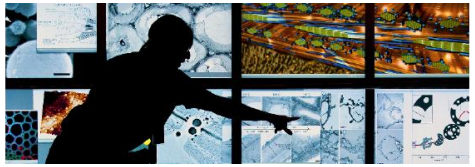
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Overview of the Simulator fOr Wind Farm Application (SOWFA)

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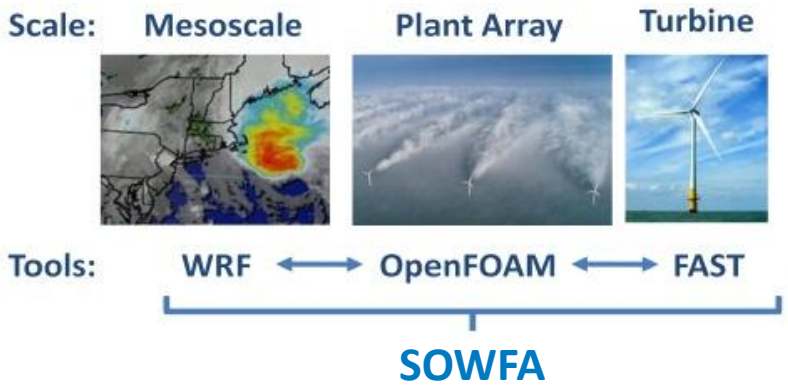
May 21, 2012

Overview of SOWFA

- Simulator fOr Wind Farm Applications
- Currently, it is composed of CFD tools based on OpenFOAM coupled with a NREL's FAST wind turbine structural/system dynamics model
- It is meant to be modular and open-source so that others can put in their own "modules"
- Open-source and freely available
- It can be downloaded at: http://wind.nrel.gov/designcodes/simulators/sowfa/

Overview of SOWFA

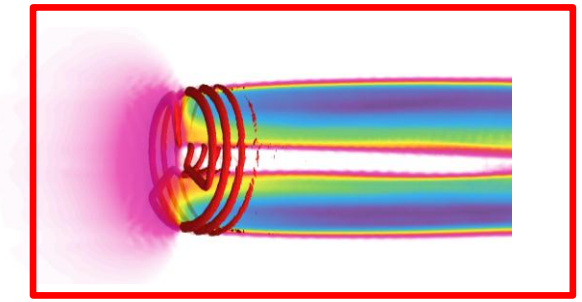
- **Simulator fOr Wind Farm Applications**
- **The overall vision is:**



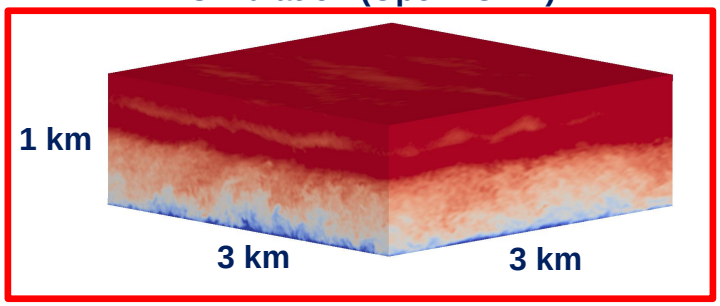
- **It will have a range of fidelity levels**
  - Wakes computed from CFD or dynamic wake meandering model
  - Inflow turbulence computed from CFD or stochastic turbulence model

Overview of SOWFA

Actuator line turbine aerodynamics models (coupled with NREL's FAST turbine dynamics model)

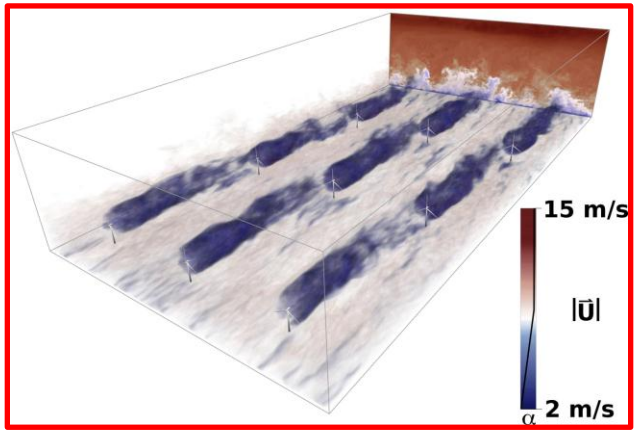


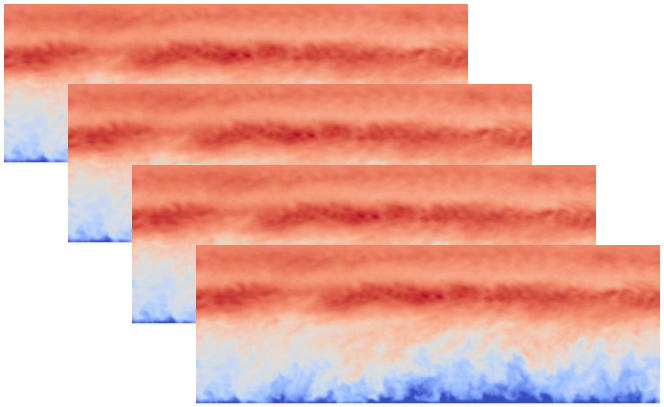
"Precursor" atmospheric simulation (OpenFOAM)



Initialize wind farm domain with precursor volume field

Wind farm simulation (OpenFOAM)





Use saved precursor data as inflow boundary conditions

Save planes of data every N time steps

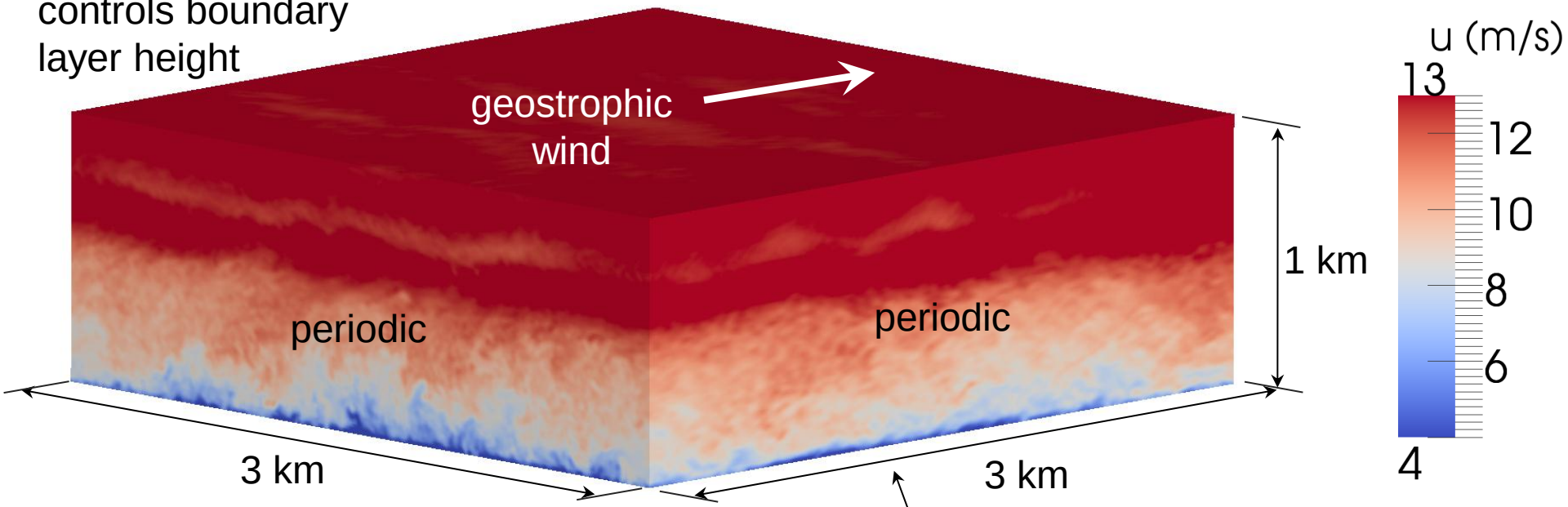
Atmospheric Boundary Layer Solver
ABLSolver and ABLTerrainSolver

Overview

ABLSolver is an atmospheric solver developed out of the buoyantBoussinesqPimpleFoam. It can be run in PISO or SIMPLE mode for either LES or RANS (or a blend). It can simulate a variety of atmospheric stabilities. We use it in LES mode to compute turbulent atmospheric precursor wind fields

capping inversion controls boundary layer height

simulation time 10000 –20000 s



Boussinesq approximation for buoyancy effects

Coriolis forces included

rough lower surface with temperature flux

Transport Equations

Momentum transport

$$\underbrace{\frac{\partial \overline{u}_i}{\partial t}}_{\text{I}} + \underbrace{\frac{\partial}{\partial x_j}\left(\overline{u}_j \overline{u}_i\right)}_{\text{II}} = \underbrace{-2\varepsilon_{i3k}\Omega_3 \overline{u}_k}_{\text{III}} \underbrace{- \frac{\partial \widetilde{p}}{\partial x_i}}_{\text{IV}} \underbrace{- \frac{1}{\rho_0}\frac{\partial}{\partial x_i}\overline{p}_0(x,y)}_{\text{V}} \underbrace{- \frac{\partial}{\partial x_j}\left(\tau_{ij}^D\right)}_{\text{VI}} \underbrace{- \frac{gz}{\rho_0}\frac{\partial}{\partial x_i}\rho_b}_{\text{VII}} + \underbrace{\frac{1}{\rho_0} f_i^T}_{\text{VIII}}$$

I. **time rate of change**
II. **convection**
III. **Coriolis force due to planetary rotation**
IV. **density-normalized pressure gradient (deviation from hydrostatic and horizontal-mean gradient)**
V. **horizontal-mean driving pressure gradient**
VI. **stresses (viscous + SGS/Reynolds)**
VII. **buoyancy**
VIII. **other density-normalized forces (from turbine actuator line model)**

Transport Equations

Momentum transport

```
fvVectorMatrix UEqn
(
    fvm::ddt(U)                                 // time derivative
  + fvm::div(phi, U)                            // convection
  + turbulence->divDevReff(U)                   // stresses (interior faces)
  + fvc::div(Rwall)                             // stresses at boundary (wall model)
  - fCoriolis                                   // Coriolis force
  + gradPd                                      // driving pressure gradient
);

UEqn.relax();

if (pimple.momentumPredictor())
{
    solve
    (
        UEqn
        ==
        fvc::reconstruct
        (
            (
              - fvc::snGrad(p_rgh)              // modified pressure gradient
              - ghf*fvc::snGrad(rhok)           // buoyancy force
            ) * mesh.magSf()
        )
    );
}
```

Transport Equations

Potential temperature transport

$$\underbrace{\frac{\partial \bar{\theta}}{\partial t}}_{\text{I}} + \underbrace{\frac{\partial}{\partial x_j}\left(\bar{u}_j \bar{\theta}\right)}_{\text{II}} = \underbrace{-\frac{\partial}{\partial x_j}\left(q_j\right)}_{\text{III}}$$

I. **time rate of change**

II. **convection**

III. **SFS temperature fluxes**

[1] provides a good explanation of atmospheric boundary layer physics.

[2] is a good outline of atmospheric boundary layer LES.

[1] R. B. Stull. *An Introduction to Boundary Layer Meteorology*. Springer Science + Business Media B. V., 2009.

[2] C.-H. Moeng. A Large-Eddy Simulation Model for the Study of Planetary Boundary Layer Turbulence. *Journal of the Atmospheric Sciences*, Vol. 41, No. 13,

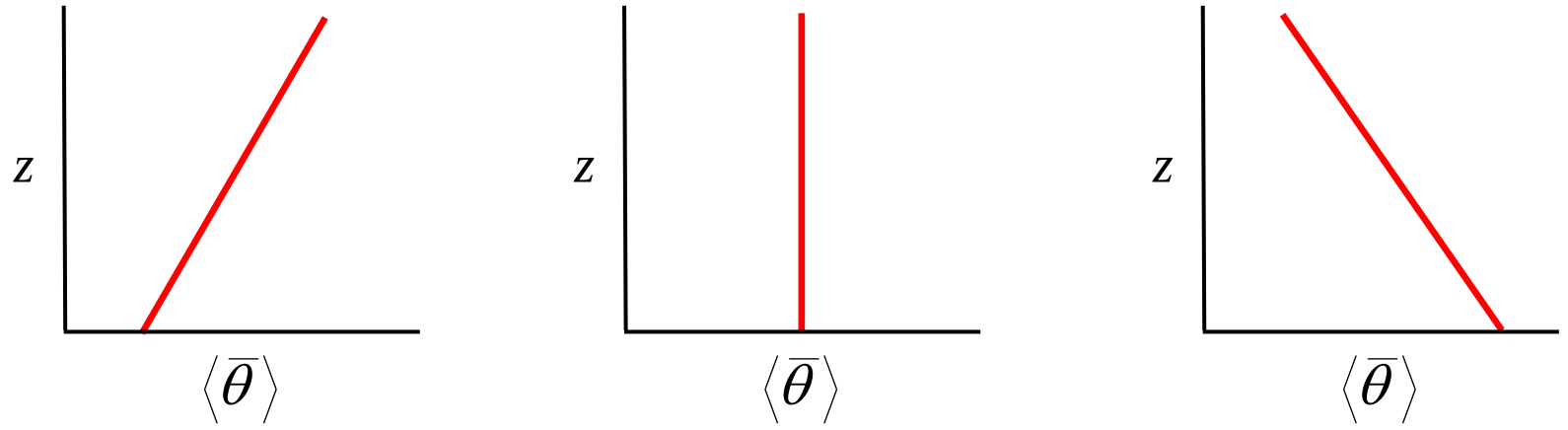
Transport Equations

Potential temperature transport

```
kappat = turbulence->nut()/Prt;
kappat.correctBoundaryConditions();

volScalarField kappaEff("kappaEff", turbulence->nu()/Pr + kappat);

fvScalarMatrix TEqn
(
    fvm::ddt(T)                          // time derivative
  + fvm::div(phi, T)                     // convection
  - fvm::laplacian(kappaEff, T)          // diffusion (molecular + turbulent)
  - fvc::div(qwall)                     // temperature flux at boundary
);

TEqn.relax();
TEqn.solve();

rhok = 1.0 - ( (T - TRef)/TRef );       // Boussinesq buoyancy density
```

