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University of Nova Gorica Graduate school, Physics

Turbulence modeling and its applications Seminar

Matej Andrejašič

Ajdovščina, 11th January 2010

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Laminar flow

streamlines are smooth and regular,

urbulent flow

- streamlines break up,
- fluid elements move in a random, irregular and torous fashion.



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- mathematical model that approximates the physical behavior of turbulent flow.
- much simpler than the full time dependent Navier-Stokes equations,
- complex enough to capture the essence of the relevant physics.

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$$\rho \frac{\partial u_i}{\partial t} + \rho \mathbf{U}_j \frac{\partial u_i}{\partial \mathbf{x}_i} =$$

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Navier-Stokes equation

$$\rho \frac{\partial u_i}{\partial t} + \rho \mathbf{U}_j \frac{\partial u_i}{\partial x_i} = -\frac{\partial p}{\partial x_i} +$$

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Navier-Stokes equation

$$\rho \frac{\partial u_i}{\partial t} + \rho \mathbf{U}_j \frac{\partial u_i}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{\partial t_j}{\partial x_i}$$

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Navier-Stokes equation

$$\rho \frac{\partial u_i}{\partial t} + \rho \mathbf{U}_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial t_{ij}}{\partial x_j}$$

Viscous stress tensor

$$t_{ij}=$$
2 μ s $_{ij}$

Strain-rate tensor

$$\mathbf{s}_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

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 $t_{ij} = 2\mu s_{ij}$

Unsteady, compressible, threedimensional viscous flow.

Strain-rate tensor

$$\mathbf{s}_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

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Mass conservation equation

$$\frac{\partial u_i}{\partial x_i} = \mathbf{C}$$

Incompressible flow.

Statistical approach

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nstantaneous velocity	Reynolds time average	
$\mu_i(\mathbf{x}, t) = U_i(\mathbf{x}, t) + \mu_i'(\mathbf{x}, t)$	$U_i(\mathbf{x}, t) = \frac{1}{\pi} \int_{t}^{t+T} u_i(\mathbf{x}, t) dt$	

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Reynolds 1895

nstantaneous velocity	Reynolds time average	
$u_i(\mathbf{x},t) = U_i(\mathbf{x},t) + u'_i(\mathbf{x},t)$	$U_i(\mathbf{x},t) = \frac{1}{T} \int_t^{t+T} u_i(\mathbf{x},t) dt$	

Time averaged equations of motion

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$ho rac{\partial U_i}{\partial t} +
ho U_j rac{\partial U_i}{\partial x_j} = -rac{\partial P}{\partial x_i} + rac{\partial}{\partial x_j} \left(2\mu S_{ij} - \overline{
ho u_j' u_i'}
ight)$$

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Time averaged equations of motion

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Reynolds-stress tensor

$$\tau_{ij} = -\overline{\rho U_i' U_i'}$$

Fundamental problem of turbulence modeling.

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Zero additional equations

Boussinesq eddy-viscosity approximation (1877)

molecular gradient diffusion process

$$y_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

 μ ... molecular viscosity μ_T ... eddy viscosity.

 \approx turbulent stress

$$au_{ij} = \mu_T \left(rac{\partial U_i}{\partial x_j} + rac{\partial U_j}{\partial x_i}
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Reynolds stress tensor

$$\tau_{ij} = \mu_T \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)$$

Boussinesq eddy-viscosity approximation.

Eddy viscosity

$$\mu_{T} = \rho I_{mix}^{2} \left| S_{ij} \right|$$

Prandtl's (1925) mixing length hypothesis.

