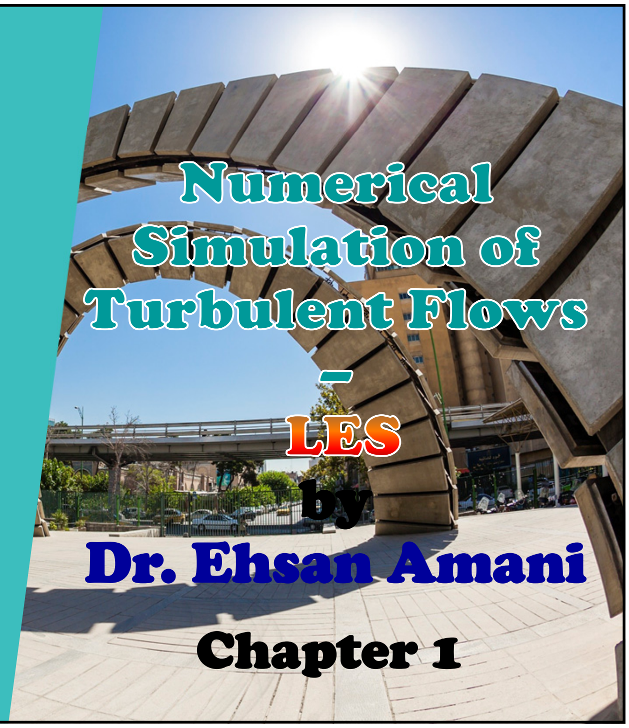


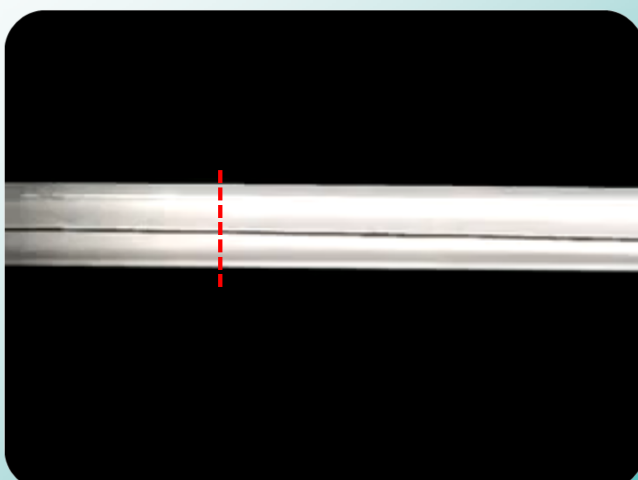
Numerical Simulation of Turbulent Flows – LES

by

Dr. Ehsan Amani

Chapter 1

Turbulence



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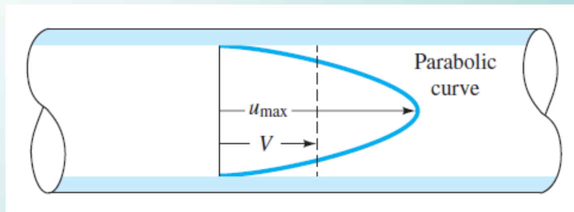
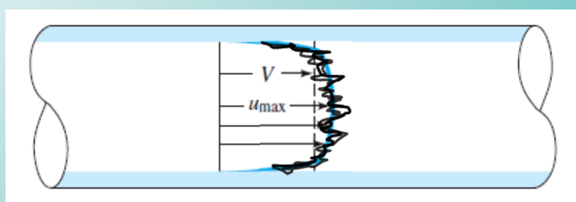
Turbulence

Laminar Flow



Turbulent Flow



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Techniques for Turbulence Simulation

Governing Equations of Fluid Mechanics

- Mass conservation
- Momentum conservation

Navier-Stokes equations

- Species transport
- Energy conservation

Scalar transport equations

Turbulence information

- The non-linear governing PDEs contains the whole information on turbulent fields.
- Accept solutions fluctuating over a wide range of scales when some parameters (e.g. *Re* number) exceeds a threshold.

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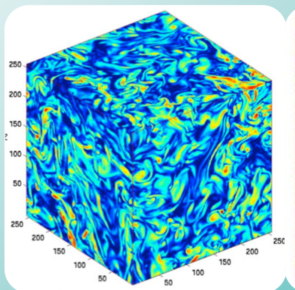
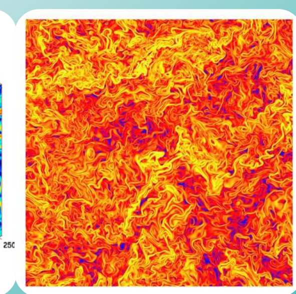
Techniques for Turbulence Simulation

DNS (Direct Numerical Simulations)