Potential Temperature

- **Temperature that a parcel of dry air would have if adiabatically brought from some pressure level to a reference pressure, usually 100kPA**
- **Simplifies the study of atmospheric stability**



stable **neutral** unstable

Buoyancy Force

- **This is an incompressible formulation, with constant density, so we need a way to account for buoyancy effects caused by variable density**
- **Use the Boussinesq approximation**
- **Ratio of "buoyant density" to constant density is**

$$\frac{\rho_k}{\rho_0} = 1 - \left(\frac{\bar{\theta} - \theta_0}{\theta_0} \right) \qquad \theta_0 = 300\text{K}$$

$$1 - \left(\frac{299\text{K} - 300\text{K}}{300\text{K}} \right) = 1.0033$$

locally stable (**cool** air pushed **up** into **warm** air): **negative force**

$$1 - \left(\frac{300\text{K} - 300\text{K}}{300\text{K}} \right) = 1$$

locally neutral (air pushed into air of equal temperature): **zero force**

$$1 - \left(\frac{301\text{K} - 300\text{K}}{300\text{K}} \right) = 0.9967$$

locally unstable (**warm** air pushed **up** into **cool** air): **positive force**

Coriolis Force

- **Due to planetary rotation, there is an apparent force called Coriolis force**
- **If +x is east, +y is north, and +z is up, then**

$$-2\varepsilon_{ijk}\Omega_j\bar{u}_k$$

$$\Omega_j = \omega\begin{bmatrix} 0 \\ \cos\phi \\ \sin\phi \end{bmatrix}$$

- **Ω_j is the rotation rate vector at a location on the planetary surface, ω is the planetary rotation rate (rad/s), and ϕ is the lattitude**

Subgrid-Scale Model

Gradient-diffusion hypothesis

$$\tau_{ij}^{D} = -\upsilon^{SFS}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)$$

$$q_j = -\kappa^{SFS}\frac{\partial \overline{\theta}}{\partial x_j}$$

Smagorinsky model[1]

$$\upsilon^{SFS} = \left(C_s\Delta\right)^2\left[2\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)\right]^{1/2}$$

$$\kappa^{SFS} = \frac{\upsilon^{SFS}}{\mathrm{Pr}_t}$$

[1] J. Smagorinsky. General Circulation Experiments with the Primitive Equations, *Monthly Weather Review*, Vol. 91, 1963, pp. 99–164.

Subgrid-Scale Model

$C_s = 0.13 - 0.17$ (we use closer to 0.13)

Smagorinsky constant

$\Delta = V^{1/3}$

SFS filter width
(V is grid cell volume)

Need to reimplement this

$$\mathrm{Pr}_t = \frac{1}{\left(1 + 2\frac{l}{\Delta}\right)}$$

Turbulent Prandtl number

$$l = \begin{cases} \min\left(7.6\dfrac{\upsilon^{SFS}}{\Delta}\left(\sqrt{\dfrac{1}{s}}\right), \Delta\right) & \text{if} \quad s > 0 \\ \Delta & \text{if} \quad s \le 0 \end{cases}$$

Length-scale for Prt

$$s = \frac{|g_i|}{\theta_0}\frac{\partial\bar{\theta}}{\partial z}$$

Measure of stability

If locally unstable or neutral ($s \le 0$): $\mathrm{Pr}_t = 1/3$ $\kappa^{SFS} = 3\upsilon^{SFS}$

If locally stable ($s > 0$): Pr_t approaches 1 $\kappa^{SFS} \to \upsilon^{SFS}$

Subgrid-Scale Model

- **Older solver (ABLPisoSolver) had SGS model variable evaluated at cell faces, meaning only a custom-coded SGS model could be used**

- **New solver (ABLSolver) has gone back to OpenFOAM standard cell-centered approach, so any OpenFOAM standard SGS or RANS model can be used**

- **Since new solver is based on PIMPLE, can be run either as RANS in SIMPLE or LES in PISO all in one code**

Wall Shear Stress and Temp. Flux Models

- **The cost of high-Re fully-resolved LES of wall-bounded flow scales strongly with Re.**

  "The only economical way to perform LES of high Reynolds-number attached flow, therefore, is by computing the outer layer only." "Because the grid is too coarse to resolve the inner-layer structures, the effect of the wall layer must be modeled. In particular, the momentum flux at the wall (i.e., the wall stress) cannot be evaluated by discrete differentiation because the grid cannot resolve either the sharp velocity gradients in the inner layer or the quasi-streamwise and hairpin vortices that transfer momentum in this region of the flow. Therefore, some phenomelogical relation must be found to relate the wall stress to the outer-layer flow."[1]

- **The planetary surface is covered with roughness elements (dirt, rocks, vegetation) that would be extremely expensive to resolved with the grid.**
- **It is inappropriate to apply no-slip at the surface**
- **Instead apply a model for surface stress**

[1] U. Piomelli and E. Balaras, "Wall-Layer Models for Large-Eddy Simulations," Annual Review of Fluid Mechanics, Vol. 34, pp. 349–374, 2002.

Wall Shear Stress Model

- **Surface stress model predicts total (viscous + SGS) stress at surface**
- **Assumes that first cell centers away from surface lie within surface layer of the atmospheric boundary layer**
- **So at the surface**

$$\tau_{ij}^{D} = \begin{bmatrix} 0 & 0 & \tau_{13}^{tot} \\ 0 & 0 & \tau_{23}^{tot} \\ \tau_{13}^{tot} & \tau_{23}^{tot} & 0 \end{bmatrix}$$

- **The wall model models τ_{13}^{tot} and τ_{23}^{tot}**

Wall Shear Stress Model

- **SOWFA contains the wall models of**
  - Schumann[1]
  - Moeng[2] (Not yet reimplemented)
- **Schumann's model**

$$\tau_{13}^{tot} = -u_*^2 \frac{\left(\bar{u}_{1/2} - \left\langle \bar{u}_{1/2} \right\rangle\right)}{\left(\left\langle \bar{u}_{1/2} \right\rangle^2 + \left\langle \bar{v}_{1/2} \right\rangle^2\right)^{1/2}}$$

$$\tau_{23}^{tot} = -u_*^2 \frac{\left(\bar{v}_{1/2} - \left\langle \bar{v}_{1/2} \right\rangle\right)}{\left(\left\langle \bar{u}_{1/2} \right\rangle^2 + \left\langle \bar{v}_{1/2} \right\rangle^2\right)^{1/2}}$$

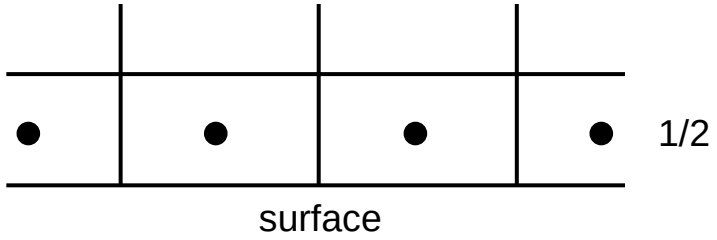
[1] U. Schumann. Subgrid-Scale Model for Finite-Difference Simulations of Turbulent Flow in Plane Channels and Annuli. Journal of Computational Physics, Vol. 18, 1975, pp. 76–404.
[2] C.-H. Moeng. A Large-Eddy Simulation Model for the Study of Planetary Boundary Layer Turbulence. Journal of the Atmospheric Sciences, Vol. 41, No. 13, 1984, pp. 2052–2062.

Wall Stress Model

$$\tau_{13}^{tot} = -u_*^2 \frac{\left(\overline{u}_{1/2} - \left\langle \overline{u}_{1/2} \right\rangle\right)}{\left(\left\langle \overline{u}_{1/2} \right\rangle^2 + \left\langle \overline{v}_{1/2} \right\rangle^2\right)^{1/2}}$$

$$\tau_{23}^{tot} = -u_*^2 \frac{\left(\overline{v}_{1/2} - \left\langle \overline{v}_{1/2} \right\rangle\right)}{\left(\left\langle \overline{u}_{1/2} \right\rangle^2 + \left\langle \overline{v}_{1/2} \right\rangle^2\right)^{1/2}}$$

- **1/2 denotes values at first cell centers away from surface**



- **Angle brackets denote a horizontal average at a certain height**

Wall Shear Stress Model

$$\tau_{13}^{tot} = -u_*^2 \frac{\left(\overline{u}_{1/2} - \left\langle \overline{u}_{1/2} \right\rangle\right)}{\left(\left\langle \overline{u}_{1/2} \right\rangle^2 + \left\langle \overline{v}_{1/2} \right\rangle^2\right)^{1/2}}$$

$$\tau_{23}^{tot} = -u_*^2 \frac{\left(\overline{v}_{1/2} - \left\langle \overline{v}_{1/2} \right\rangle\right)}{\left(\left\langle \overline{u}_{1/2} \right\rangle^2 + \left\langle \overline{v}_{1/2} \right\rangle^2\right)^{1/2}}$$

- **Friction velocity is defined as**

$$u_*^2 = \left(\left\langle \tau_{13}^{tot} \right\rangle^2 + \left\langle \tau_{23}^{tot} \right\rangle^2 \right)^{1/2}$$

- **It needs to be approximated. Use rough wall log law**

$$\frac{\left(\left\langle \overline{u}_{1/2} \right\rangle + \left\langle \overline{v}_{1/2} \right\rangle\right)^{1/2}}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z}{z_0} + f(L) \right)$$

Wall Shear Stress Model

$$\frac{\left(\left\langle \bar{u}_{1/2} \right\rangle + \left\langle \bar{v}_{1/2} \right\rangle\right)^{1/2}}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z}{z_0} + f(L)\right)$$

- **$f(L)$ is an atmospheric stability-related function that is zero for neutral stability. See Etling[1] for more information**
- **L is the Obuhkov length**
- **z_0 is the aerodynamic roughness height. It depends on height, distribution, and shape of roughness elements on planetary surface. See Stull[2] for more information**

z_0 (m)	Terrain
$1\times10^{-1} – 5\times10^{-1}$	Many trees, hedges, few buildings
$3\times10^{-3} – 2\times10^{-2}$	Level grass plains
$1\times10^{-4} – 1\times10^{-3}$	Large expanses of water

[1] D. Etling. Modelling the Vertical ABL Structure, in *Modelling of Atmospheric Flow Fields*, D. P. Lalas and C. F. Ratto, editors, World Scientific, 1996, pp. 56–57.
[2] R. B. Stull. *An Introduction to Boundary Layer Meteorology*. Springer Science

Wall Temperature Flux Model

- **A similar approach is taken to model the total temperature flux at the surface[1]**

$$q_j = \begin{bmatrix} 0 \\ 0 \\ q_3^{tot} \end{bmatrix}$$

- **Total average temperature flux, Q_s, is specified, and the wall model creates the fluctuating temperature flux q_3^{tot}**
- **Or surface heating/cooling rate is specified and q_3^{tot} is calculated[2]**

[1] C.-H. Moeng. A Large-Eddy Simulation Model for the Study of Planetary Boundary Layer Turbulence. Journal of the Atmospheric Sciences, Vol. 41, No. 13, 1984, pp. 2052–2062.

[2] S. Basu, A. A. M. Holtslag, B. J. H. Van de Wiel, A. F. Moene, G.-J. Steeneveld, "An inconvenient "truth" about using sensible heat flux as a surface boundary condition in models under stably stratified regimes," Acta Geophysica, Vol. 56, No. 1, 2008, pp. 88-99.

