LES of Turbulent Flows: Lecture 1

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Overview

How to contact me:

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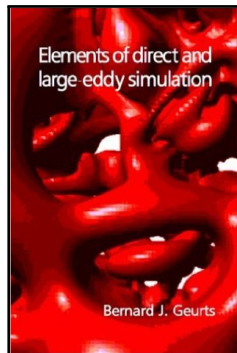- Hours: By appointment (email or stop by)

Lectures

Class schedule:

- Lectures held in WEB 1460, Tues and Thurs, 3:40p - $\sim 5{:}00$p
- We will miss a few classes due to holidays, etc.
- No class:
    - Thursday, Sept. 22
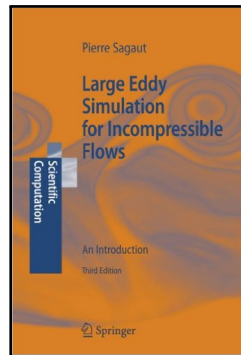   - Tuesday, October 11 and Thursday, October 13
    - Thursday, November 24

Elements of Direct and Large-Eddy Simulation
B.J. Geurts (R.T. Edwards, 2004), 329 pp.

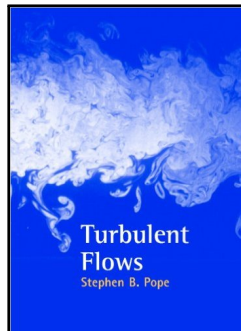**Large Eddy Simulation for Incompressible Flows**
P. Sagaut (Springer, 2000), 556 pp.

Turbulent Flows
S. B. Pope (Cambridge University Press, 2000),
771 pp.

- ME EN 5700/6700 - Fluid Dynamics
- ME EN 7710 - Environmental Fluid Dynamics
- ME EN 7720 - Turbulent Flows and Mixing

Basically, you want to be familiar with the Navier-Stokes equations of motion and the general idea of turbulence.

Grading

- Homework - 40%
- Project #1 - 25%
- Project #2 - 35%

No exams!

- This course covers topics related to Large-Eddy Simulation (LES), an advanced Computational Fluid Dynamics (CFD) technique.

- LES is quickly replacing traditional Reynolds Averaged Navier-Stokes (RANS) modeling as the method of choice for researchers and practitioners studying turbulent fluid flow phenomena in engineering and environmental problems.

Course Description

- LES explicitly solves for the larger scale turbulent motions that are highly dependent on boundary conditions, while using a turbulence model only for the smaller (and presumably more universal) motions.

- This is a distinct advantage over traditional RANS models where the effects of turbulence on the flow field are entirely dependent on the turbulence parameterizations.

Course Objectives

- Become familiar with the filtering concept in a turbulent flow and how the idea of scale separation forms the basis for LES.

- Gain familiarity with the filtered forms of the conservation equations (e.g., mass, momentum, turbulent kinetic energy), how they are derived, and how the different terms in the equations can be interpreted.

- Obtain a basic working knowledge of common subgrid-scale (SGS) parameterizations used in LES of turbulent flows.

- Understand how to carry out *a priori* analysis of SGS models from experimental and Direct Numerical Simulation (DNS) data sets.

- Understand common techniques for *a posteriori* evaluation of SGS models and what conditions are necessary and sufficient for a "good" SGS model.

- Become familiar with LES SGS models and techniques used in specific flow cases of interest (e.g., isotropic turbulence, high-Reynolds number boundary layers, turbulent reacting flows, etc.)

Course Outline

- Intro and motivation
- Analysis tools
- Turbulence and scale separation
- Equations of motion
- Filtering
- Filtered equations of motion
- Approaches to turbulence modeling
- Numerics and LES
- Basic SGS models
    - eddy viscosity
    - similarity
    - nonlinear
    - mixed
    - dynamic models

Course Outline

- Using Fourier methods to simulate isotropic turbulence (Project #1)
- Evaluating LES (*a posteriori*)
- Evaluating SGS models (*a priori*, Project #2)
- Special Topics in LES (cover some set of the following examples)
  - Boundary and initial conditions
  - Anisotropic models
  - Probability based methods
  - Lagrangian particle models
  - LES of compressible and/or reacting flows
  - LES case studies of interest

Homework

What to expect:

- Approximately 3 homework assignments will be given during the semester.

