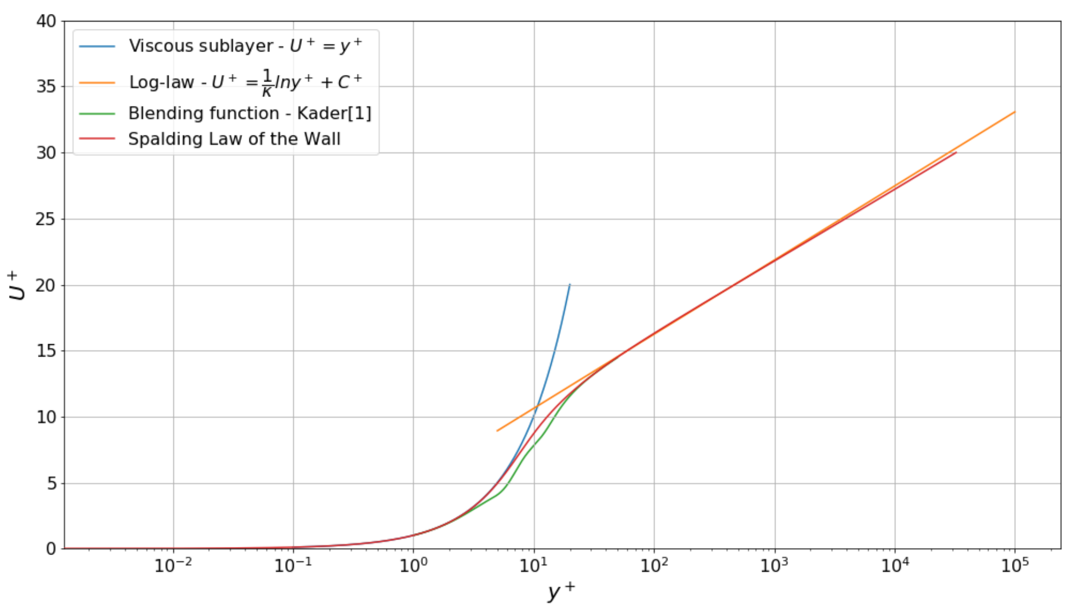
- And recall that,

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} \qquad c_f = \frac{\tau_w}{0.5\rho u_\infty^2}$$

[1] Spalding. A single formula for the law of the wall. J. of Applied Mechanics. 1961.

LES wall functions

- Plot of Kader's [1] blending function.
- In the plot, the Spalding function [2] is also represented.
- The Spalding function is another alternative to obtain a y^+ insensitive treatment.
- It is essentially a fit of the laminar, buffer and logarithmic regions of the boundary layer.



Kader's blending function,

$$u^+ = e^{\Gamma} u^+_{lam} + e^{1/\Gamma} u^+_{turb}$$

$$u^* = \begin{cases} y^* & y^* < 11.225 \\ \frac{1}{\kappa} \ln\left(E y^*\right) & y^* > 11.225 \end{cases}$$

And recall that in equilibrium conditions,

$$u^+ = u^*$$

Spalding's law,

$$y^+ = u^+ + \frac{1}{E}\left[e^{\kappa u^+} - 1 - \frac{\kappa u^+}{1!} - \frac{(\kappa u^+)^2}{2!} - \frac{(\kappa u^+)^3}{3!} - \frac{(\kappa u^+)^4}{4!}\right]$$

[1] B. Kader. Temperature and Concentration Profiles in Fully Turbulent Boundary Layers. 1981.
[2] D. Spalding. A single formula for the law of the wall. J. of Applied Mechanics. 1961.

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LES wall functions

- By substituting the know values of u_p and y_p, in the cell center next to wall, we can get an estimate of the wall shear using y^+ insensitive wall functions.
- Depending on the formulation (y^+ or y^*), a small implicit system must be solved in an iterative way in order to compute the friction velocity.
- The major advantage of y^+ insensitive wall functions, is that the first cell center next to the wall can be placed in the buffer or viscous layer without loss of accuracy associated to logarithmic profiles.
- That is, the LES model is y^+ insensitive.
- LES wall functions are valid across the whole boundary layer (even in the buffer layer), and for values $y^+ < 300$
- Remember, grid requirements for wall resolving LES are similar to those of DNS simulations.

Short description of some LES turbulence models

Model	Short description
Smagorinsky	Simple algebraic model (0-equations). Because of its simplicity and low computational cost it is widely used. It is not a particularly good choice for wall-bounded flows, but for flows far from solid boundaries it can be quite adequate. The model constants can depend on the flow conditions. This model is a good starting point for complex simulations.
Smagorinsky-Lilly	Simple algebraic model (0-equations). Because of its simplicity and low computational cost it is widely used. It overcomes some of the limitations of the Smagorinsky model by using damping functions in near-wall regions, therefore, it works better with wall-bounded flows. The model constants can depend on the flow conditions.
Wall-Addaptive Local Eddy Viscosity model (WALE)	Simple algebraic model (0-equations). Retains the simplicity and low computational cost of of the Smagorinsky model. Wall damping effects are accounted for without using the damping function explicitly. It predicts accurately the flow near the walls and transition. The model constants can depend on the flow conditions.
Dynamic Smagorinsky	This model is based on the similarity concept and Germano's identity. It is more universal because the constants are computed dynamically. The model predicts accurately the wall behavior, transition, and allow energy backscatter. The computation of dynamic constants requires additional computational power and fluctuations while computing the constant can cause stability issues.
Dynamic Kinetic Energy Transport	This model overcomes some of the limitations of the Smagorinsky-Lilly and dynamic Smagorinsky models. It solves an additional transport equation for the subgrid scale kinetic energy. The model predicts accurately the wall behavior, transition, and allow energy backscatter, it also allows for history of the kinetic energy. It is more computational expensive as it solve an additional equation and it performs explicit filtering.

