CFD for Atmospheric Flow and Wind Engineering
Wind energy applications using RANS
VKI Lecture Series

Niels N. Sørensen

Department of Wind Energy · DTU

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DTU will develop and create value using the natural sciences and the technical sciences to benefit society.
DTU Wind Energy Department

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![Organization Chart]

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  - Campus Service
  - Law & Contracts
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**WIND ENERGY SYSTEMS**
- Wind resources and siting
- Wind power integration and control
- Offshore wind energy
- Wind energy and society

**WIND TURBINE TECHNOLOGY**
- Aero-elastic design
- Structural design and safety
- Mechanical components
- Electro-technical components

**WIND ENERGY BASICS**
- Aero and hydro dynamics
- Boundary-layer meteorology and turbulence
- Light, strong materials
- Remote sensing and measurement technology
Atmospheric flow modeling
- Methods for atmospheric model verification
- Fundamental atmospheric processes
- Determination of external wind conditions for siting and design of wind turbines
Wake flow in a $5 \times 5$ turbine park computed by the Actuator Disk method
Advanced Wind Turbine Aerodynamics - modeling and exp. validation
Today we will focus on CFD applications within the area of wind turbine siting:

- Pin-pointing of rough flow conditions
- Determination of optimal turbine positions
- Determination of Annual Energy Production (AEP)
- Advanced flow physics, thermal stratification and forested terrain
What are we typically looking for

Locating rough wind conditions

The studies are typically connected to siting of wind turbines, and typically we are looking for severe flow conditions. The cases are typically ones where the linear models are insufficient.

- High levels of turbulence
- High velocity gradients
- High values of directional shear
- High flow inclination
- Recirculating flow
To determine the optimal position of wind turbines based on the available wind resources is slightly more difficult.

- The previously discussed rough conditions must be avoided
- The actual variation of the wind direction should be accounted for through a statistical description
- The optimum depend on much more than just the wind resource
What are we typically looking for

Wind Resources

Wind resources are more than just the CFD computations:

♦ The wind rose gives the frequency of a given wind sector

♦ The Weibull distribution gives the frequency of a given wind speed in a selected sector

\[ f(U) = \frac{k}{A} \left( \frac{U}{A} \right)^{k-1} \exp \left( - \left( \frac{U}{A} \right)^k \right) \]
When comparing computed results with measurements in the Atmospheric Boundary Layer (ABL), we are comparing with a time varying signal where the wind speed is changing along with the wind direction:

- Typically, a CFD simulation would be a steady-state simulation for one specific flow direction
- In reality, the statistical distribution of the wind direction and a series of computations are needed
- It is impossible to control the experimental conditions, and data will be contaminated by unwanted effects
Atmospheric flows

Solving flow in the atmosphere

There are several features characterizing flow in natural terrain, and below the most prominent are listed:

- The atmosphere is to a good approximation incompressible \((M < 0.1)\)
- High Reynolds number flows (turbulence)
- A large span of geometrical scales are involved (0-50 km)
- Complex surface geometries
- The wall boundary is nearly always rough
- Thermal stratification
- Earth rotation, Coriolis effects
- Forested terrain
Atmospheric flows

The Nature of turbulence

- Irregularity
  - Turbulence is irregular or random.

- Diffusivity
  - Turbulent flow causes rapid mixing, increases heat transfer and flow resistance. These are the most important aspect of turbulence from an engineering point of view.

- Three-dimensional vorticity fluctuations (rotational)
  - Turbulence is rotational, and vorticity dynamics plays an important role. Energy is transferred from large to small scale by the interaction of vortices's.

- Dissipation
  - Turbulent flow are always dissipative. Viscous shear stresses perform deformation work which increases the internal energy of the fluid at the expenses of kinetic energy of turbulence.

- Continuum
  - Even though they are small the smallest scale of turbulence are ordinary far larger than any molecular length scale

- Flow feature
  - Turbulence is a feature of the flow not of the fluid.
Modeling a channel flow at low Reynolds number:

\[
\begin{array}{cccccc}
Re_H & Re_\tau & N_{DNS}^3 & N_{LES}^3 & N_{RANS}^3 \\
230.000 & 4.650 & 2.1 \times 10^9 & 1.0^8 & 1.0 \times 10^4 \\
\end{array}
\]

Where:

\[
Re_\tau = \frac{u_\tau H}{2} / \nu.
\]

\[
N_{DNS}^3 \geq Re_\tau^{2.25}, \text{and } N_{LES}^3 \geq \left( \frac{0.4}{Re_\tau^{0.25}} \right) Re_\tau^{2.25}
\]