- These assignments will focus on basic topics and ideas that will be needed in the projects (statistics of turbulence, filtering, power spectra estimation, model formulations, etc.).

- The assignments will be given throughout the semester when material is covered with an emphasis on the time period *before* the 1st project.

Homework

Homework #1
- Topics: Statistics, turbulence, spectra
- Assigned: Thursday, August 23
- Due: Thursday, September 15

Homework #2
- Topics: 3D spectra from DNS data
- Assigned: Thursday, September 15
- Due: Thursday, October 6

Homework #3
- Topics: SGS modeling
- Assigned: Thursday, October 6
- Due: Thursday, October 27

Project #1

- Topic: *a posteriori* study
- Assigned: Tuesday, October 25
- Due: Tuesday, November 22

The application of LES SGS models in 3D turbulence simulations. Students will be provided a basic 3D numerical code which they will add their own SGS models to and will then examine the effect of base model type, model coefficient specification, and grid resolution on the resolved simulated velocity fields. The project will be submitted in the form of a short report (~ 4 pages) outlining the basics of the simulation code used, the chosen SGS models, and the results of parameter studies.

Project #2

- Topic: *a priori* study
- Assigned: Tuesday, November 1 or 8
- Due: Thursday, December 8

Project #2

Doing *a priori* analysis of LES SGS models from experimental or numerical data. Data sets from various experimental setups (high speed turbulence sensors, PIV) or high resolution DNS will be provided for students to use in the projects based on their research interests. Alternatively, if students have appropriate data sets (experimental or numerical) that they wish to use for their project they will be free to do so. The project will be submitted in the form of a short report (~ 4-6 pages) including: basics and background of the SGS models to be tested, a short description of the data set used in the analysis, and a short summary of key results/insights gained from the tests. In addition to the project report, all students will be required to give a short presentation (~ 15 minutes) during the last weeks of class.

Elements of Direct and Large-Eddy Simulation
B.J. Geurts (R.T. Edwards, 2004), 329 pp.

A readable book covering everything from turbulence theory to
LES subgrid scale models and numerical techniques. It contains
mostly incompressible flow with some applications to compressible
flow. While not as complete as some other books (measured by the
number of different methods), this is a nice first book to go over.

Large Eddy Simulation for Incompressible Flows
P. Sagaut (Springer, 2000), 556 pp.

Not really an introduction but more of a nice reference for LES
SGS model techniques. It contains some turbulence theory but its
best information is on filtering and SGS models. Probably the
most complete collection of SGS models in any one place. It can
be a difficult read due to the effort to include so many references.

Turbulent Flows
S. B. Pope (Cambridge University Press, 2000), 771 pp.

This book is not strictly speaking a book on LES. It is a book about incompressible turbulent flows that contains a very nice section on modeling. The modeling section includes a chapter on LES. The inclusion of general turbulence theory and LES together makes this book an ideal companion for texts that focus on LES and many times give brief or incomplete descriptions of the turbulent flow phenomena and mathematics the models are based on. Two related examples are isotropic turbulence theory (e.g., Kolmolgorov's hypothesis) and spectral analysis, both of which Pope gives excellent descriptions of.

LES Books

Mathematics of Large Eddy Simulation of Turbulent Flows
Berselli, Iliescu, and Layton (Springer, 2005), 348 pp.

This book is a nice text on LES focused on the mathematics of
LES. It is written in the style of a math text book (complete with
theorems, Lemmas, proofs and remark statements throughout the
text). The mathematical viewpoint makes several sections very
strong (including those related to filtering and approximate
deconvolution) but at the same time makes the text a somewhat
incomplete viewpoint of LES. For example phenomenological
modeling strategies are not discussed. Some very important
developments (e.g., dynamic modeling) are also missing from the
textbook.