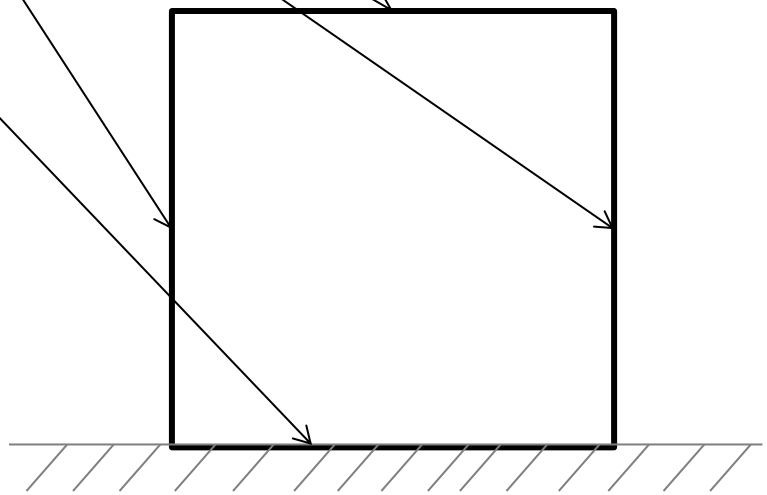
How to Incorporate Wall Model

- **OpenFOAM has standard wall shear stress models that look at the surface velocity gradient and assign a surface eddy-viscosity such that their product gives the correct stress**
- **This does not allow for the use of a non-linear surface shear stress model, like that of Moeng**
- **SOWFA includes wall model BCs for Rwall and qwall**

How to Incorporate Wall Model

```
fvVectorMatrix UEqn
    (
        fvm::ddt(U)
      + fvm::div(phi, U)
      + turbulence->divDevReff(U)
      + fvc::div(Rwall)
      - fCoriolis
      + gradPd
    );
```

sums contribution from interior faces
sums contribution from wall face



Rwall is a volSymmTensorField that is zero on the interior and only takes on a value on patches in which the wall shear stress BC is applied

If nuEff is zero on the patch, then there is no contribution from divDevReff on that patch, only on the interior

Temperature flux model works similarly

I credit David Lapointe-Thériault from ETS in Montreal for this method of splitting up the stresses at faces between interior and wall and treating them separately while still usind divDevReff()

Numerical Scheme

- **ABLSolver uses the PISO[1] (Pressure Implicit Splitting Operation) – SIMPLE (Semi-Implicit Method for Pressure Linked Equations) to "implicitly" solve the momentum and pressure equation**
  - Predictor-Corrector approach with Rhie-Chow interpolation
  - I started with buoyantBoussinesqPimpleFoam, which only includes a temperature predictor
  - Having a temperature predictor only does not closely enough couple equations, so I also call the temperature equation in the corrector loop
  - Fixed the velocity overshoot problem seen at the top of the boundary layer in older ABLPisoSolver

- **I credit David Lapointe-Thériault from ETS in Montreal for figuring out the better temperature coupling through inclusion of T equation in corrector loop**

[1] R. I. Issa. Solution of the Implicitly Discretized Fluid Flow Equations by Operator-Splitting. *Journal of Computational Physics*, Vol. 62, 1985, pp. 40–65.

Numerical Scheme

- **Finite-volume formulation**
  - Linear interpolate of cell-center values to cell faces when needed
  - Equivalent to second-order central differencing
  - Rhie-Chow[1]-like flux interpolation is used to avoid pressure-velocity decoupling

[1] C. M. Rhie and W. L. Chow. Numerical Study of the Turbulent Flow Past an Airfoil with Trailing Edge Separation. *AIAA Journal*, Vol. 21, No. 11, 1983, pp. 1552–1532.

Linear System Solvers

- **Velocity and Temperature**
  - Biconjugate Gradient
  - Diagonal incomplete LU matrix preconditioner
- **Pressure**
  - Preconditioned Conjugate Gradient
  - Diagonal incomplete Cholesky or multigrid matrix preconditioner

OR

  - Geometric agglomerated algebraic multigrid solver
  - Diagonal incomplete Cholesky smoother

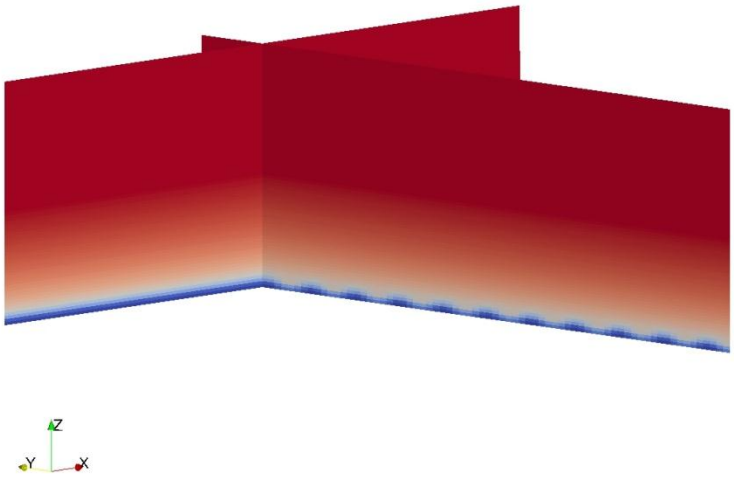
Initial Conditions for Precursor Flow

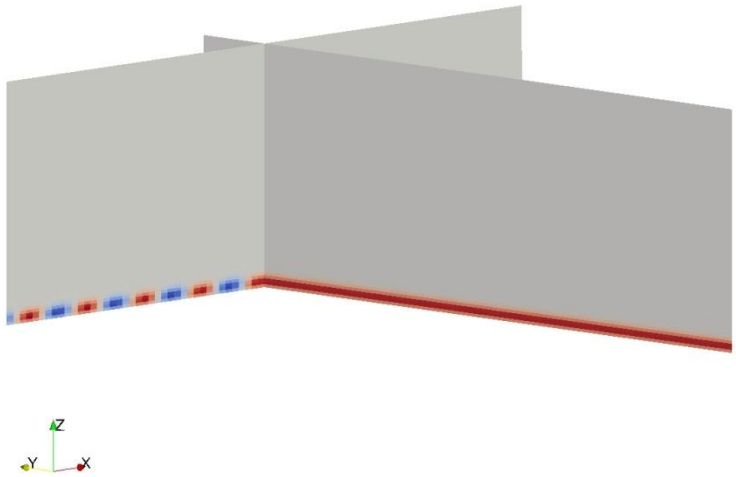
Initial conditions

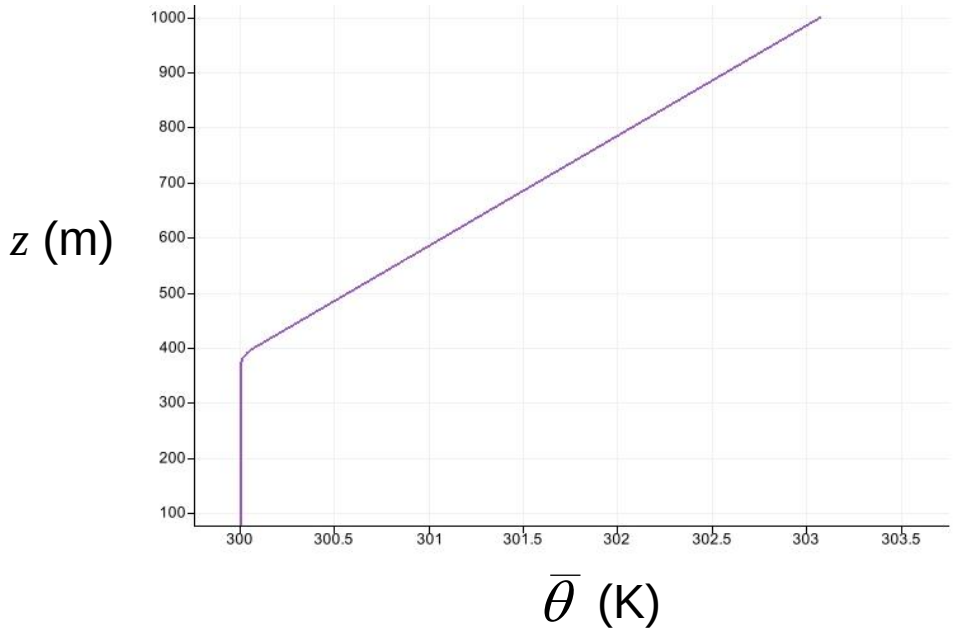
- **Velocity**
  - Given a logarithmic base profile
  - Non-random, divergence-free perturbations added near surface to cause turbulence to quickly happen (similar to method used by DeVillier's in channel flow[1]).
- **Temperature**
  - Constant temperature (300K) up to some height, then temperature increases
  - This creates a capping inversion that caps the boundary layer and slows boundary layer vertical growth
- **Pressure variable**
  - Initialized to zero
- **Initial conditions set using "setABLFields" utility, but could use something like "funkySetFields"**

[1] De Villiers, E., "The Potential of Large Eddy Simulation for the Modeling of Wall Bounded Flows", PhD Thesis, Imperial College, London, 2006.

Initial Conditions for Precursor Flow







Solver Outputs

- **"averaging" file structure**
  - Within averaging directory are time directories corresponding to run start times. If you start a run at 0, there will be a "0" directory. If you restart a run at 1000, there will also be a "1000" directory.
  - Most files are structured as follows where each line represents a different time step, and starting at the third column, each column represents a horizontally-averaged value at a progressively greater height on the grid

$$
\begin{array}{llllll}
\text{time}^0 & \text{dt}^0 & \text{value}_0 & \text{value}_1 & \text{value}_2 \ \ldots \ \text{value}_J \\
\text{time}^1 & \text{dt}^1 & \text{value}_0 & \text{value}_1 & \text{value}_2 \ \ldots \ \text{value}_J \\
 & & & & \ldots \\
\text{time}^N & \text{dt}^N & \text{value}_0 & \text{value}_1 & \text{value}_2 \ \ldots \ \text{value}_J
\end{array}
$$

  - Heights corresponding the value_0 through value_J are in the hLevelsCell file
    - hLevelsCell are cell-centered heights

Solver Outputs

- **“averaging” file structure**

Cell-center quantities	Description
T_mean	$\langle \bar{\theta} \rangle$
U_mean, V_mean, W_mean	$\langle \bar{u} \rangle$ $\langle \bar{v} \rangle$ $\langle \bar{w} \rangle$
uu_mean, vv_mean, ww_mean	$\langle u'u' \rangle$ $\langle v'v' \rangle$ $\langle w'w' \rangle$
uv_mean, uw_mean, vw_mean	$\langle u'v' \rangle$ $\langle u'w' \rangle$ $\langle v'w' \rangle$
wuu_mean, wvv_mean, www_mean	$\langle w'u'u' \rangle$ $\langle w'v'v' \rangle$ $\langle w'w'w' \rangle$
wuv_mean, wuw_mean, wvw_mean	$\langle w'u'v' \rangle$ $\langle w'u'w' \rangle$ $\langle w'v'w' \rangle$
Tu_mean, Tv_mean, Tw_mean	$\langle \theta'u' \rangle$ $\langle \theta'v' \rangle$ $\langle \theta'w' \rangle$

Solver Outputs

- **"averaging" file structure**

Cell-face quantities	Description
R11_mean, R22_mean, R33_mean	$\langle \tau_{11}^D \rangle$ $\langle \tau_{22}^D \rangle$ $\langle \tau_{33}^D \rangle$
R12_mean, R13_mean, R23_mean	$\langle \tau_{12}^D \rangle$ $\langle \tau_{13}^D \rangle$ $\langle \tau_{23}^D \rangle$
q1_mean, q2_mean, q3_mean	$\langle q_1 \rangle$ $\langle q_2 \rangle$ $\langle q_3 \rangle$
phiM	ϕ_m Non-dimensional velocity shear

Global quantities	Description
ReLES	Re_{LES} LES Reynolds number[1]
scriptR	$\Re$ Near surface ratio of resolved to subgrid scale stress[1]
uStar	u_* Friction velocity
zi	z_i Boundary layer depth

[1] J. Brasseur and T. Wei. Designing Large-Eddy Simulation of the Turbulent Boundary Layer to Capture Law-of-the-Wall Scaling, *Physics of Fluids*, Vol. 22, No. 2, 2010.

Guidelines for Use

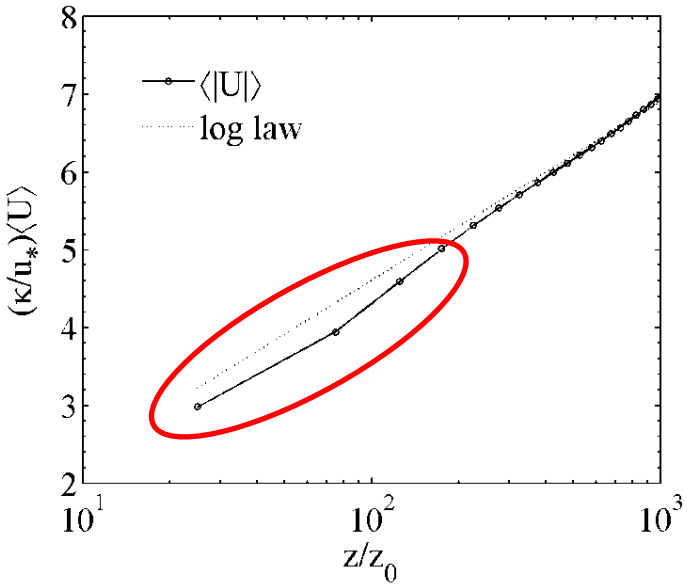
- **ABLSolver meant for flat terrain with "structured" mesh**
  - Only because it has built in planar averaging to give vertical mean profiles
- **Use ABLTerrainSolver if the bottom is not flat (exactly same solver, but takes time averages)**
  - At some point I want to make the averaging type function objects so that there is one ABL solver, and you choose either horizontal or time averaging function objects depending on the situation
- **Flat-bottom precursors should be run with periodic lateral boundaries**
- **The more stable the case, in general the longer the time to quasi-equilibrium (up to 50,000 s).**
- **Unstable cases should have at least 5 km x 5 km x 2 km domain, neutral should have at least 3 km x 3 km x 1 km domain, and stable can be smaller, but I do not have a rule of thumb**
- **If the domain is the smallest recommended, drive hub-height wind at some angle no aligned with x-y; otherwise low-speed structures become "stuck" by periodicity and cycle through over and over.**
- **We have some preliminary inflow BC conditions for U and T for ABLTerrainSolver since it probably won't be run periodic. In our experience, using these BC's to apply fluctuations to T helps initiate turbulence, but still a long fetch is needed.**
- $+x$ **must be east,** $+y$ **must be north,** $+z$ **must be up**
- **Must use adequate vertical grid resolution, small enough cell aspect ratio, and proper Smagorinsky constant to recover law-of-the-wall scaling**