Using approximate boundary conditions, e.g. in the form of log-law conditions, these numbers can be lowered.
Reynolds averaging of the Navier-Stokes equation, splitting the velocities in the mean and the fluctuating component

\[ u_i(\vec{r}, t) = U_i(\vec{r}) + u'(\vec{r}, t) , \text{ where } U_i(\vec{r}) = \lim_{T \to \infty} \frac{1}{T} \int_t^{t+T} u_i(\vec{r}, t) \, dt \]

Inserting the Reynolds decomposed velocity in the Navier-Stokes and continuity equations

Perform time averaging of the equations. The equations are in principle time independent, or steady state.
Governing equations

**The Reynolds Averaged Navier-Stokes**

The flow equations and additional equations have the following form:

**Continuity equation:**

\[
\frac{\partial}{\partial t}(\rho) + \frac{\partial}{\partial x_j}(\rho U_j) = 0
\]

**Momentum equations:**

\[
\frac{\partial}{\partial t}(\rho U_i) + \frac{\partial}{\partial x_j}(\rho (U_i U_j + u'_i u'_j)) - \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] + \frac{\partial P}{\partial x_i} = S_v,
\]

**Auxiliary equations:**

\[
\frac{\partial}{\partial t}(\rho \phi) + \frac{\partial}{\partial x_j}(\rho (U_j \phi + u'_j \phi')) - \frac{\partial}{\partial x_j} \left[ \mu \frac{\partial \phi}{\partial x_i} \right] = S_\phi
\]
Governing equations

**Boussinesq Eddy Viscosity Approximation**

Reynolds Stresses:

\[ \rho u'_i u'_j = \frac{2}{3} \rho k \delta_{ij} - \mu_t \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) , \]

Scalar flux:

\[ \rho u'_i \phi' = -\frac{\mu_t}{\sigma_\phi} \left( \frac{\partial \phi}{\partial x_i} \right) . \]

Pressure:

\[ \frac{\partial \hat{P}}{\partial x_i} = \frac{\partial P}{\partial x_i} - \rho g . \]
To close the flow equations we need an expression for the $\mu_t$, this is typically handled by the turbulence model:

For atmospheric flow in equilibrium over flat terrain we have a very simple model:

$$
\mu_t = \rho \kappa U_t z .
$$

Typically a two equation model will be used for more complex cases, e.g., the $k-\epsilon$ or the $k-\omega$ model

$$
\mu_t = \rho C_\mu \frac{k^2}{\epsilon} .
$$

The two additional transport equations has a form similar to the previous stated general transport equation, and mainly the deviation between the models are in the source terms on the RHS.
Governing equations
The Reynolds Averaged Navier-Stokes

Continuity equation:

$$\frac{\partial}{\partial x_j}(\rho U_j) = 0$$

Momentum equations:

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial \rho U_i U_j}{\partial x_j} - \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] + \frac{\partial \hat{P}}{\partial x_i} = S_{vol},$$
Governing equations

The Reynolds Averaged Navier-Stokes

Continuity equation:

$$\frac{\partial}{\partial x_j}(\rho U_j) = 0$$

Momentum equations:

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial \rho U_i U_j}{\partial x_j} - \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] + \frac{\partial P}{\partial x_i} = Cor_i + g_i (\tilde{\rho} - \rho) + S_{vol},$$

Where:

$$Cor_i = \rho 2\Omega \sin(\lambda) \varepsilon_{ijk} e_k U_j , g_i^T = (0, 0, -G).$$

Temperature equation:

$$\frac{\partial}{\partial t}(\rho T) + \frac{\partial}{\partial x_j}(\rho U_j T) - \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\phi} \right) \frac{\partial T}{\partial x_i} \right] = S_T$$
Governing equations

Turbulence modeling

\[
\frac{\partial \rho k}{\partial t} + \frac{\partial \rho U_i k}{\partial x_i} - \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] = P - \rho \epsilon .
\]

\[
\frac{\partial \rho \epsilon}{\partial t} + \frac{\partial \rho U_i \epsilon}{\partial x_i} - \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right] = C_{\epsilon 1} \frac{\epsilon}{k} P - C_{\epsilon 2} \rho \frac{\epsilon^2}{k} .
\]
Turbulence modeling

\[
\begin{align*}
\frac{\partial \rho k}{\partial t} + \frac{\partial \rho U_i k}{\partial x_i} - \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] &= P - \rho \epsilon + \mu_t g_i \frac{\partial \rho}{\partial x_i} . \\
\frac{\partial \rho \epsilon}{\partial t} + \frac{\partial \rho U_i \epsilon}{\partial x_i} - \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right] &= C_{e1} \frac{\epsilon}{k} P - C_{e2} \rho \epsilon^2 + C_{e3} \frac{\epsilon}{k} \mu_t g_i \frac{\partial \rho}{\partial x_i} .
\end{align*}
\]