LES Books

Large-Eddy Simulations of Turbulence
Lesieur, Metais, and Comte (Cambridge University Press, 2005),
219 pp.

This is a shorter compact text on LES. Of the textbooks listed
here, it contains one of the better descriptions of LES of
compressible flow. It is also one of the better references for
EDQNM (eddy-damped quasi-normal Markovian) theory, spectral
LES, and structure function based SGS models. It is also the only
text listed that explicitly discusses LES and atmospheric flows
(although not in great detail).

Implicit Large Eddy Simulation
Grinstein, Margolin, and Rider (Cambridge University Press, 2007),
546 pp.

This book is a collection of papers on implicit LES techniques.
The papers are logically chosen to give the reader a good overview
of the development and motivation of this technique. This book is
a nice starting point for a researcher interested in using ideas from
those working in implicit LES. The first 2 chapters give a nice
introduction to the technique and the motivations and historical
developments.

**Large Eddy Simulation of Complex Engineering and
Geophysical Flows**
Galperin and Orszag (Cambridge University Press, 2010), 624 pp.

One of the first comprehensive books on LES, this book is a
collection of chapters from different authors chosen and arranged
in a logical way to include a wide range of topics starting at a
basic level with an introduction to SGS modeling and a historical
overview of the development of LES and then moving into specific
topic areas in geophysics and engineering. It includes several nice
papers on building-block ("canonical" type) flows.

Large Eddy Simulation of Turbulent Incompressible Flows
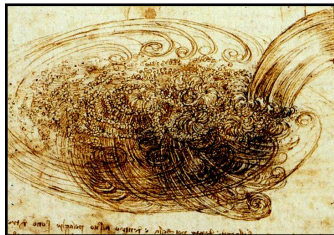Volker (Springer, 2004), 261 pp.

A mathematically minded text this book contains a lot of information. It takes a similar approach to Berselli et al. (2006) but is harder to read. Its organization has more of a class notes feel than a well developed text. One unique feature is that it does contain a chapter devoted to testing many of the models discussed in the text in actual flows (2D and 3D mixing layers).

Leonardo da Vinci and Turbulence

- Lived from 1452–1519.
- First to attempt scientific study of turbulence (*turbolenza*).
- He pioneered the notion of flow visualization to study turbulence.

Leonardo da Vinci and Turbulence

He let water flow through a square hole into a pool and observed:

> *Observe the motion of the surface of the water, which resembles that of hair, which has two motions, of which one is caused by the weight of the hair, the other by the direction of the curls; thus the water has eddying motions, one part of which is due to the principal current, the other to random and reverse motion.*

Leonardo da Vinci and Turbulence

In another, he placed obstacles in water:

> *So moving water strives to maintain the course pursuant to the power which occasions it, and if it finds an obstacle in its path it completes the span of the course it has commenced by a circular and revolving movement.*
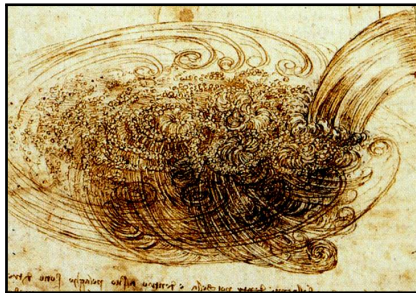
Earliest reference to the importance of vortices!

Leonardo da Vinci and Turbulence

In another, he placed obstacles in water:

> *... the smallest eddies are almost numberless, and large things are rotated only by large eddies and not by small ones, and small things are turned by small eddies and large.*

Seems to hint at Richardson's turbulent cascade!

Why study turbulence?

- Turbulence is everywhere.
- Smoke from a chimney, water flowing in a river, wind across a rough surface, flow around vehicles, combustion, solar wind.
- Most real flows in environmental and engineering applications are turbulent.
- It remains one of the great unsolved problems in physics.