- No modeling
- Resolution of all scales
- Prohibitive computational costs
- Moderate *Re* number and simple geometries

Homogeneous isotropic turbulence ►





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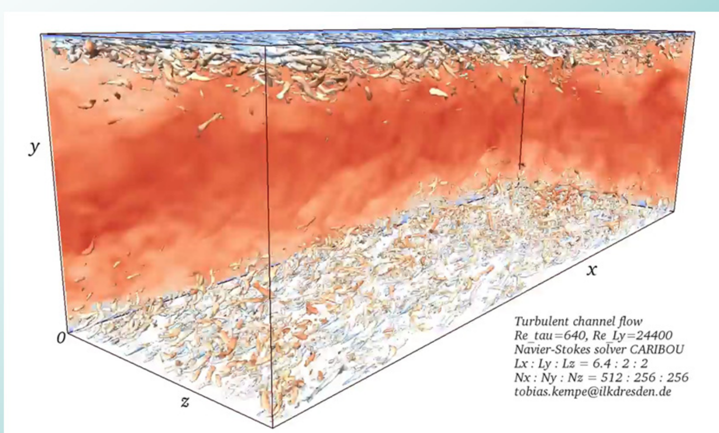
Techniques for Turbulence Simulation

DNS (Direct Numerical Simulations)



Fully developed channel flow ▲

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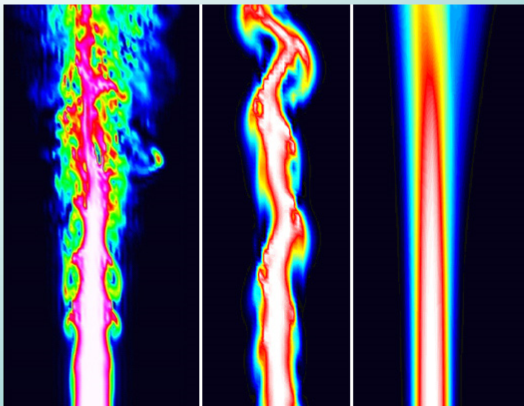
Techniques for Turbulence Simulation

Filtering (LES) and Averaging (RANS)

- Removing high-frequency fluctuations

Turbulent Flame



Experiment LES RANS

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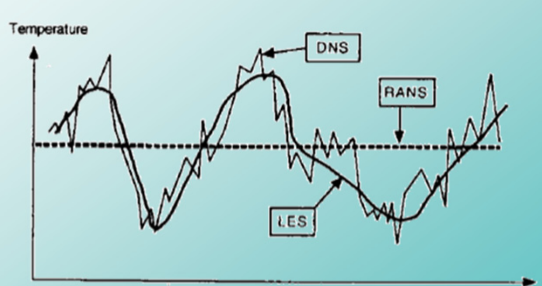
Techniques for Turbulence Simulation

Filtering and Averaging

- Physical space



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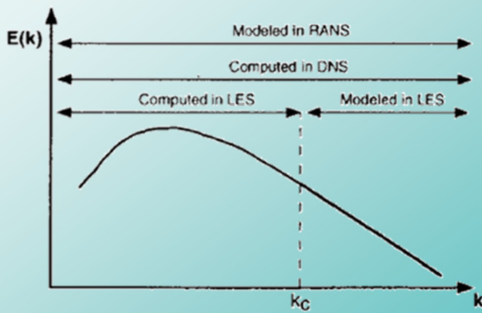
Techniques for Turbulence Simulation

Filtering and Averaging

- Spectral space



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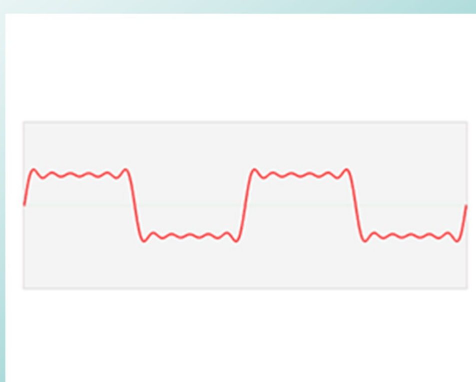
Techniques for Turbulence Simulation

Filtering and Averaging

- Spectral space



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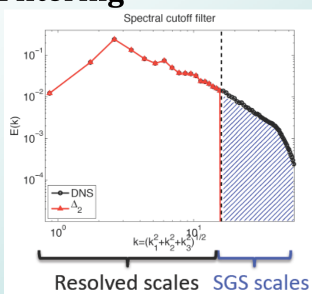
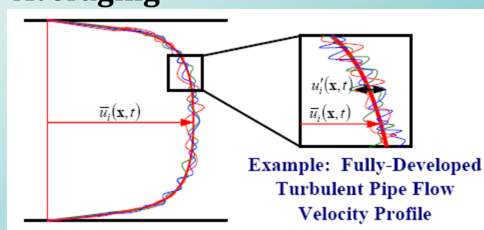
Techniques for Turbulence Simulation