Guidelines for Use

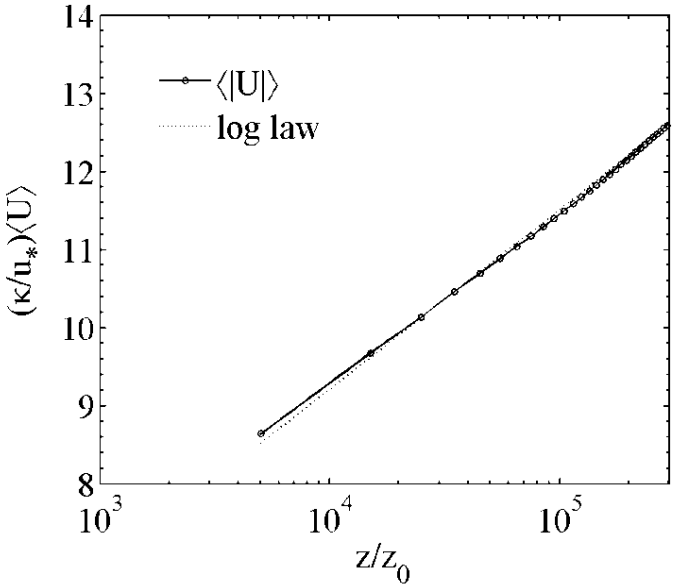
- $+x$ must be east, $+y$ must be north, $+z$ must be up
- Must use adequate vertical grid resolution, small enough cell aspect ratio, and proper Smagorinsky constant to recover law-of-the-wall scaling

Guidelines for Use

- **Law-of-the-wall scaling**
  - This follows the work of Brasseur and Wei[1]
  - The problem:



Log-law mismatch



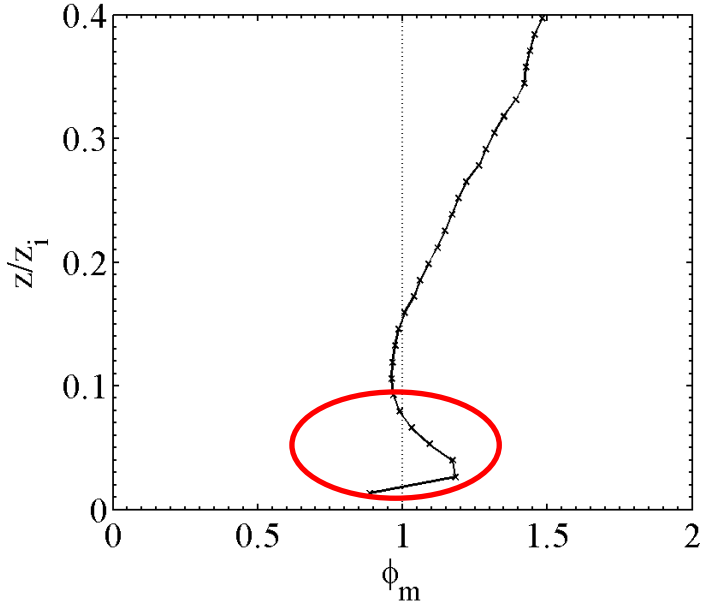
Improved log-law agreement

[1] J. Brasseur and T. Wei. Designing Large-Eddy Simulation of the Turbulent Boundary Layer to Capture Law-of-the-Wall Scaling, *Physics of Fluids*, Vol. 22, No. 2, 2010.

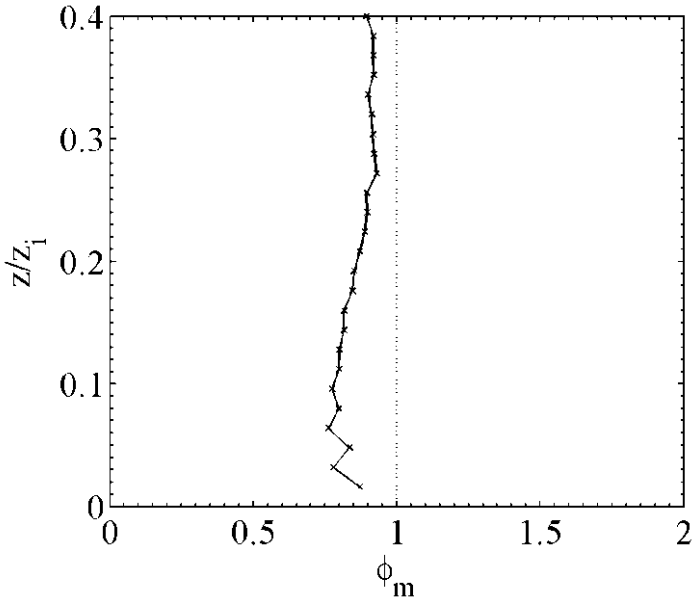
Guidelines for Use

- **Law-of-the-wall scaling**
  - This follows the work of Brasseur and Wei[1]
  - The problem:

$$\phi_m = \frac{\kappa z}{u_*} \frac{\partial \langle U \rangle}{\partial z}$$



overshoot



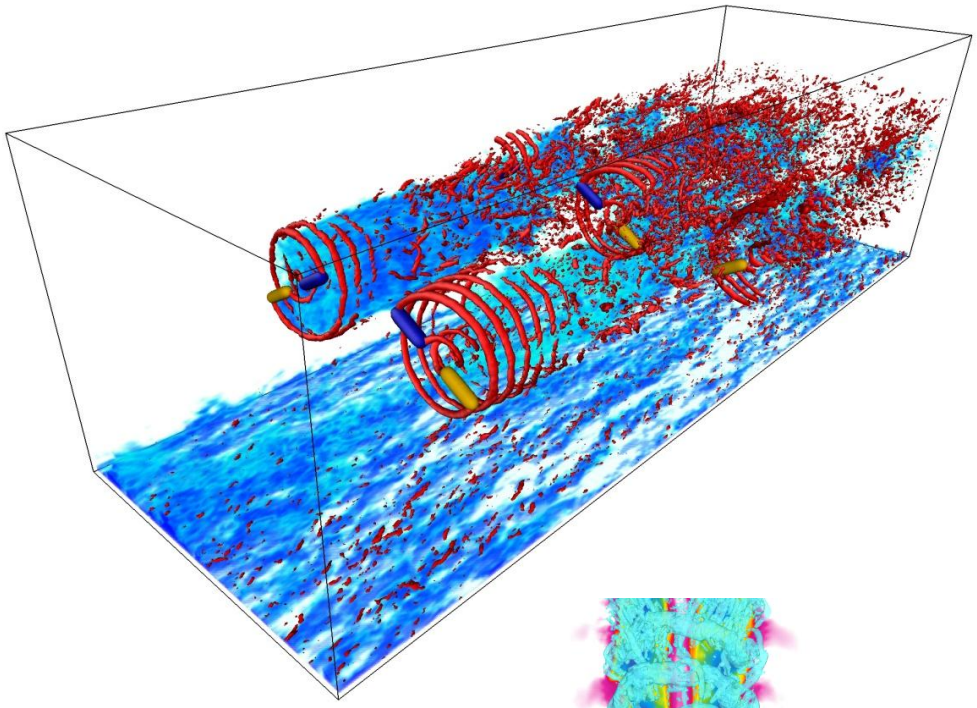
Improved log-law agreement

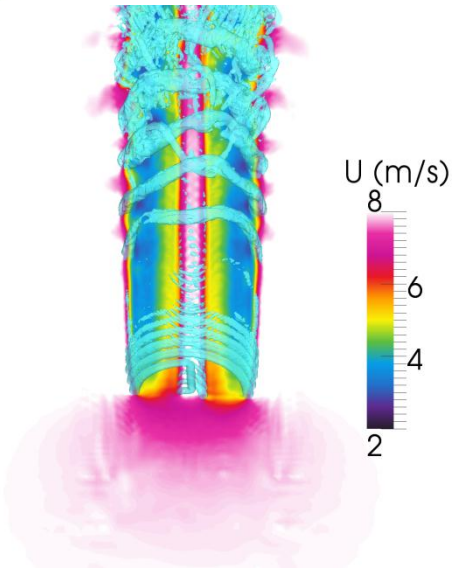
[1] J. Brasseur and T. Wei. Designing Large-Eddy Simulation of the Turbulent Boundary Layer to Capture Law-of-the-Wall Scaling, *Physics of Fluids*, Vol. 22, No. 2, 2010.

Actuator Line Turbine Model
horizontalAxisALM class

Overview

- Resolving turbine blade geometry with high-Re LES is infeasible
- An actuator approach does not require a very fine grid around turbine blades
- Creates wake, tip, root, and bound vortices
- Does not create blade boundary layer turbulence
- Depends upon airfoil look-up tables





Theory

- Method of Sørensen and Shen[1]
- Blades discretized into spanwise sections of constant airfoil, chord, twist, oncoming wind
- Airfoil lookup tables used to calculate lift and drag at each actuator section
- Force on flow is equal and opposite to blade force
- Force is normalized and projected back to flow

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_j \overline{u}_i\right) = -2\varepsilon_{i3k}\Omega_3 \overline{u}_k - \frac{\partial \widetilde{p}}{\partial x_i} - \frac{1}{\rho_0}\frac{\partial}{\partial x_i}\overline{p}_0(x,y) - \frac{\partial}{\partial x_j}\left(\tau_{ij}^D\right) - \frac{gz}{\rho_0}\frac{\partial}{\partial x_i}\rho_b + \frac{1}{\rho_0} f_i^T$$

[1] Sørensen, J. N. and Shen, W. Z., "Numerical Modeling of Wind Turbine Wakes", *Journal of Fluids Engineering* 124, 2002, pp. 393-399.

Theory

- **Force Projection**
  - How do you take force calculated at actuator line points and project it onto the CFD grid as a body force?
  - How do you smooth the force to avoid numerical oscillation?
  - Sørensen and Shen use a Gaussian projection

$$f_i^T(r) = \frac{F_i^A}{\varepsilon^3 \pi^{3/2}} \exp\left[-\left(\frac{r}{\varepsilon} \right)^2 \right]$$

  - F_i^A is the actuator element force
  - f_i^T is the force field projected as a body force onto CFD grid
  - r is distance between CFD cell center and actuator point
  - ε controls Gaussian width.

Theory

- **Projection Width**
  - Troldborg[1] recommends $\varepsilon / \Delta x = 2$ where Δx is the grid cell length near actuator line
  - We found this to be the minimum in order to maintain an oscillation-free solution using central differences
  - We think ε should be tied to some physical blade length, like chord, but have not come up with a definitive guideline.
  - See the AIAA paper by Martínez et al.[2]
  - A good way to choose epsilon is to choose a wind speed/TSR and run a case and see how power compares to what it should be. If power is low, make epsilon bigger and vice versa, and try again. Repeat. Now you have 3 data points that should bracket the power you want. Fit a cubic spline to epsilon vs. power and find the epsilon that corresponds to the desired power. In our experience, this epsilon then holds for all other wind speeds and TSR.

[1] Troldborg, N., "Actuator Line Modeling of Wind Turbine Wakes", PhD Thesis, Technical University of Denmark, Lyngby, Denmark, 2008.
[2] Martinez, L. A., Leonardi, S., Churchfield, M. J., Moriarty, P. J., "A Comparison of Actuator Disk and Actuator Line Wind Turbine Models and Best Practices for Their Use", AIAA Paper 2012-900, Jan. 2012.

Actuator Line Model Features

- **Generator Torque Control**
  - 5 region control like NREL 5MW (see 5MW Reference Turbine Report)
  - Generator speed vs. generator torque lookup table
- **Pitch Control**
  - PID, based on NREL 5MW Reference Turbine Report
  - Can provide P, I, and D gains, but must compute those gains following NREL 5MW Reference Turbine Report
- **Yaw Control**
  - Not yet implemented, but coming soon
- **Can be run in a FAST-coupled mode (we will discuss this later in the tutorial)**

[1]J. Jonkman, S. Butterfield, W. Musial, and G. Scott, "Definition of a 5-MW Reference Wind Turbine for Offshore System Development," NREL Report TP-500-38060, Feb. 2009

Actuator Line Model Outputs

- **Solution files (inside time directories)**
  - bodyForce: body force projected onto flow field

- **“turbineOutput” directory**
  - Outputs various turbine information such as power, torque, rotor speed, etc.
  - Outputs information at each blade point such as angle of attack, velocity magnitude, lift, drag, etc.

Actuator Line Model Outputs

- **“turbineOutput” file structure**
  - Within turbineOutput directory are time directories corresponding to run start times. If you start a run at 0, there will be a “0” directory. If you restart a run at 1000, there will also be a “1000” directory.
    - Within the specific time directories are a files for global turbine data files for quantities like power, torque, rotor speed, etc.
    - Also there are files for blade local quantities like lift, drag, angle of attack, etc. vs. span.