\[ \ell_e \equiv \begin{cases} 
\ell_0 &= 0.00027 \frac{U_g}{f} \\
\ell_{M-Y} &= 0.075 \frac{\int_0^{\infty} z \sqrt{k} dz}{\int_0^{\infty} z \sqrt{k} dz} 
\end{cases} , \quad C_{e1}^* = C_{e1} + (C_{e2} - C_{e1}) \frac{\ell}{\ell_e} . \]

\[ C_{e3} = (C_{e1} - C_{e2}) \alpha_B \] , where :

\[
\begin{cases} 
\alpha_B = 1 - \frac{\ell}{\ell_e} & \text{if } L > 0 \\
\alpha_B = 1 - \left[ 1 + \frac{C_{e2} - 1}{C_{e2} - C_{e1}} \right] \frac{\ell}{\ell_e} & \text{if } L < 0 
\end{cases} ,
\]

\[ L = \frac{T_0}{k g} \frac{c_p u_*^3}{H_0} . \]
Computational Fluid Dynamics

Basic CFD

♦ Governing Equation
  ♦ Incompressible Reynolds Averaged Navier-Stokes eqn.
  ♦ Stratification modeled through Boussinesq approximation.
  ♦ Coriolis force.

♦ Discretization
  ♦ Order of the discretization scheme
  ♦ Computational domain, e.g. structured or unstructured terrain following coordinates

♦ Boundary Conditions
  ♦ Inflow Conditions
  ♦ Rough wall boundary conditions
  ♦ Side and outlet conditions
Computational Fluid Dynamics

Discretization Methods

- Finite Differences
  - Differential form, using Taylor Series or Polynomial Fitting
  - Structured meshes
- Finite Volume
  - Integral form, using Gauss or Divergence Theorem
  - Structured and unstructured meshes
- Finite Element
  - Integral form, using shape or weight functions
  - Structure, unstructured grids
- Other Methods
  - Spectral Methods, Smoothed Particle Hydrodynamics
For the discrete equations to be solved the following properties should be fulfilled

- **Consistency and convergence**
  - The difference between the discretized and the exact equations should become zero in the limit of infinitely small cells.

- **Stability**
  - A numerical procedure is said to be stable if it does not magnify the errors that appear in the course of the numerical solution process.

- **Conservation**
  - The numerical method should reflect the conservation property of the governing equation.

- **Boundedness and Realizability**
  - Physically non-negative quantities (density, concentration etc) must always be positive. Some convective schemes may produce nonphysical negative values on coarse and skewed computational meshes.
For the Finite Volume and Finite Difference methods, the typical solution methods are listed below:

- **Artificial Compressibility Methods**
  - Explicit Methods
  - Implicit Methods

- **Fractional Step Methods**
  - Explicit Methods
  - Implicit Methods

- **Pressure Correction Methods**
  - SIMPLE
  - PISO
  - SIMPLEC
The two fundamental things controlling the results from a numerical model, assuming that every thing is performed correctly are:

- The model equations
  - Are the model equations adequate for the present purpose etc.
- The boundary conditions
  - Boundary conditions are needed for all variables at all external boundaries of the computational domain.
  - Boundary conditions needs to represent the problem in question

In the following slides we will look at some typical boundary conditions.
The atmospheric equilibrium profile in neutral flow is the well known logarithmic profile:

\[
U(z) = \frac{u_\tau}{\kappa} \ln \left( \frac{z}{z_0} \right), \quad \mu_t = \rho \kappa u_\tau z,
\]

\[
\epsilon(z) = \frac{C_4^{\frac{3}{4}} k^{\frac{3}{2}}}{\kappa z}, \quad k(z) = \frac{u_\tau^2}{\sqrt{C_\mu}},
\]

\[
C_{\epsilon 1} = C_{\epsilon 2} - \frac{\kappa}{C_\mu^{\frac{1}{2}} \sigma_\epsilon}.
\]

Be aware that this profile do not involve any boundary layer height!
Boundary Conditions

Lateral side face boundary conditions

Often periodic or symmetry conditions are used at the cross-flow planes.