Final remarks on LES/DES turbulence models

A few acronyms that you will find while working with DES and LES models

- **LES**: large eddy simulation (it resolves 80% of the energy spectrum).
- **VLES**: very large eddy simulation (it resolves 50% of the energy spectrum).
- **LES-NWR**: LES with near wall resolution (it resolves the boundary layer).
- **LES-NWM**: LES with near wall modelling (it uses wall functions).
- **DES**: detached eddy simulation (hybrid RANS-LES).
- **DDES**: delayed DES (DES with shielding functions).
- **DDES-SA**: DDES or DES based on the Spalart-Allmars RANS model.
- **DDES-SST**: DDES or DES based on the $k - \omega$ SST RANS model.
- **ALES**: adaptive LES (LES with adaptive mesh refinement).
- **SGS**: subgrid scales
- **HRM**: high Reynolds part of the boundary layer (logarithmic layer).
- **LRN**: low Reynolds part of the boundary layer (viscous layer).

Final remarks on DES/LES turbulence models

- The mesh requirements of LES-NWR are close to those of DNS, therefore, it is highly recommended the use of wall functions.
- LES wall functions are valid in the whole boundary layer (including the buffer region).
- Remember, DES/LES methods are intrinsically 3D and unsteady.
- LES simulations are very sensitive to mesh element type; it is highly recommended to use hexahedral meshes.
- If you are dealing with external aerodynamics and detached flows, DES simulations are very affordable.
- In DES, as it is not necessary to resolve eddies located in the wall region, you can use coarser meshes in stream-wise and span-wise directions.
- The WALE and dynamic methods are the best LES choices. However, you can use the Smagorinsky method for simple flows or getting an initial solution.
- For LES simulations, keep the CFL below 1.
- DES simulations have more relaxed time-stepping requirements, but in general you should not go above 4 (for accuracy reasons).

Final remarks on DES/LES turbulence models

- Use RANS simulations as starting point for LES/DES simulations.
- When it comes to post-processing SRS simulations it can be quite time consuming, especially if we are dealing with large meshes.
- Most of the times we are interested in computing averaged quantities, so do not forget to compute the unsteady statistics.
- Not all discretization schemes are born with LES in mind. In LES simulation we must use low dissipation and non-dispersive discretization methods (bounded schemes).
- Same applies for element type. Tetrahedral elements are not very desirable when conducting LES simulations, even if we use high-accuracy and non-dispersive methods.
- Hexes are preferred over the rest of element types. Remember, many LES filters are designed with hexes in mind.
- Low dissipation methods translate in energy preserving methods, that is, the energy spectrum should not increase (or accumulate) with large wave number (small scales).

Final remarks on LES/DES turbulence models

Wall distance units and some rough estimates

- DES and RANS simulations do not have stream-wise and span-wise wall distance units requirements as in LES simulations. Therefore, they are more affordable.
- If you are conducting DES simulations, it is highly recommended to resolved the boundary layer.
- In DES simulations you can also use wall functions.
- LES wall functions are valid across the whole boundary layer, even in the buffer layer).
- The upper limit of y^+ for LES and DES simulations should be less than 300 ($y^+ < 300$).
- Remember, it is strongly recommended to use wall functions with LES simulations. Otherwise your meshing requirements will be close to those of DNS.
- If you are doing DNS, y^+ should be close or less than 1.
- The spanwise and streamwise values should be less than 10, but ideally close to 1.

Final remarks on LES/DES turbulence models

A few mesh resolution guidelines and rough estimates

- The mesh is everything in CFD, and when it comes to turbulence modeling it is extremely important to have meshes with good quality and acceptable resolution.
- Some general guidelines for meshes to be used with RANS/DES/LES:
  - Resolve well the curvature.
  - Allow a smooth transition between cell of different sizes (at least 3 cells).
  - Identify the integral scales and try to cluster at least 5 cells in the domain regions where you expect to find the integral scales.
- Some guidelines specific to RANS meshes:
  - When it comes to RANS, the most important metric for mesh resolution is the y^+ value. Identify your wall treatment a-priory and mesh your domain according to this requirement.
  - If you are doing 3D simulations, there are no strict requirements when it comes to the span-wise and stream-wise directions, but as a general rule you can use Δx^+ and Δz^+ values as high as 300 the value of Δy^+.