Turbulence is Hard

Werner Heisenberg, maybe:

> " When I meet God, I am going to ask him two
> questions: Why relativity? And why turbu-
> lence? I really believe he will have an answer
> for the first. "

Horace Lamb, maybe:

> " I am an old man now, and when I die and go to
> heaven there are two matters on which I hope
> for enlightenment. One is quantum electrody-
> namics, and the other is the turbulent motion
> of fluids. And about the former I am rather
> optimistic. "

- **Turbulence is random**
  The properties of the fluid (ρ, P, u) at any given point (x,t) cannot be predicted. But statistical properties – time and space averages, correlation functions, and probability density functions – show regular behavior. The fluid motion is stochastic.

- **Turbulence decays without energy input**
  Turbulence must be driven or else it decays, returning the fluid to a laminar state.

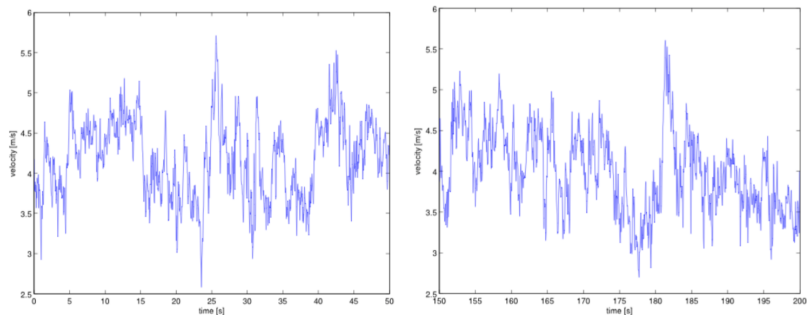- **Turbulence displays scale-free behavior**
  On all length scales larger than the viscous dissipation scale but smaller than the scale on which the turbulence is being driven, the appearance of a fully developed turbulent flow is the same.

- **Turbulence displays intermittency**
  "Outlier" fluctuations occur more often than chance would predict.
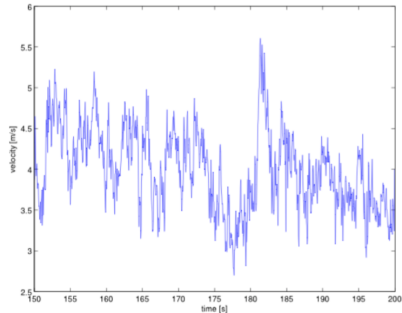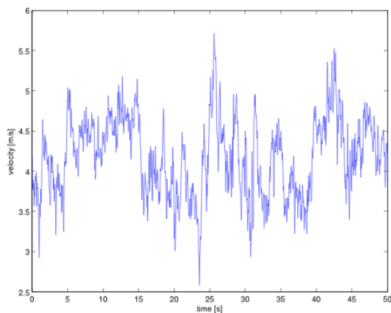
Basic Observations of Turbulence

Figure: Sonic anemometer data at 20Hz taken in the ABL.

The above figure is an example of the random nature of turbulent flows. Pope (2000) notes that using the term "random" means nothing more than that an event may or may not occur (it says nothing about the nature of the event)

Basic Observations of Turbulence

We can observe a few things from the velocity time trace:

- The signal is highly disorganized and has structure on a wide range of scales (that is also disorganized).

- The signal appears unpredictable.

- Some of the properties of the signal appear to be reproducible.

What Makes Turbulence Such a Difficult Problem?

Beyond these properties, consider turbulent flow in general.

- To understand turbulence, we must resolve the entire range of temporal and spatial scales of the flow.
- This range may be described by the Reynolds number (Re=UL/ν) – the ratio of inertia to viscous forces.
- As Re increases, the range of length scales that must be increases dramatically.

What Makes Turbulence Such a Difficult Problem?

These scales often fall outside of those conditions that are easily measured:

- high-velocities (aerodynamics)
- high-temperatures (combustion)
- hazardous substances (nuclear engineering)
- very large scales (geophysics or astrophysics)

This is why numerical simulations of turbulent flows are important!