Closure problem (origin)

Filtering



Averaging



+ non-linearity = closure problem

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Techniques for Turbulence Simulation

Closure problem (governing equations)

- **Mass:**

$$\frac{\partial \overline{\rho}}{\partial t}+\frac{\partial \overline{\rho}\tilde{u}_j}{\partial x_j}=0$$

- **Momentum (i =1, 2, 3):**

Reynolds stresses

$$\frac{\partial \overline{\rho}\tilde{u}_i}{\partial t}+\frac{\partial \overline{\rho}\tilde{u}_j\tilde{u}_i}{\partial x_j}=-\frac{\partial \overline{\rho}\widetilde{u_i''u_j''}}{\partial x_j}+\frac{\partial \overline{\tau}_{ij}}{\partial x_j}$$

- **Species** (N species with k=1,..,N):

$$\frac{\partial \overline{\rho}\tilde{Y}_n}{\partial t}+\frac{\partial \overline{\rho}\tilde{u}_j\tilde{Y}_n}{\partial x_j}=-\frac{\partial \overline{\rho}\widetilde{u_j''Y_n''}}{\partial x_j}-\frac{\partial \overline{J_j^n}}{\partial x_j}+\bar{\dot{\omega}}_n \qquad n=1,\ldots,N$$

- **Total enthalpy** ($ht = h + u_i u_i/2$):

$$\frac{\partial \overline{\rho}\tilde{h}}{\partial t}+\frac{\partial \overline{\rho}\tilde{u}_j\tilde{h}}{\partial x_j}=-\frac{\partial \overline{\rho}\widetilde{u_j''h''}}{\partial x_j}+\frac{\partial \overline{J_j^h}}{\partial x_j}-\sum_{n=1}^{N}h_{ref,n}\bar{\dot{\omega}}_n$$

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Techniques for Turbulence Simulation

Closure problem (modeling)

- RANS (Reynolds-Averaged Navier-Stokes equations) [stationary]
  - Eddy-viscosity models (Gradient diffusion assumption)
    - Zero-equation models
    - One-equation models
    - Two-equation models (k-ε, k-ω, …)
    - Three-equation models
    - Four-equation models (v^2-f)
    - Non-linear models
  - RSM (Reynolds Stress (transport) Model)
- LES (Large Eddy Simulation) [stationary and instationary]
- PDF (Probability Density Function) [combustion]

Techniques for Turbulence Simulation

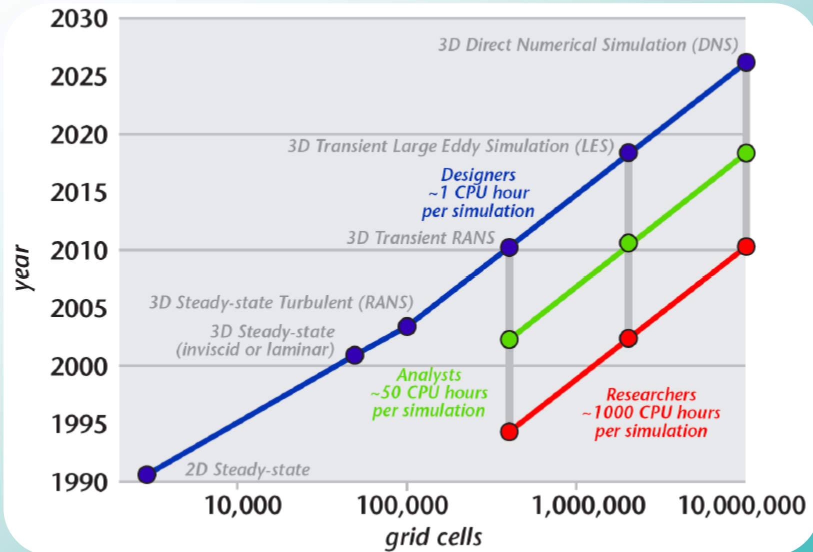
Closure problem (modeling)

- RANS
- LES
- PDF

Hybrid RANS-LES

FDF (Filtered Density Function)

Current state of LES simulations



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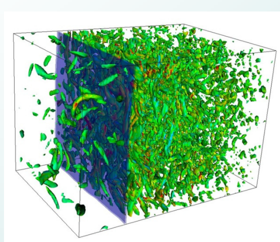
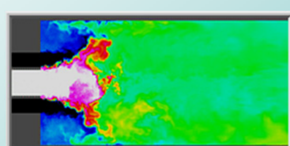
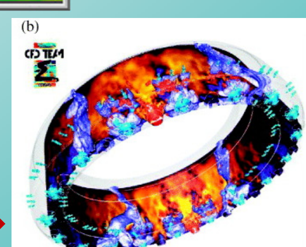
Current state of LES simulations