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Imix ... mixing length

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n additional differential transport equations

Boussinesq eddy viscosity approximation: $\tau_{ij} = \mu_T \left(\frac{\partial U_i}{\partial x_i} + \frac{\partial U_j}{\partial x_i} \right)$

Prandtl (1945): eddy viscosity depends upon the kinetic energy of the turbulent fluctuations, *k*.

urbulence kinetic energy

$$k = \frac{1}{2}\overline{U'_iU'_i}$$

Eddy viscosity

$$\mu_T = constant \cdot \rho k^{1/2} I$$

$$\tau_{ii} = -\rho \overline{u_i' u_i'} = 2\rho k$$

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$$\rho \frac{\partial k}{\partial t} + \rho U_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial U_i}{\partial x_j} - \rho \epsilon + \frac{\partial}{\partial x_j} \left[(\mu + \mu_T / \sigma_k) \frac{\partial k}{\partial x_j} \right]$$

Turbulence kinetic energy dissipation per unit mass

$$\epsilon = \nu \frac{\partial u_i'}{\partial x_k} \frac{\partial u_i'}{\partial x_k}$$

Reynolds stress tensor

$$au_{ij} = \mathbf{2} \mu_T S_{ij} - rac{2}{3}
ho k \delta_{ij}$$

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Turbulence kinetic energy dissipation

 $\epsilon \propto k^{3/2}/I$

Prandtl

Eddy viscosity

$$\mu_T = \rho k^{1/2}$$

l - the only unspecified part of the one equation model

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Turbulence kinetic energy dissipation

 $\epsilon \propto k^{3/2}/I$

Prandtl

Eddy viscosity

$$\mu_T = \rho k^{1/2} I$$

l - the only unspecified part of the one equation model

Spalart and Allmaras (1992) - model equations for the eddy viscosity.

Eddy viscosity

$$\mu_{T} = \mu_{T}(\nu, \tilde{\nu})$$

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- Transport equation for turbulence kinetic energy, *k*.
- Transport equation for dissipation of turbulence kinetic energy, ϵ .

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- Transport equation for turbulence kinetic energy, *k*.
- Transport equation for dissipation of turbulence kinetic energy, ϵ .

Launder and Sharma (1974) - Standard $k - \epsilon$ model:

Eddy viscosity

$$\mu_T \propto
ho k^2/\epsilon$$

Turbulence length scale	
$I \propto k^{3/2}/\epsilon$	

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OpenFOAM - CFD

simpleFoam - steady, incompressible, viscous, threedimensional flow

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2D

■ $Re = 2.0 \cdot 10^6$

Airfoil - pressure, velocity magnitude and streamlines

Spalart-Allmaras model $k - \epsilon$ model Turbulence modeling and its applications 0.5 0.4 0 -0.4 -0.4 -0.8 0.5 0.4 0 -0.4 -0.4 -0.8 -1.2 0.8 0.4 Airfoil

Re=2.0·10⁶, $\alpha = 10^{\circ}$

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Airfoil - k and ϵ

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Turbulence kinetic energy

Dissipation of turbulence kinetic energy

Re=2.0·10⁶, $\alpha = 10^{\circ}$

 $k - \epsilon \text{ model}$



Airfoil - eddy viscosity ν_T



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$$Re=2.0\cdot10^6, \alpha=10^\circ$$

Square - pressure, velocity magnitude and streamlines



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Square - k and ϵ

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 $\underset{\textit{Re=2.0·10^{6}, \alpha = 0^{\circ}}}{\textit{k-e}}$

Turbulence kinetic energy

Dissipation of turbulence kinetic energy



Square - eddy viscosity ν_T

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 $\text{Re=2.0·10^6}, \alpha = \textbf{10}^\circ$

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Turbulence modeling - one of the greatest interests of science.

 Spalart-Allmaras model - fast, quite accurate and stable, excellent for first computation.

 $k - \epsilon$ model - quite accurate, unreliable at large pressure gradients.

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Bibliography

- Turbulence modeling one of the greatest interests of science.
- Spalart-Allmaras model fast, quite accurate and stable, excellent for first computation.
- **•** $k \epsilon$ model quite accurate, unreliable at large pressure gradients.

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