Actuator Line Model Outputs

- **Global quantity file structure**

```
turbine^0 time^0  dt^0  value
turbine^1 time^0  dt^0  value
…
turbine^M time^1  dt^0  value

turbine^0 time^1  dt^1  value
turbine^1 time^1  dt^1  value
…
turbine^M time^1  dt^1  value

          …

turbine^0 time^N  dt^N  value
turbine^1 time^N  dt^N  value
…
turbine^M time^N  dt^N  value
```

Actuator Line Model Outputs

- **Blade radius dependent file structure**

turbine^0 blade^0 time^0 dt^0 value$_0$ value$_1$ value$_2$ … value$_J$
turbine^0 blade^1 time^0 dt^0 value$_0$ value$_1$ value$_2$ … value$_J$
turbine^0 blade^2 time^0 dt^0 value$_0$ value$_1$ value$_2$ … value$_J$

turbine^1 blade^0 time^0 dt^0 value$_0$ value$_1$ value$_2$ … value$_J$
turbine^1 blade^1 time^0 dt^0 value$_0$ value$_1$ value$_2$ … value$_J$
turbine^1 blade^2 time^0 dt^0 value$_0$ value$_1$ value$_2$ … value$_J$
…

turbine^M blade^0 time^0 dt^0 value$_0$ value$_1$ value$_2$ … value$_J$
turbine^M blade^1 time^0 dt^0 value$_0$ value$_1$ value$_2$ … value$_J$
turbine^M blade^2 time^0 dt^0 value$_0$ value$_1$ value$_2$ … value$_J$

…

turbine^0 blade^0 time^N dt^N value$_0$ value$_1$ value$_2$ … value$_J$
turbine^0 blade^1 time^N dt^N value$_0$ value$_1$ value$_2$ … value$_J$
turbine^0 blade^2 time^N dt^N value$_0$ value$_1$ value$_2$ … value$_J$

turbine^1 blade^0 time^N dt^N value$_0$ value$_1$ value$_2$ … value$_J$
turbine^1 blade^1 time^N dt^N value$_0$ value$_1$ value$_2$ … value$_J$
turbine^1 blade^2 time^N dt^N value$_0$ value$_1$ value$_2$ … value$_J$
…

turbine^M blade^0 time^N dt^N value$_0$ value$_1$ value$_2$ … value$_J$
turbine^M blade^1 time^N dt^N value$_0$ value$_1$ value$_2$ … value$_J$
turbine^M blade^2 time^N dt^N value$_0$ value$_1$ value$_2$ … value$_J$

Actuator Line Model Outputs

Global turbine quantities	Description
powerRotor	Rotor power/density (W)
rotSpeed	Rotor speed (rpm)
thrust	Thrust (N)
torqueRotor	Rotor torque (N-m)
torqueGen	Generator torque (N-m)
azimuth	Rotor azimuth angle (degrees)
nacYaw	Nacelle yaw angle (degrees)
pitch	Blade collective pitch (degrees)

Actuator Line Model Outputs

Blade Local quantities	Description
alpha	Angle of attack (degrees)
axialForce	Force along rotor shaft axis (N)
Cd	Coefficient of drag
Cl	Coefficient of lift
drag	Drag force (N)
lift	Lift force (N)
tangentialForce	Force in rotor rotation tangential direction (N)
Vaxial	Component of velocity along rotor shaft axis (m/s)
Vradial	Component of velocity along blade radius (m/s)
Vtangential	Component of velocity in rotation tangential direction (m/s)
x, y, z	Actuator point position in space (m)

Guidelines for Use

- $+x$ must be east, $+y$ must be north, $+z$ must be up
- Use at least 20 CFD grid cells across the rotor diameter
- Use at least 50 CFD grid cells across the rotor if you want to well resolve tip/root vortices
- Set epsilon based on cubic fit approach in slide 42

Implementation

- **Turbine model implemented as a class**
  - “horizontalAxisWindTurbinesALM”
  - See src/turbineModels/horizontalAxisWindTuribinesALM
- **Any solver can be modified to contain an object of the class**
- **That object is the entire turbine array**

Implementation

- **Modifying pisoFoam to include turbine class**
  - Add this to createFields.H to declare object of turbine class

```
// Create an object of the horizontalWindTurbineArray class if there
// is to be a turbine array
//
turbineModels::horizontalAxisWindTurbinesALM turbines(U);
```

  - Add this to the includes part of the solver code

```
#include "horizontalAxisWindTurbinesALM.H"
```

  - Add this line to solver code momentum equation to apply forces

```
fvVectorMatrix UEqn
(
      fvm::ddt(U)
    + fvm::div(phi, U)
    + turbulence->divDevReff(U)
    - turbines.force()
```

  - Add this line at the beginning or end of the time loop to advance the turbine one time step

```
turbines.update();
```

Implementation

- **Make/options file needs to be modified**

```
 EXE_INC = \
    -I$(LIB_SRC)/turbulenceModels/incompressible/turbulenceModel \
    -I$(LIB_SRC)/transportModels \
    -I$(LIB_SRC)/transportModels/incompressible/singlePhaseTransportModel \
    -I$(LIB_SRC)/finiteVolume/lnInclude \
    -I$(WM_PROJECT_USER_DIR)/src/turbineModels/lnInclude

EXE_LIBS
    -L$(FOAM_USER_LIBBIN) \
    -lincompressibleTurbulenceModel \
    -lincompressibleRASModels \
    -lincompressibleLESModels \
    -lincompressibleTransportModels \
    -lfiniteVolume \
    -lmeshTools \
    -llduSolvers \
    -luserTurbineModels
```

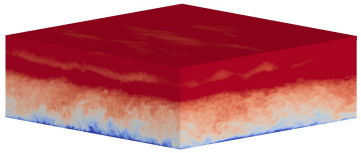
FAST Coupling to OpenFOAM

Coupling FAST to OpenFOAM

- **NREL's FAST[1] (Fatigue, Aerodynamics, Stress, and Turbulence) tool is a model for wind turbine structural, aero, and system dynamics**
- **Its aerodynamics part is through blade element momentum theory (BEM)**
- **Here, we coupled FAST to the actuator line model**
- **The "momentum" part of BEM is replaced by CFD**
  - CFD feeds FAST inflow information at blade elements
  - Aerodynamic forces computed by look-up table ("blade element" theory--just like normal actuator line)
  - Turbine structural and system response computed
  - Aerodynamic forces fed back to CFD

[1] Jonkman, J. and Buhl, M., FAST User's Guide, NREL/EL-500-38230, NREL technical report, 2005. Accessible at: http://wind.nrel.gov/designcodes/simulators/fast/FAST.pdf

Coupling FAST to OpenFOAM



OpenFOAM

Do while (t < tmax)

call FLOW_Solver

call openFOAM2FAST

call FAST

call Fast2OpenFOAM

End do

Turbulence is different than a TurbSim result!

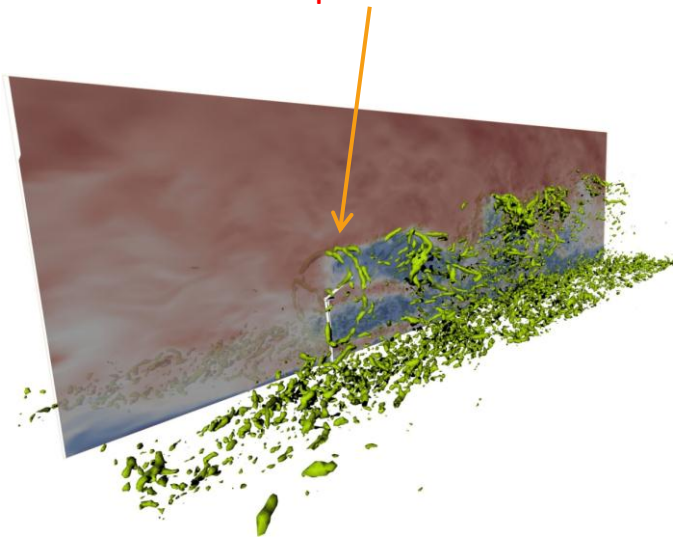
Multiple-Turbine capability

(NREL aero-elastic code)

velocity

Compute structural response and blade rotation

aeroforces w/ blade coord. in actuator line representation



Implementation

- **Similar to standard actuator line**
- **Turbine model implemented as a class**
  - “horizontalAxisWindTurbinesFAST”
  - See src/fastturb/horizontalAxisWindTuribinesFAST
- **Any solver can be modified to contain an object of the class**
- **That object is the entire turbine array**

Implementation - fastPisoSolver

```
…

label pRefCell = 0;
scalar pRefValue = 0.0;
setRefCell(p, mesh.solutionDict().subDict("PISO"), pRefCell, pRefValue);

singlePhaseTransportModel laminarTransport(U, phi);

autoPtr<incompressible::turbulenceModel> turbulence
(
   incompressible::turbulenceModel::New(U, phi, laminarTransport)
);

turbineModels::horizontalAxisWindTurbinesFAST turbfast(U);
```

createFields.H

-Create an object of the horizontalWindTurbinesFAST class if there is to be a turbine array

•Add “createFields.H” file to the includes part of the solver code (pisoFoam.C)

```
int main(int argc, char *argv[])
{
   #include "setRootCase.H"
   #include "createTime.H"
   #include "createMesh.H"
   #include "createFields.H"
   #include "initContinuityErrs.H”
```

Implementation - fastPisoSolver

pisoFoam.C

```
…
#include "horizontalAxisWindTurbinesFAST.H“
…

extern "C"
{
  void fastinit_( float& , int& );
  void fastread_( float*, float*, float*);
  void fastrun_( );
  void fastgetbldpos_( float*, float*, float*);
  void fastgetbldforce_(float*, float*, float*);
  void fastend_( );
}

int main(int argc, char *argv[])
{
    … #include "createFields.H“ …

   //* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //
   // initialize FAST
   Info << "Number of Turbs: " << turbfast.turbNum << endl;
   float tstep = runTime.deltaT().value();
   for(int turbNo=0; turbNo<turbfast.turbNum; turbNo++)
   {
    if(Pstream::myProcNo() == turbNo)
    {
     fastinit_(tstep, turbNo);
     fastgetbldpos_(turbfast.bldptx[turbNo], turbfast.bldpty[turbNo], turbfast.bldptz[turbNo]);
    }
    turbfast.getBldPos(turbNo);
   }
```

Declare wrapper functions written Fortran90

-Initialize FAST
-Read wind information from OpenFOAM
-Run FAST
-transfer updated blade element positions to OpenFOAM
-transfer updated aerodynamic forces from blade elements to OpenFOAM
-Terminate FAST

FAST initialization

-Get number of blades
-Get time-step from OpenFOAM => FAST time step
-Loop through each turbines
-Turbine ID = MPI_RANK (CPU #)

-For given CPU #, initialize FAST

-Get current blade elem. pos.

-Transfer blade elem. Pos. to OpenFOAM

Implementation - fastPisoSolver.C

pisoFoam.C

Continued from last slide…

```
// Pressure-velocity PISO corrector
{

 for(int turbNo=0; turbNo<turbfast.turbNum; turbNo++)
 {
  turbfast.getWndVec(turbNo);
  if(Pstream::myProcNo() == turbNo)
  {
   fastread_(turbfast.uin[turbNo], turbfast.vin[turbNo], turbfast.win[turbNo]);
   fastrun_();
   fastgetbldpos_(turbfast.bldptx[turbNo], turbfast.bldpty[turbNo], turbfast.bldptz[turbNo]);
   fastgetbldforce_(turbfast.bldfx[turbNo], turbfast.bldfy[turbNo], turbfast.bldfz[turbNo]);
  }
  turbfast.computeBodyForce(turbNo);
 }

 // Momentum predictor
 fvVectorMatrix UEqn
 (
  fvm::ddt(U)
    + fvm::div(phi, U)
    + turbulence->divDevReff(U) - turbfast.force()
 );

…
 fastend_();
…
```

-Loop through turbines

-get wind data for specified turbine

-transfer OpenFOAM wind data to FAST
-run FAST
-pass updated blade elem. pos. to OpenFOAM
-pass updated aerodynmic force to OpenFOAM

-project the aerodynamic force into the OpenFOAM computational domain

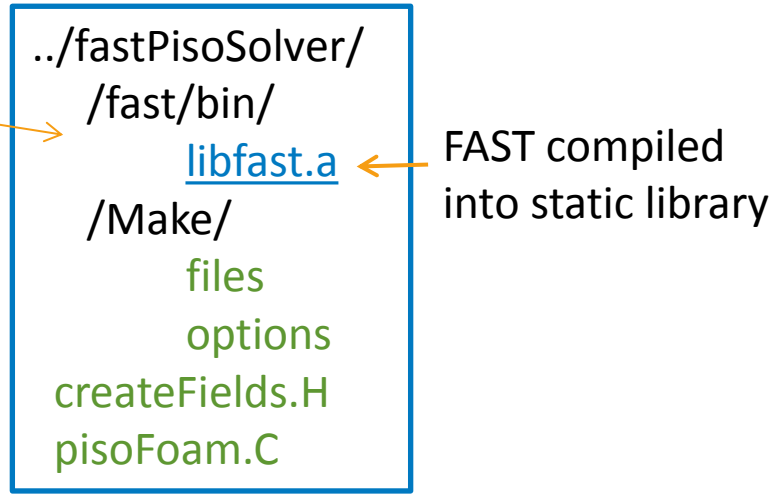
-added the aerodynamic force from FAST as a bodyforce term in momentum eq.

