LES of Turbulent Flows: Lecture 21

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Overview

1. Boundary Conditions for LES
2. Inflow Boundary Conditions
    - Stochastic Recontruction
    - Precursor Simulations Inflow Conditions
    - Rescaling
    - Synthetic Field Generation

Boundary Conditions for LES

- Like all numerical techniques for PDEs, LES requires the specification of boundary conditions
- Lateral or inflow/outflow conditions
- Boundary conditions at solid walls (particularly interesting for LES)
- Initial conditions (for time integration) can also be an important issue for some flows (*e.g.*, decaying isotropic turbulence)

Boundary Conditions for LES

- Note: in some flows, the top (upper) boundary conditions are also important
- One common example is of the ABL when buoyancy effects are present resulting in gravity waves
- The two most common ways of dealing with this are <u>Rayleigh dampening</u>, where a sponge layer of points is defined, and <u>linear wave canceling</u> (Klemp and Durran 1983)

Boundary Conditions for LES

- We will talk about inflow boundary conditions, open (exit) boundary conditions, and boundary conditions at solid boundaries.
- Today we will focus on inflow conditions (others to come in future lectures)

Inflow Boundary Conditions

- Issues related to lateral (flow direction) BCs are not specific to LES
- In DNS, nearly identical issues are present
- In RANS (many times), this issue is not important since appropriate conditions based on mean fields are all that may be needed

Inflow Boundary Conditions

- Simplest case: **Periodic BCs**
- The idea is that what leaves the domain is returned identically
- For true boundary-layer flow (that grows in the flow direction) or flows with complex geometry, **many times we can't use periodic BCs**
- The figure on the next slide illustrates the importance of proper inflow BCs in a turbulent flow
- We will cover a few ways to deal with this (see Sagaut Ch 10.3)

Inflow Boundary Conditions

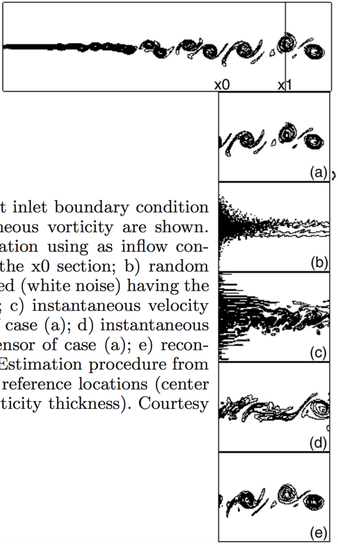
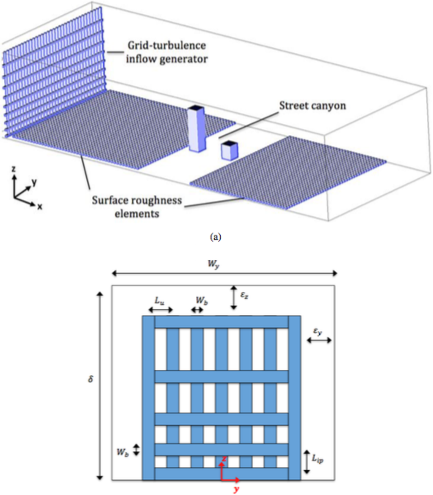


Fig. 10.16. Illustration of the influence of the turbulent inlet boundary condition (DNS of a 2D mixing layer). Iso-contours of instantaneous vorticity are shown. *Top:* reference 2D simulation. *Below:* Truncated simulation using as inflow conditions: a) exact instantaneous velocity field stored at the x0 section; b) random velocity fluctuations spatially and temporally uncorrelated (white noise) having the same Reynolds stress tensor components as in case (a); c) instantaneous velocity field preserving temporal two point correlation tensor of case (a); d) instantaneous velocity field preserving spatial two point correlation tensor of case (a); e) reconstructed velocity field with the aid of Linear Stochastic Estimation procedure from the knowledge of exact instantaneous velocity field at 3 reference locations (center of the mixing layer and $\pm\delta_\omega/2$ where δ_ω is the local vorticity thickness). Courtesy of Ph. Druault and J.P. Bonnet, LEA.