- Symmetry conditions are easy to use, but will restrain any movement across the symmetry plane.
- Symmetry conditions will limit the flow direction to one aligned with the symmetry planes.
- Periodic conditions are less restrictive on the flow, but put additional requirements on the terrain. The terrain will have to be physically periodic.
Boundary Conditions
Outflow conditions

The outflow conditions can be crucial for the computations:

- Simple fully developed flow assumptions are often used.
  - The outlet should be placed far from the area of interest
  - There should not be recirculation through the outlet
  - The terrain may have to be modified to fulfill these requirements

\[
\frac{\partial \phi}{\partial n} = 0 .
\]

The pressure will typically be extrapolated using either linear or quadratic extrapolation.

- Convective boundary conditions, will allow reversed flow through the outlet.

\[
\frac{\partial \phi}{\partial t} - U \frac{\partial \phi}{\partial n} = 0 .
\]
Wall Boundary Conditions

Most atmospheric flows deals with rough wall conditions!

In contrast to typically engineering flows, the roughness are much larger than the viscous sub-layer. The viscous sub-layer is totally ignored.

$$ U(z) = \frac{U_\tau}{\kappa} \ln \left( \frac{Z}{Z_o} \right) $$

If using commercial general purpose solver, the lack of this simple boundary conditions may be an issue.
Wall boundary conditions are given by the log-law

- The velocity boundary conditions are implemented through the friction at the wall
- The implementation assures that flow separation can be handled by evaluating the friction velocity from the turbulent kinetic energy
- The computational grid is placed on top of the roughness elements, and the actual roughness heights are ignored in connection with the grid generation
- The TKE boundary condition is an equilibrium between production and dissipation, implemented through a Von Neumann condition and specifying the production term from the equilibrium between production and dissipation
- The epsilon equation is abandoned at the wall, and instead the value of the dissipation is specified according to the equilibrium expression for dissipation
Boundary Conditions

Special needs for the wall boundary

A specialty of atmospheric flows are the spatially varying roughness height, typically reflecting the vegetation and land use.

- Grassland $\sim 5 \times 10^{-2}$ meter
- Snow or Ice $1 \times 10^{-4}$ meter
- Barren or Sparsely Vegetated $\sim 1 \times 10^{-2}$ meter
Domain size and terrain resolution:

- Typically we need to resolve a relative large area $\sim 10 \times 10 \text{ km}^2$
- We only have a limited number of grid points or cells available
- Assuming a uniform mesh with 20 meter resolution and 1000 meter high domain, we would need $\sim 12.5 \text{ million cells}$
  - This would leave us with a cell height at the wall of 10 meters which is much to coarse.
- To avoid excessive grid numbers we need to work with stretched meshes
  - For an identical mesh with stretched vertical distribution, we may lower the cell size at the wall to $\sim 0.1 \text{ meter}$ without changing the total grid number.
- Grid generation is a compromise, using the fewest number of points to have the best possible solution. Typically cell clustering will be used both horizontally and vertically.
Typically we have a problem where to specify boundary conditions, especially the external conditions (inflow, outflow, side and top boundary conditions).

Solutions:
- Make a very large domain and specify simple conditions at inlet
  - Expensive or requires a zooming grid
- Obtain the inflow conditions from external means
  - Measured values
  - Nested computations, Meso Scale Modeling
    - Compatibility issues
- Use symmetry or periodic conditions at the cross flow boundaries
  - Places requirements on the terrain behavior in the cross flow direction
  - Grid is only usable for a single flow direction
- Stratified computations will typically need transient inflow data
  - Use of periodic conditions, taking inflow inf. from inside of the domain
  - Precursor simulation
Computational domain

Typical Polar Zooming Grid

A terrain map around the area of interest is typically given:
Computational domain

Typical Polar Zooming Grid

A typically zooming grid topology is constructed
To avoid complex terrain at the outer boundaries, the terrain is smoothed far from the area of interest.
Computational domain

Typical Polar Zooming Grid

Typical grid distribution
Computational domain

Typical Polar Zooming Grid

Zoom of the final grid
Computational domain

Typical Aligned Grid Topology

A terrain map around the area of interest is typically given:
Computational domain

**Typical Aligned Grid Topology**

A typical aligned grid topology is constructed
Computational domain

**Typical Aligned Grid Topology**

A domain like the present one will result
Computational domain

**Typical Aligned Grid Topology**

To avoid complex terrain at the outer boundaries, the terrain is smoothed far from the area of interest, here periodic in the cross-stream direction.
Computational domain

Typical Aligned Grid Topology

A typical grid distribution could look like this.
Computational domain

Typical Aligned Grid Topology

A Zoom of the final grid
Computational domain
Surface Grid Construction

From linearized models there is a heritage of simple grid generation, where a horizontal distribution of the grid points are performed followed by a interpolation in a height map.
Computational domain