-terminate FAST (loops through all the turbines)

Implementation – Make file

- **Make/options file needs to be modified**

```
EXE_INC = \
    -I$(LIB_SRC)/turbulenceModels/incompressible/turbulenceModel \
    -I$(LIB_SRC)/transportModels \
    -I$(LIB_SRC)/transportModels/incompressible/singlePhaseTransportModel \
    -I$(LIB_SRC)/finiteVolume/lnInclude \
    -I$(WM_PROJECT_USER_DIR)/src/fastturb/lnInclude

EXE_LIBS
    -Lfast/bin \
    -L$(FOAM_USER_LIBBIN) \
    -lincompressibleRASModels \
    -lincompressibleLESModels \
    -lincompressibleTransportModels \
    -lfiniteVolume \
    -lmeshTools \
    -luserfastturb \
    -lgfortran \
    -lfast
```



FAST Input files: NREL 5MW Turbine

/caseStudyDir/

Required files are:

Primary.fst
specifies configurations for initial conditions, controls, turbine geometry and mass, drive train, output file formats, etc…

USERWIND.wnd
file used to invoke reading in external flow data

NRELOffshrBsline5MW_AeroDyn.ipt
AeroDyn input for air specification, blade geometry, airfoil data (coefficients for lift/drag table are included in /caseStudyDir/AeroData/)

NRELOffshrBsline5MW_Blade.ipt
Specifies blade properties: stiffness, mode shapes etc..

NRELOffshrBsline5MW_Tower_Onshore.ipt
ditto for Tower properties

FAST Actuator Line Model Inputs

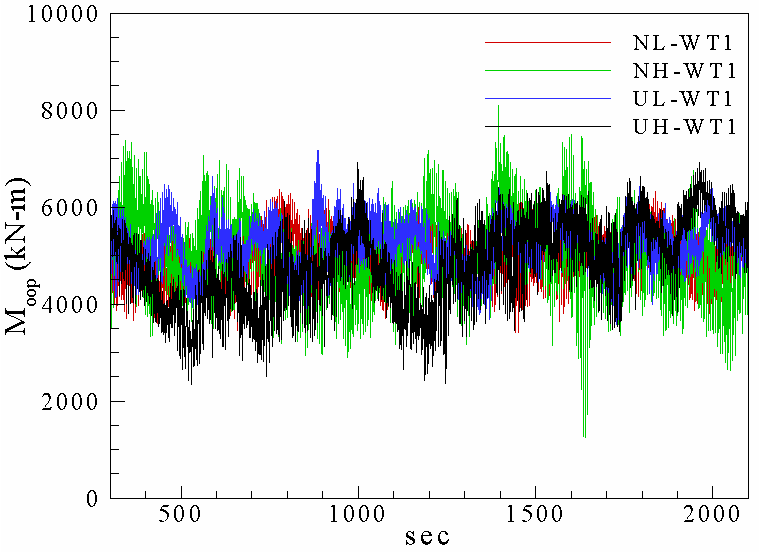
constant/**turbineArrayPropertiesFAST**

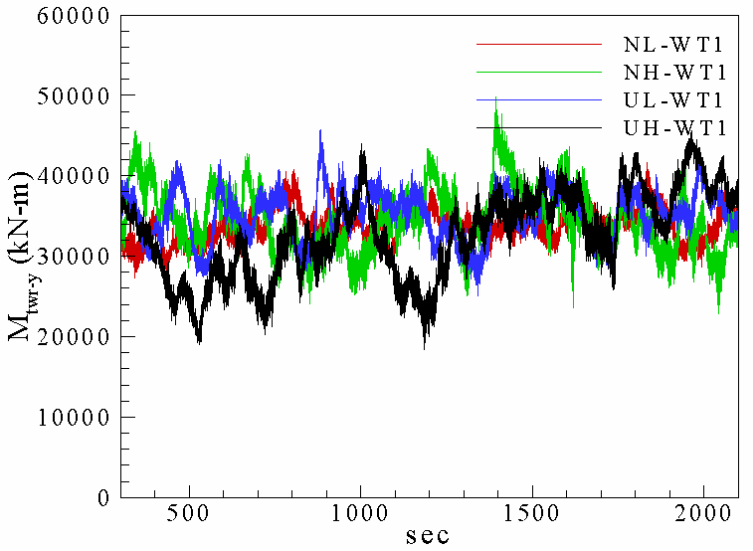
```
turbine0
{
    refx                200.0;          - x location of tower base
    refy                  0.0;          - y location of tower base
    refz                  0.0;          - z location of tower base
    hubz                100.0;          - hub height
}

turbine1
{
    refx                400.0;
    …


general
{
    yawAngle              0.0;          - turbine yaw angle
    numberofBld           3             - # of blades
    numberofBldPts       62;            - # of actuator elements per blade
    rotorDiameter       126.3992;       - rotor diameter
    epsilon               5.0;          - Gaussian width parameter
    smearRadius          13.15;         - radius beyond which Gaussian has no effect
    effectiveRadiusFactor 1.21;         - scale factor for rotor diameter
    pointInterpType       1;            - option for linear interpolation of velocities
}
```

FAST Actuator Line Model Outputs

- **Load files : primary0.out, primary1.out, …**
- **These include time histories of load parameters specified in primary.fst**

  e.g. out-of-plane blade root bending moments, torque, yaw bearing moments, power, rotor speed …
- **Can be imported into Excel / MatLab for figures**

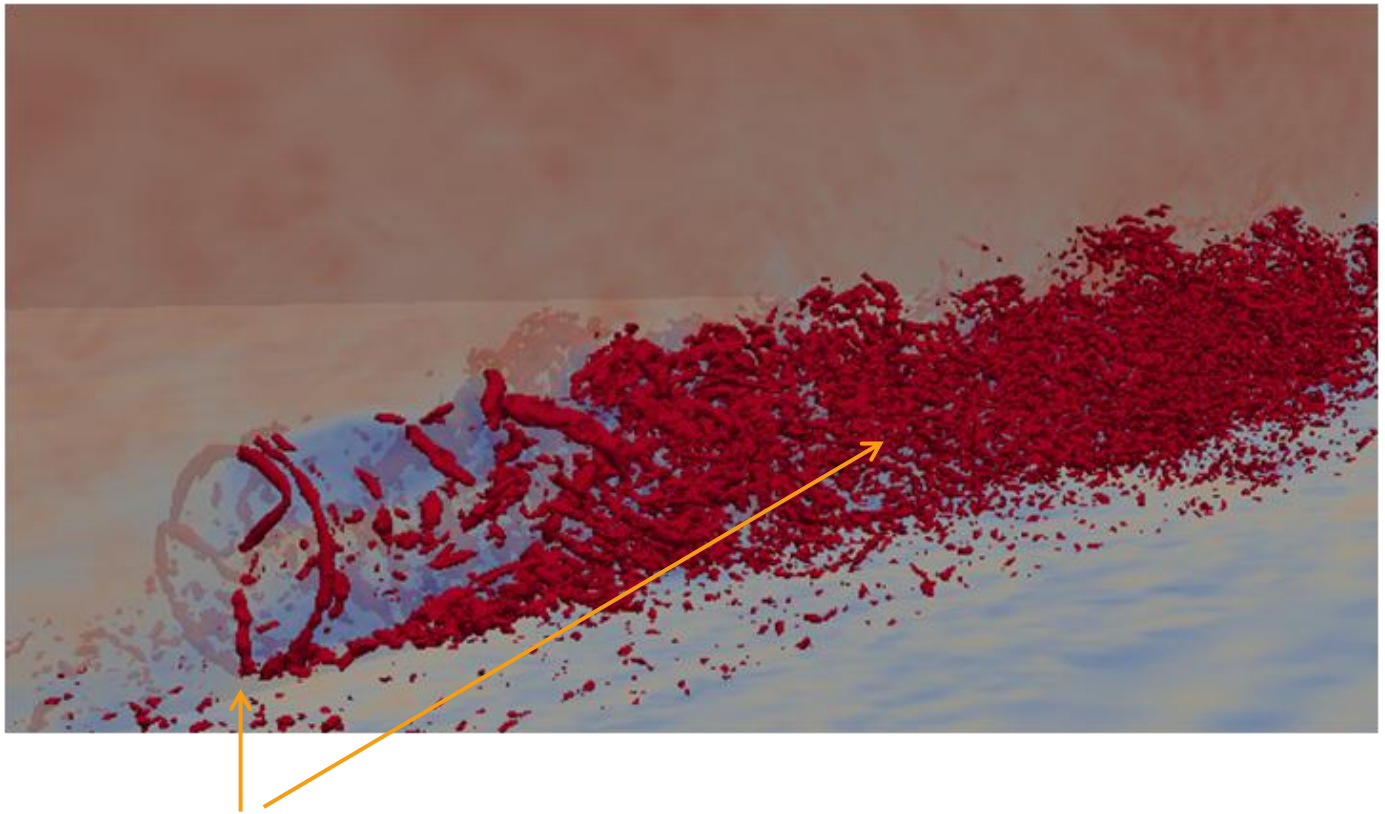




Guidelines for Use

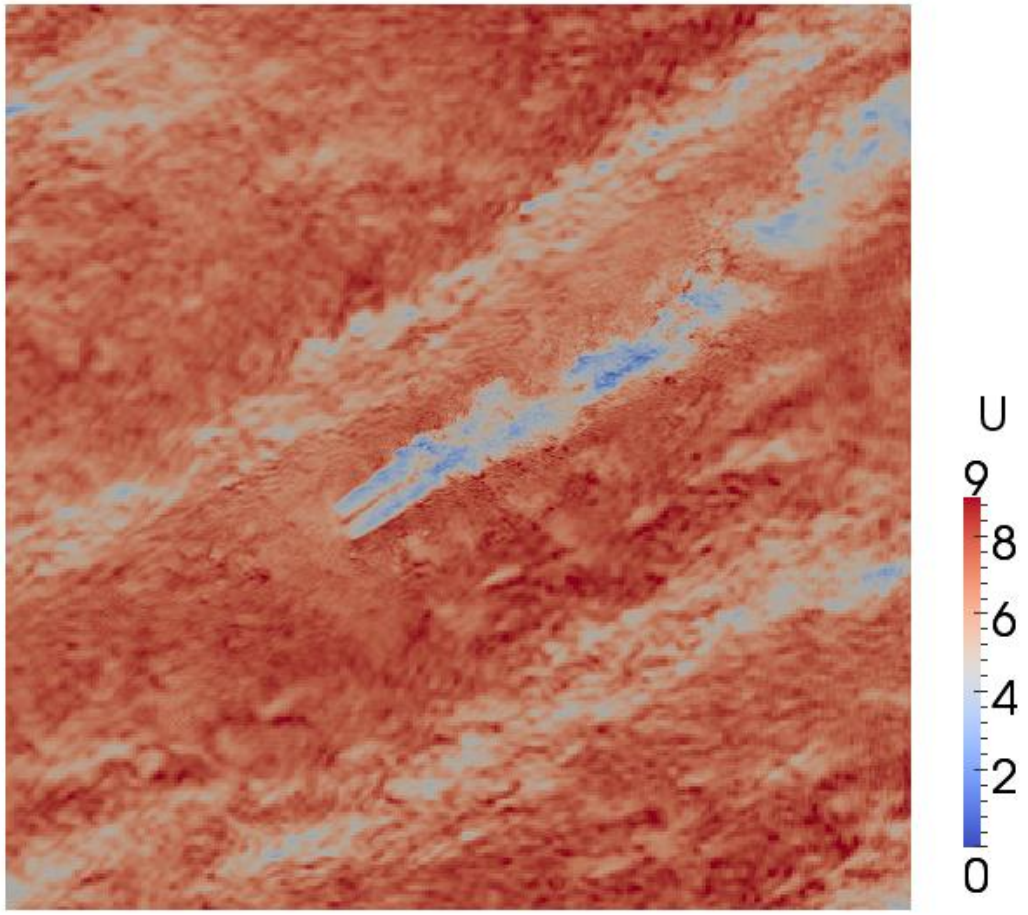
- **See actuator line guidelines**

Sample Output



Two NREL 5-MW turbines subjected to neutrally stable low-roughness atmospheric conditions showing the instantaneous streamwise velocity contours with iso-surface of Q invariant fixed at 0.0275 1/s

Sample Output



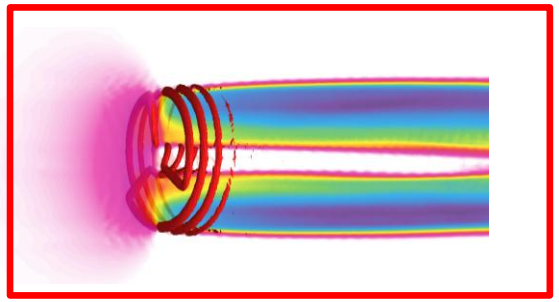
NREL 5MW turbine in unstable high-roughness atmospheric flow with mean speed at 8 m/s @ hub height