Inflow Boundary Conditions



Example from ME Ph.D. student Arash Nemati Hayati (in review)

Inflow Boundary Conditions

Courtesy Arash Nemati Hayati (requires Adobe)

Inflow Boundary Conditions

Courtesy Arash Nemati Hayati (requires Adobe)

Stochastic Recontruction

- Deterministic information is lost when describing the flow statistically
- The idea is to generate instantaneous realizations that are statistically equivalent to the flow (*i.e.*, same statistical moments)
- Most techniques try to specify boundary conditions by adding random noises (with same statistical moments as fluctuations) to the mean profile

$$\tilde{u}(x_o, t) = \langle \tilde{u}(x_o) \rangle + u'(x_o, t)$$

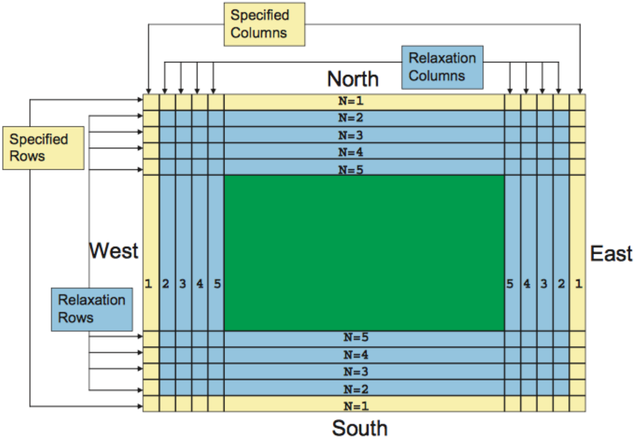
Stochastic Reconstruction

- Many of these techniques use an assumed energy spectrum combined with assumed BL profiles, or require other *a priori* knowledge of turbulence statistics of the exact flow
- See Sagaut page 356 for a list of these methods
- While energy levels and 1-pt correlations (Reynolds stresses) info is retained, 2-pt space-time correlations are not reproduced
- That means phase information is lost, which can be important for shear flows (jet, mixing layer, BL) where consistency of fluctuations is important

Stochastic Recontruction

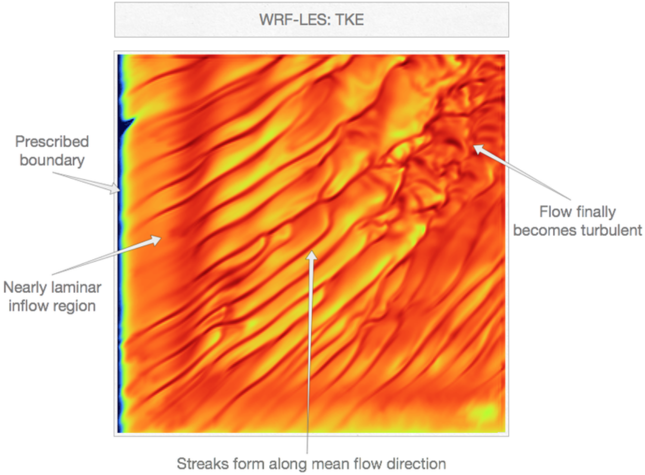
- What does this mean practically?
- There is a region in the computational domain where the flow has to regenerate the space-time consistency (a spin-up zone)
- The data here is useless and the zone can be large
- The scale of the zone is not known *a priori*, which makes locating a place of interest within the domain very hard

Stochastic Recontruction



- An example from the WRF model. Imagine a standalone domain or a nested domain within a larger domain. This is how boundaries are defined.

Stochastic Recontruction

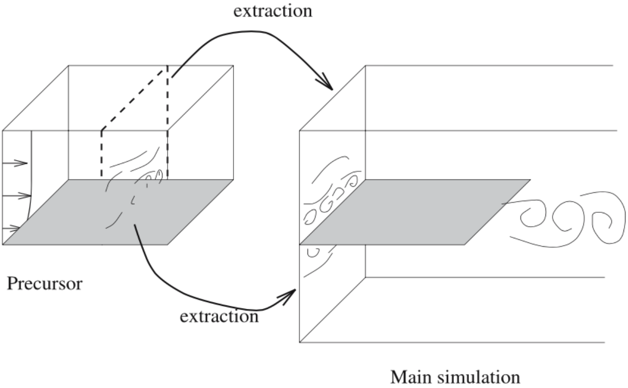


Example: LES grid nested within a large-scale WRF model run. Notice the large spin-up zone and small turbulence region.