Surface Grid Construction

From linearized models there is a heritage of simple grid generation, where a horizontal distribution of the grid points are performed followed by an interpolation in a height map.
From linearized models there is a heritage of simple grid generation, where a horizontal distribution of the grid points are performed followed by a interpolation in a height map.
Having performed a simulation, it is necessary to have some idea of the quality of the solution:

- **Iterative Convergence**
  - Are the governing equations solved
- **Grid Convergence**
  - Are the solution on the present grid level independent of the grid resolution
- **Comparing with Measurements**
  - Do the model agree with reality
Solution Evaluation and Test Cases

Convergence of the iterative method

Are the equations solved:

\[ A_p \phi_p - \sum A_{nb} \phi_{nb} = F \]

Typically we compute the residual of the equation in each cell, using:

\[ Res = |F - (A_p \phi_p - \sum A_{nb} \phi_{nb})| \]

The sum of the residual over all cells in the computational grid is computed and compared to the starting residual.

\[ Reduction = \frac{\sum_{AllCells} Res}{\sum_{AllCells} Res_0} \]

Typically a reduction of \(1 \times 10^{-4}\) to \(1 \times 10^{-5}\) is used. The fact that the residual is only changing slightly from prior iteration is not a good measure for convergence.
Solution Evaluation and Test Cases

Grid Convergence

Is the present solution a sufficient approximation of the specified computational case?

- Often we don’t know the desired solution, and the only check is to see if the numerical model is consistent and converged.

- A typical way to do this is to do consecutive grid refinements, and verify that the solution converges towards a value with the correct decrease in error e.g. 2. order.

- This procedure will only assure that we have a solution to the numerically specified problem, given by the numerical model and the boundary conditions, not that the present problem approximate the physical problem in question.
Solution Evaluation and Test Cases

**Richardson Extrapolation**

Error Estimation:
Assuming that the discrete equation has order $P$ we can write

$$
\Phi = \phi_h + \alpha h^p + H , \epsilon_h = \alpha h^p + H
$$

Using this on two grid levels $h$ and $2h$ we can estimate the error on the fine level

$$
\epsilon_h \sim \frac{\phi_h - \phi_{2h}}{2^p - 1} , \text{here assuming a doubling of the grid size}
$$

The order of the scheme can be estimated using three grid levels:

$$
p = \log \left( \frac{\phi_{4h} - \phi_{2h}}{\phi_{2h} - \phi_h} \right) \frac{1}{\log(2)}
$$

Here we again have assumed a doubling of the grid size. The above procedure assumes that we are in the asymptotic range, where the error is dominated by the discretization error.
Here is an example of iterative convergence of our EllipSys code for five grid levels, from a series of computations on the Bolund blind comparison cases.

- The typical residual limit of $1 \times 10^{-4}$ is indicated.
- For verification the convergence is taken further.
- The velocity is shown at a position at the hill center.
### Grid Convergence

<table>
<thead>
<tr>
<th>Grid Level</th>
<th>h</th>
<th>2h</th>
<th>4h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity [m/s]</td>
<td>7.97</td>
<td>7.88</td>
<td>7.6</td>
</tr>
</tbody>
</table>

- Estimated order 1.64
- Estimated error on level one $\sim 0.5\%$

Even though the Bolund case has very complex terrain features, these are limited to a very small area $\sim 200 \times 200$ meter.
Solution Evaluation and Test Cases

The effect of the order of the method

Comparing the solution on three grid refinements, using either a second and a first order scheme, reveals the importance of using at least a second order scheme:
The figure is taken from the Bolund comparison.
Having proven that the solution is iteratively converged and grid converged we will need to confirm that the model actually agrees with the physical case in question:

- We need good experimental data
- We need well defined inflow conditions
- We need a high density of the measuring points
Conclusion

Conclusion and Outlook

We have looked into the basics of performing CFD based micro-scale ABL modeling, addressing

- Model equation, discretization, domain and grid generation.
- We have discussed how to evaluate the solution a the problem of comparing with measurements.
- We are ready to see some application of the described methodologies.
Conclusion

Presentations with applications

Applications:

- Neutral Flow:
  - Rough flow identification
  - Bolund comparison
  - Grid requirement

- Atmospheric Boundary Layer
  - Effect of Coriolis and finite BL height
  - Stratified flow, Benakanahali

- Forested terrain

- Wind farm simulations
Bolund case: Andreas Bechmann
Thermally stratified flow: Tilman Koblitz, Andrey Sogachev
Forest flow: Louis-Étienne Boudreault, Andrey Sogachev
Turbine park simulations: M. Paul van der Laan
And the remaining modeling team at DTU Wind Energy