Wind Plant Simulation
windPlantSolver

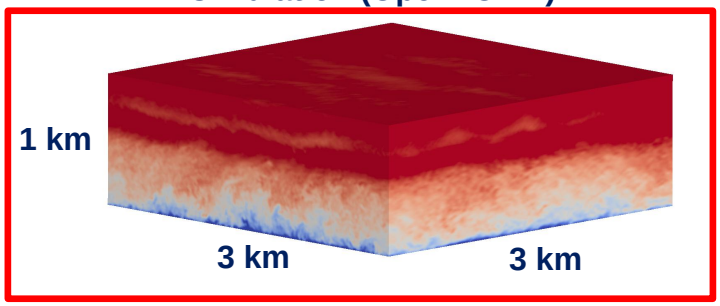
Wind Plant Simulation

- **Combination of the elements discussed above**

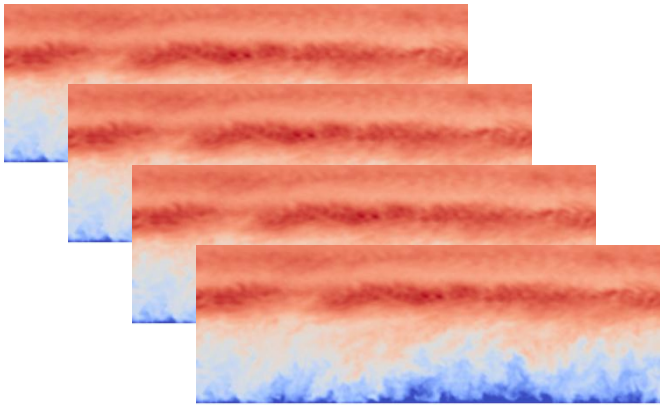
Actuator line turbine aerodynamics models (coupled with NREL's FAST turbine dynamics model)



"Precursor" atmospheric simulation (OpenFOAM)



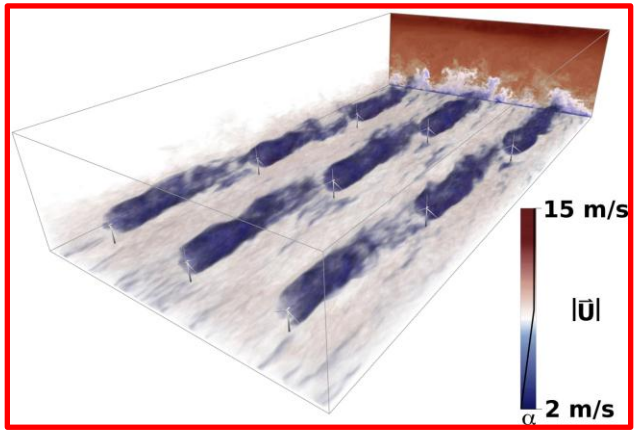
Initialize wind farm domain with precursor volume field



Save planes of data every N time steps

Use saved precursor data as inflow boundary conditions

Wind farm simulation (OpenFOAM)



windPlantSolver

- **It is simply ABLTerrainSolver with the horizontalAxisALM class included (but can still be used on flat terrain—it just does time averages)**

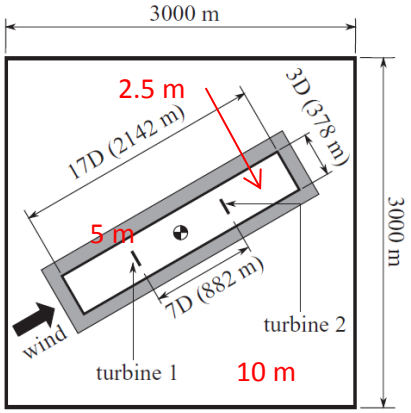
Output

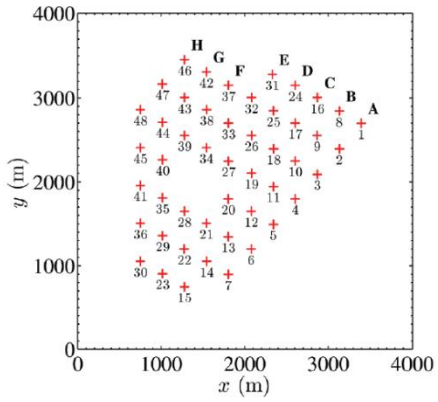
- **All the turbine information**
- **Instantaneous Fields**
  - U, T, p, u', T'
- **Mean Fields**
  - Umean, Tmean
- **Correlation Fields**
  - $\langle u'_i u'_j \rangle$, $\langle T u'_j \rangle$

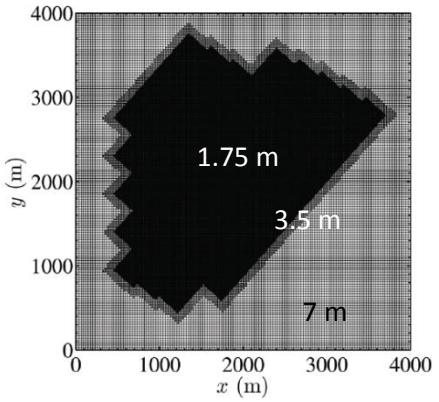
Guidelines for Use

- **Make sure domain boundaries have either predominant inflow or outflow**
  - Remember that with Coriolis, wind changes directions with altitude
  - Possible to have wind flowing in near ground and flowing out above
  - We do not have a good boundary condition for that case

- **Use local mesh refinement around the turbines**
  - but do it gently (i.e. give the turbulence time to cascade down before going to the next local refinement region)
  - We use toposet (with rotatedBox option) and refineMesh







Guidelines for Use

- **We generally use a time step such that the actuator line tip does not travel through more than one cell per time step**
- **Can use larger time steps with actuator disk and swept actuator line (which will be part of SOWFA soon).**

Compiling The Codes

Compiling the codes

- **Make sure you have OpenFOAM 2.0 or higher installed**
- **Download the SOWFA codes from our git repository**
  - https://github.com/NREL/SOWFA
    - git clone https://github.com/NREL/SOWFA
    - cd SOWFA
    - git pull
- **I keep a clean SOWFA directory, but do a copy of directory structure with soft linked files to my user-2.0.x directory**
  - cp –rs /home/mchurchf/OpenFOAM/SOWFA /home/mchurchf/OpenFOAM/mchurchf-2.0.x
  - cd mchurchf-2.0.x
- **Then in mchurchf-2.0.x, I run**
  - ./Allwclean
  - ./Allwmake
- **In this way, you can have once central SOWFA directory that you periodically git pull to, and have multiple different compiled versions of it (i.e, you may have user-2.0.x, user 2.2.x, and user-2.3.x directories that all link back SOWFA, but each run with the different versions of OpenFOAM, and which also contain your own non-SOWFA custom files)**
- **See the README files**

Example Cases:
Precursor Atmospheric Boundary Layer Simulation

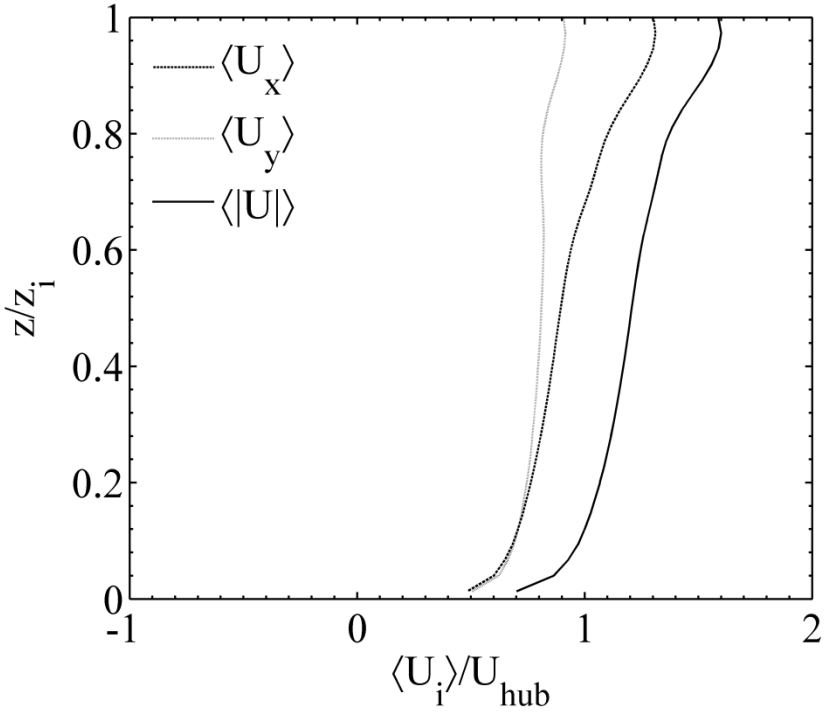
Atmospheric Boundary Layer

- **See "tutorials/precursorABL"**
- **Uses the solver ABLPisoSolver**
- **2 cases: Neutral and unstable ($-z_i/L \approx 4$)**
- **Wind: 9 m/s from 225 deg at 90 m**
- **Domain size: 3km × 3km × 1 km (x × y × z)**
  - Periodic in the horizontal
- **Grid size: 150 × 150 × 50**
  - 20 m resolution throughout
  - Coarser than we would normally run a simulation
- **Run on 32 processors**
  - Took about 27 min of wall clock time per 1000 s of simulation
  - Ran to 14,000 s of simulation time

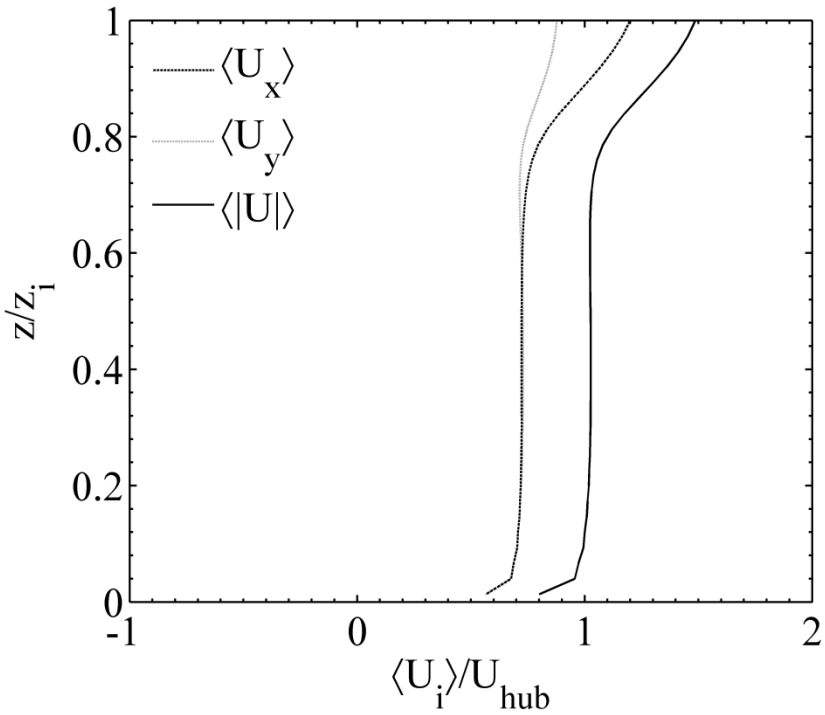
The Process (see the “Allrun” script)

- **Build a coarse mesh with blockMesh (serial)**
  - Builds a hexahedral mesh
- **Decompose the domain with decomposePar (serial)**
- **Use refineHexMesh (parallel) to globally refine mesh to desired resolution**
  - Splits hexahedral cells in half in each direction
- **Initialize the solution with setFieldsABL (parallel)**
- **Run the solver from time 0 to quasi-equilibrium**
- **Run the solver from quasi-equilibrium to +2000 s**
  - Run with sampling of contour planes and boundary data (boundary data to be used later in wind plant simulation as turbulent inflow)