Precursor Simulations Inflow Conditions

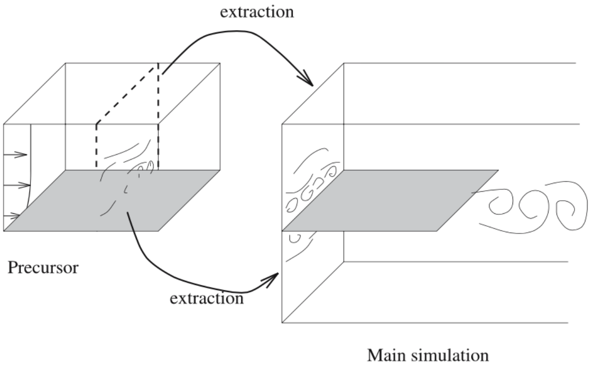
- One of the most effective ways to generate inflow conditions is to specify inflow from “homogeneous” (*e.g.*, horizontally homogeneous where we can use periodic conditions) pre-run flow simulations
- The idea is to perform a simulation of the upstream flow, called a *precursor simulation*, with a degree of resolution equivalent to that desired for the final simulation

Precursor Simulations Inflow Conditions



- From Sagaut page 362: A precursor simulation of an attached boundary layer flow is performed. An extraction plane is defined, whose data are used as an inlet boundary condition for a simulation of the flow past a trailing edge

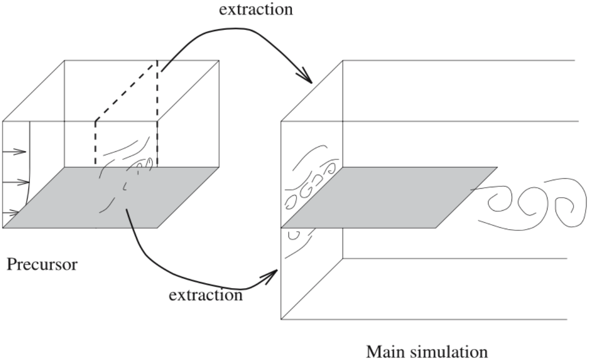
Precursor Simulations Inflow Conditions



Pros:

- Requires very few assumptions
- We don't need an "adjustment" zone (as many other techniques do)

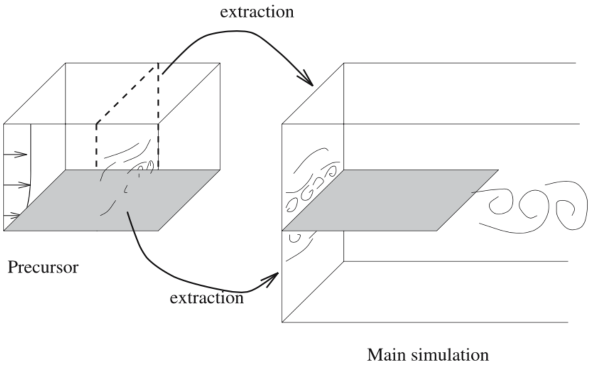
Precursor Simulations Inflow Conditions



Cons:

- Precursor simulations can be expensive (sometimes as much as the actual simulation of interest!) and they require large data storage and I/O.
- The cost is sometimes decreased through interpolation in time between different precursor time steps

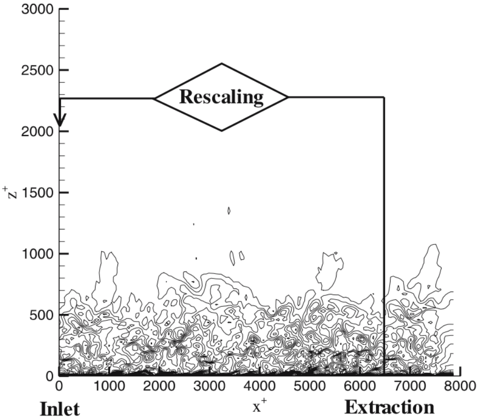
Precursor Simulations Inflow Conditions



Cons:

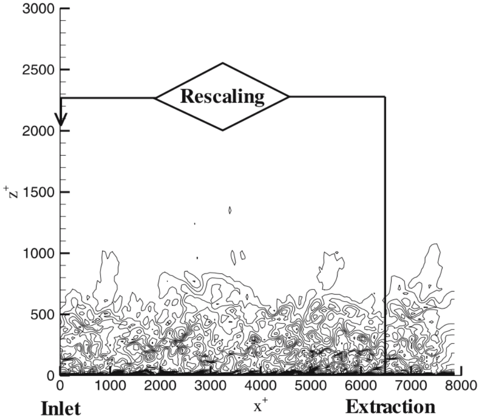
- There is no feedback of information from the 2nd simulation since the precursor is computed separately (*i.e.* 1-way feedback)
- This can be an issue when a signal (*e.g.*, acoustic wave) is emitted by the 2nd

Rescaling



- The flow from a downstream location, separated from the inflow enough to be considered independent is scaled (using known flow properties) to become the new inflow. Avoids need for precursor simulations

Rescaling



- The flow at the extraction plane must be rescaled before being used at the inlet plane because the mean flow is not parallel (*i.e.*, the BL thickness grows)

Rescaling

Lund et al. (1998) algorithm

- Separate extracted flow into mean and fluctuating parts

$$u_i^e(\vec{x}, t) = U_i^e(y, z) + u_i'^e(\vec{x}, t)$$

- The mean component classical scalings related to the mean velocity profile of the turbulent boundary layer (see Sagaut Sect 10.2.1)
- Law of the wall

$$U^{\text{inner}} = u_\tau(x) f_1(z^+) \quad \text{where} \quad z^+ = \frac{z u_\tau}{\nu}$$

- Velocity defect law

$$U_\infty - U^{\text{outer}} = u_\tau(x) f_2(\eta) \quad \text{where} \quad \eta = \frac{z}{\delta}$$

Rescaling

Lund et al. (1998) algorithm

- These dictate that the mean velocity at the inlet must be related to the outlet by

$$U_{\text{inlet}}^{\text{inner}} = \gamma U_{\text{recycle}}(y_{\text{inlet}}^{+})$$

and

$$U_{\text{inlet}}^{\text{outer}} = \gamma U_{\text{recycle}}(\eta_{\text{inlet}}) + (1-\gamma)U_{\infty}$$

where

$$\gamma = \frac{u_{\tau,\text{inlet}}}{u_{\tau,\text{recycle}}}$$

- From this, the mean velocity can be rescaled by interpolating the mean velocity at the recycle point to the same (non dimensional) height at the inlet

Rescaling

Lund et al. (1998) algorithm

- Vertical velocity and fluctuating velocity are rescaled in a similar manner using empirical/theoretical functions
- These are then combined using

$$
\begin{aligned}
(u_i)_{\text{inlet}} = & \left[(U_i)_{\text{inlet}^{\text{inner}}} + (u_i')_{\text{inlet}^{\text{inner}}}\right]\left[1 - W(\eta_{\text{inlet}})\right] \\
& + \left[(U_i)_{\text{inlet}^{\text{outer}}} + (u_i')_{\text{inlet}^{\text{outer}}}\right] W(\eta_{\text{inlet}})
\end{aligned}
$$

where W is a weighting function that smoothly matches the profiles (tanh chosen by Lund et al 1998)

Rescaling

Caveats:

- Very efficient in practice, but must be used carefully
- The recycling plane must be far enough from the inlet to prevent spurious couplings in the computed solution – satisfied by taking a distance larger than the correlation length of the fluctuations in the streamwise direction
- Method is only valid for fully turbulent self-similar boundary layers
- Scaling laws must hold

Synthetic Field Generation

Features of turbulence we seek to match synthetically

- Spatial correlation
- Temporal correlation
- Coherent across a broad range of scales

Random noise

- see examples above, this method tends to fail as a result of unrealistic velocity fields

Synthetic Field Generation

Fourier Based Methods

- General idea is to use Fourier expansion to specify the velocity field fluctuations
- Main advantage: spatial correlations are automatically preserved/included by use of continuous basis (sine/cosine) functions
- In general, assume (1D)

$$u_x(y,t) = U_x(y) + u'(y,t) = U_x(y) + D_{\text{norm}} \sum_{i=1}^{N} a_i'(t) \cos(iky + \phi'(t))$$

where D_{norm} is a scaling factor for the domain and discretization ($1/N$ for a domain of extent 1), a_i' are the Fourier coefficients, and ϕ' are phase shift coefficients that can be used to control time correlations

Synthetic Field Generation

- Other techniques include probability of detection (POD) and filtering-based methods
- Again, these are not as widely used to due to likelihood of failure due to unrealistic velocity fields