From homogeneous shear flows





To multi-phase flow combustion
in complex geometries

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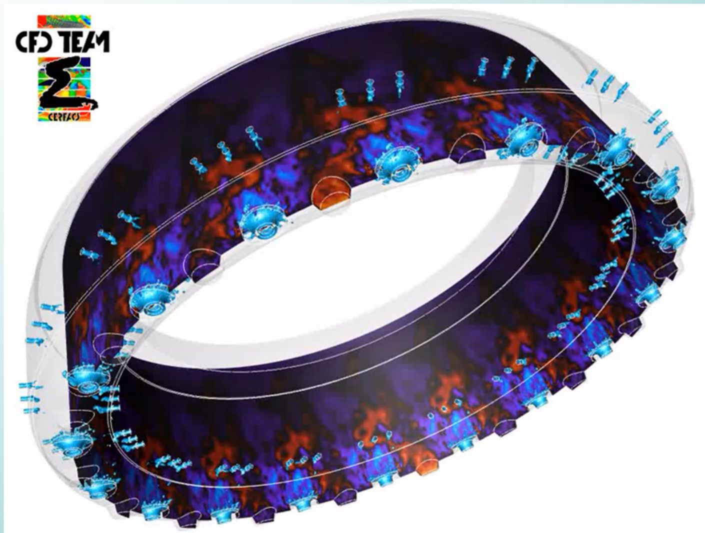
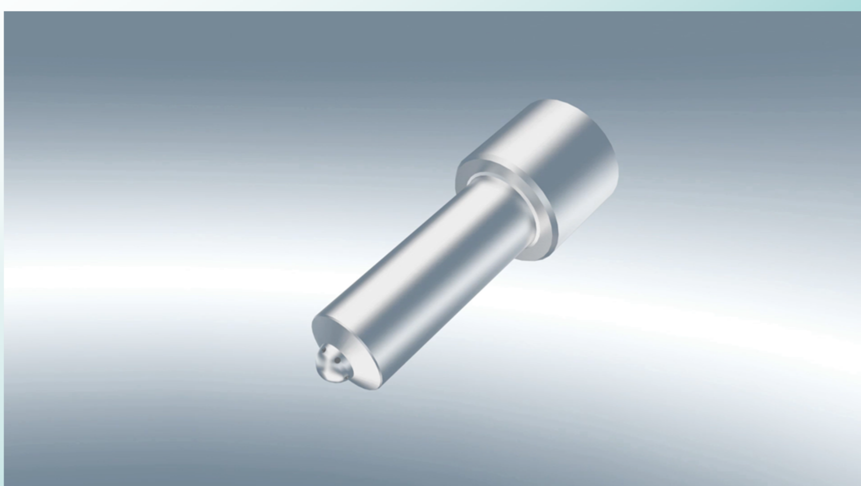
Current state of LES simulations



Ignition of a full helicopter combustor ▲

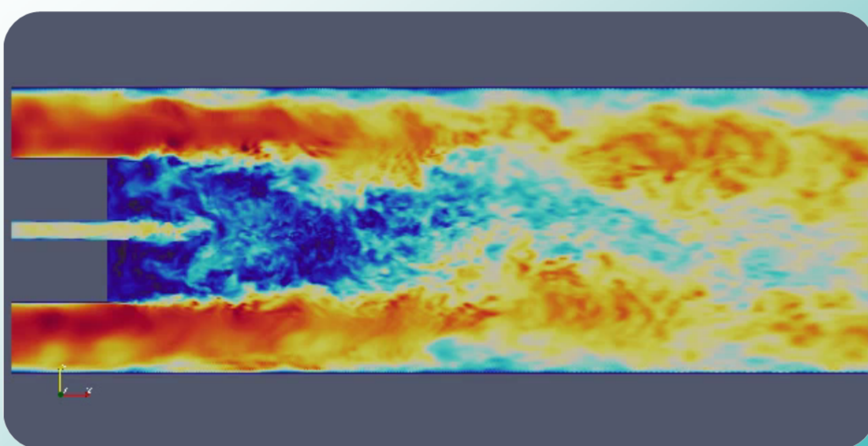
Current state of LES simulations



Spray atomization ▲

Current state of LES simulations

Chamber flow ▼



Course Outline

Turbulence

- Governing Equations (Chap II)
- Mathematical tools for studying turbulence
  - Statistical (Chap III) versus deterministic
  - Physical space (Chap V & VI) versus spectral space (Chap VII)

Turbulence Simulation

- RANS (Chap V)
- LES (Chap VI & VII) ★★★
- Introduction to PDF (Chap VIII) *