Final remarks on LES/DES turbulence models

A few mesh resolution guidelines and rough estimates

- Some guidelines specific to DES meshes:
  - Close to the walls, the mesh requirements are very similar to those of RANS meshes.
  - It is extremely important to resolve well the integral length scales.
  - DES simulations are intrinsically 3D.
  - Do not use DES with internal flows.
  - Try to avoid the use of symmetry (axial and planar).

Final remarks on LES/DES turbulence models

A few mesh resolution guidelines and rough estimates

- Some guidelines specific to LES meshes:
  - When it comes to LES meshes, it is recommended to use wall functions. Otherwise the meshing requirements are similar to those of DNS.
  - It is recommended to use values in the range of $10 < y^+ < 60$. LES uses wall functions that can deal with the buffer layer.
  - In LES, it is extremely important to resolve well the stream-wise and span-wise directions. Recommended values are: $\Delta x^+ < 1000$ and $\Delta z^+ < 1000$
  - LES simulations are intrinsically 3D.
  - Try to avoid the use of symmetry (axial and planar).
  - Use hexahedral meshes.

Turbulence modeling guidelines and tips

- Compute Reynolds number and determine whether the flow is turbulent.
- Try to avoid using turbulent models with laminar flows.
- Choose the near-wall treatment and estimate y normal distance before generating the mesh.
- Run the simulation for a few time steps and get a better prediction of y^+ and correct your initial prediction of y.
- The realizable $k-\epsilon$ or $k-\omega$ SST models are good choices for general applications.
- The standard $k-\epsilon$ model is very reliable, you can use it to get initial values for more sophisticated models.
- If you are interesting in resolving the large eddies and the inertial range, and modeling the smallest eddies, DES or LES are the right choice.
- If you do not have any restriction in the near wall treatment method, use wall functions.

Final remarks on LES/DES turbulence models

Turbulence modeling guidelines and tips

- Use the default model constants unless you know what are you doing or you are confident that you have better values.
- Set reasonable boundary and initial conditions for the turbulence model variables.
- Always monitor the turbulent variables, some of them are positive bounded.
- Avoid strong oscillations of the turbulent variables.
- If you are doing LES or DES, remember that these models are intrinsically 3D and unsteady.
- In LES you should choose your time-step in such a way to get a CFL of less than 1 and preferably of about 0.5 for LES. DES simulations can use larger CFL values (up to 4 for reasonable accuracy).
- If you are doing RANS, it is perfectly fine to use upwind to discretize the turbulence closure equations.
- After all, turbulence is a dissipative process. However, some authors may disagree with this, make your own conclusions.

Turbulence modeling guidelines and tips

- On the other hand, if you are doing LES you should keep numerical diffusion to the minimum, so you should use second order methods.
- LES/DES methods can be sensitive to mesh element type, it is highly recommended to use hexahedral meshes.
- Mesh quality if of paramount importance, try to avoid bad elements near the inlets (as they can introduce numerical diffusion) or at the walls (as they can affect the boundary layer or wall functions).
- If you are doing unsteady simulations, always remember to compute the average values (ensemble average).
- Avoid the use of adaptive time-stepping and adaptive save intervals, as they may introduce oscillations in your solution.
- If you are working with combustions and aero-acoustics, you will get best results using LES models but at the cost of higher computational requirements.
- If you are dealing with external aerodynamics and detached flows, DES simulations are really affordable, and surprisingly, they give good results most of the times.

Turbulence modeling guidelines and tips

- DNS requires no modeling, but it demands high mesh resolution for the large scales all the way through at least the beginning of the dissipation scales. This requires and incredible amount of mesh cells (in the order of Re^3 or worse).
- LES requires modeling of part of the inertial subrange and into the beginning of the dissipation scales. The amount of required modeling is set by the mesh resolution that can be afforded (at worse in the order of Re^2 which is much less than the mesh resolution for DNS but still is a high requirement).
- In general, LES models are less expensive than DNS, but much more expensive than RANS/URANS.
- RANS/URANS requires modeling of everything from the integral scales into the dissipation range and only mean quantities are computed. Despite this, they perform very well.
- The hybrid method DES, model everything close to the walls and resolves all the scales in the far field (as in LES). DES methods have mesh resolution requirements between RANS and LES.
- The work-horse of turbulence modeling in CFD: RANS

Final remarks on LES/DES turbulence models

Future of Turbulence Modelling in Industrial Applications

- Many authors state that the future trends are quite clear: moving from RANS models to LES models.
- However, I politely disagree with this as many industrial applications are quite complex in order to simulate them using LES models.
- LES simulations are unattractive in industry due to the excessive amount of computational resources needed (which cost money), and the amount of time needed to get the outcomes (and time is money).
- RANS models are the work horse of industrial applications and will continue to be until a big leap in computing hardware or solution strategy happens.
- However, academia is moving slowly towards LES and new computing platforms (which hopefully will consume less energy than wind tunnels), so we are the ones responsibly for triggering that big change.
- DES simulations are starting to become more affordable and are slowly replacing URANS.
- DNS remains out of reach for all engineering use. However, it provides a very good base for model development and testing.

These statements are the author's personal opinion (J. Guerrero).