Results

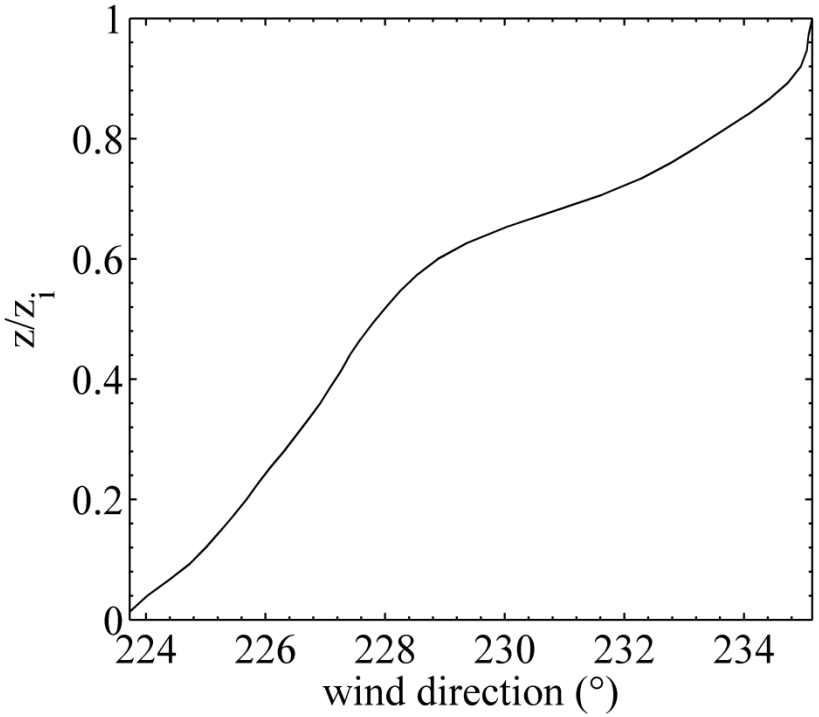


neutral

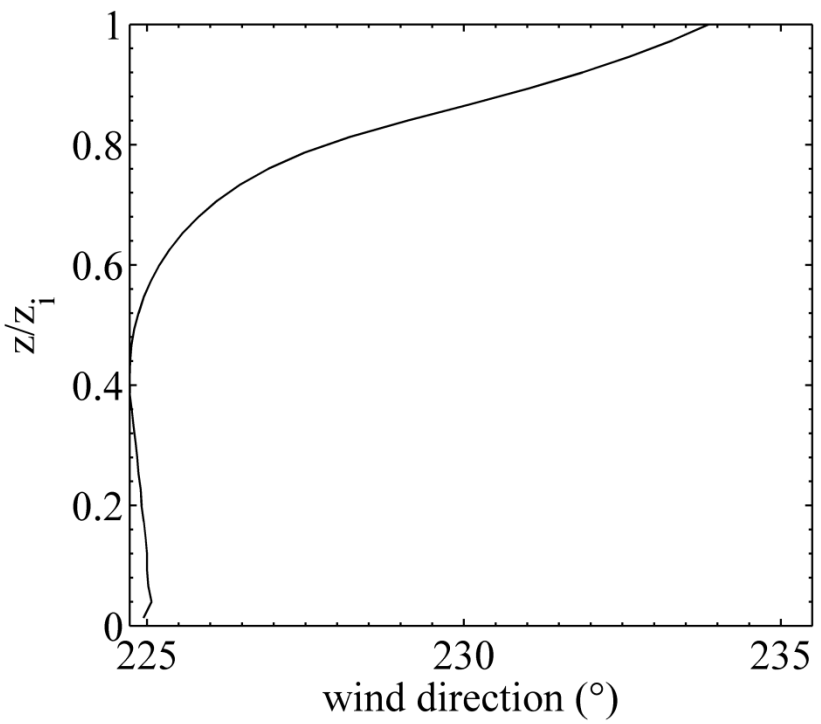


unstable

Results

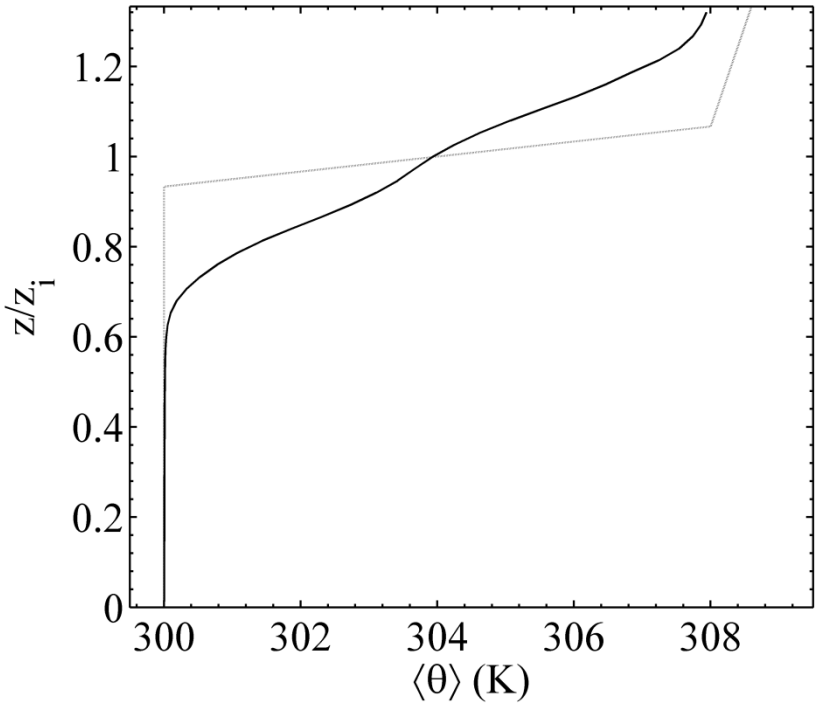


neutral

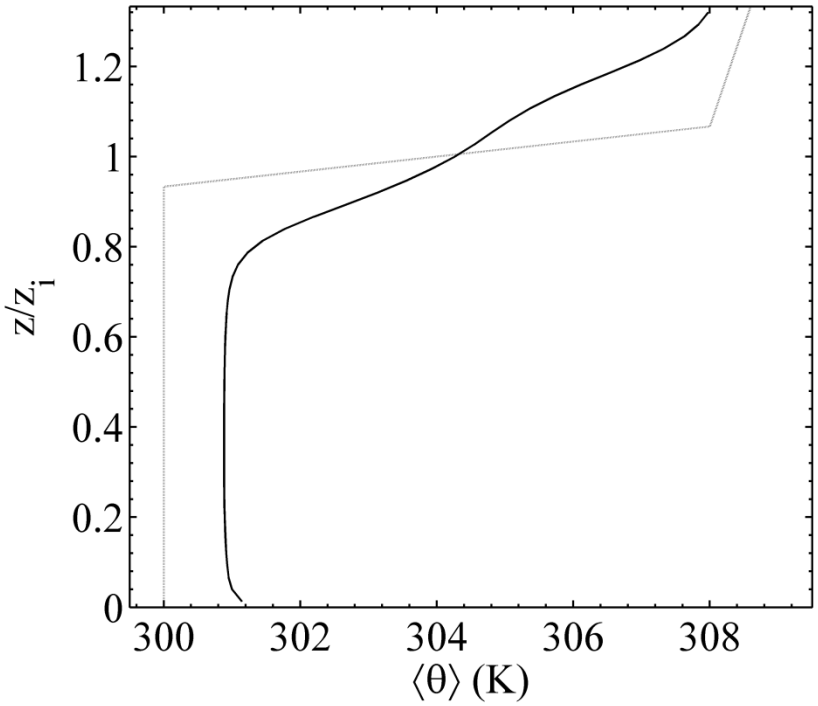


unstable

Results

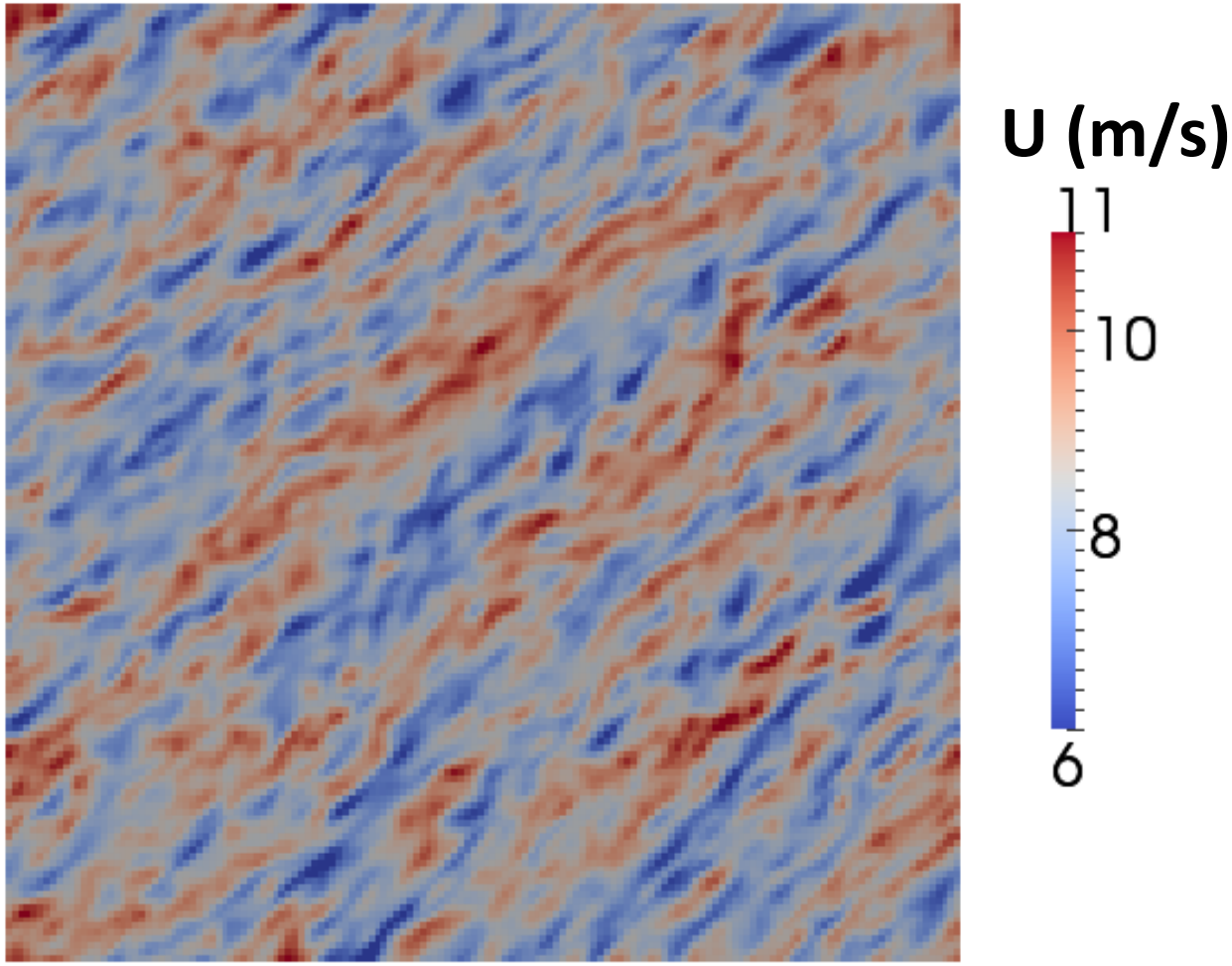


neutral



unstable

Results

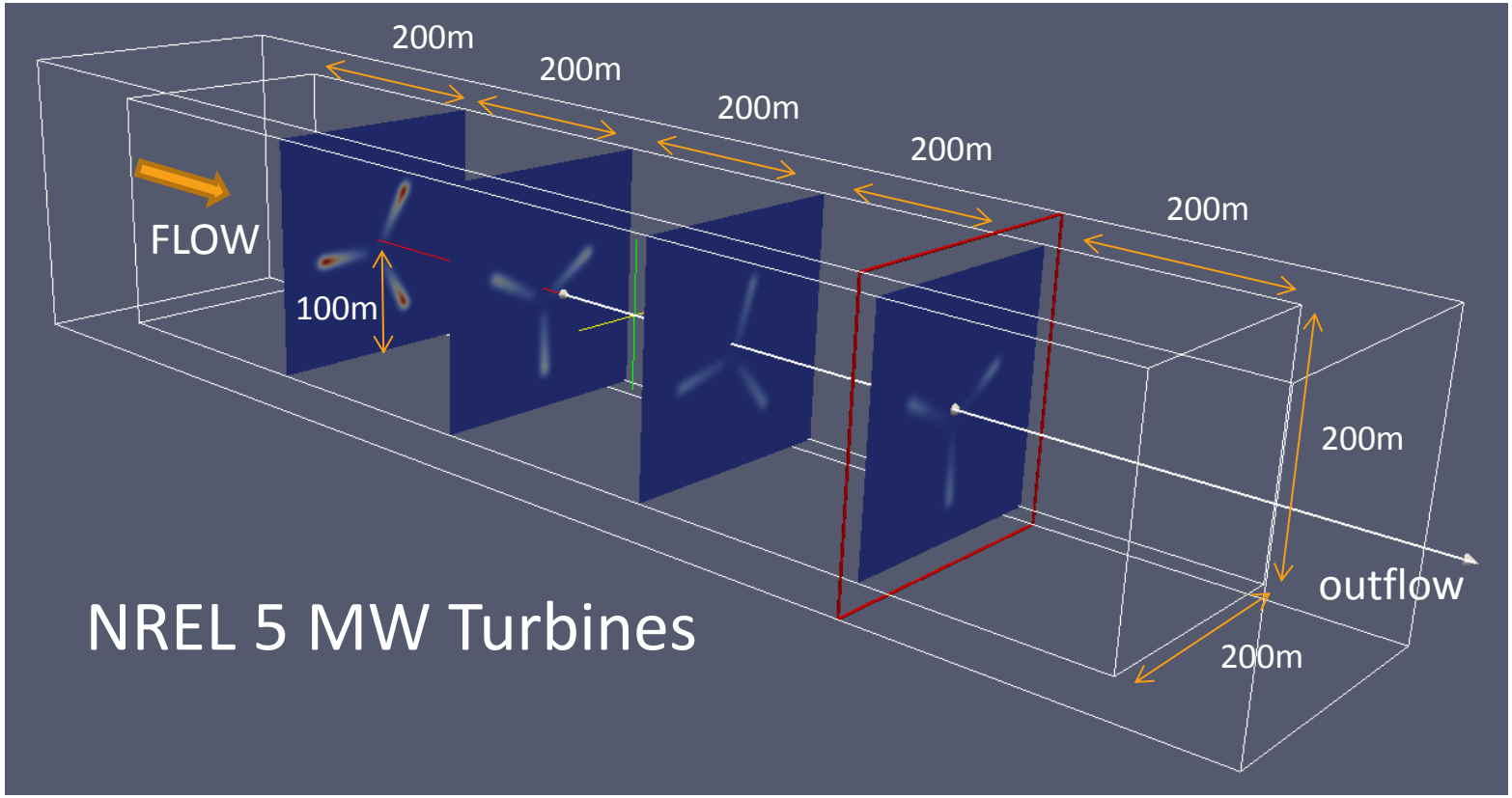


Example Cases:
FAST-Couple Actuator Lines in Duct Flow

Case Study: fastDuct

../tutorials/fastDuct/

Computational Domain



Uniform inflow condition at U_∞ = 8 m/s
Periodic BCs laterally (y and z directions)

Sample Run

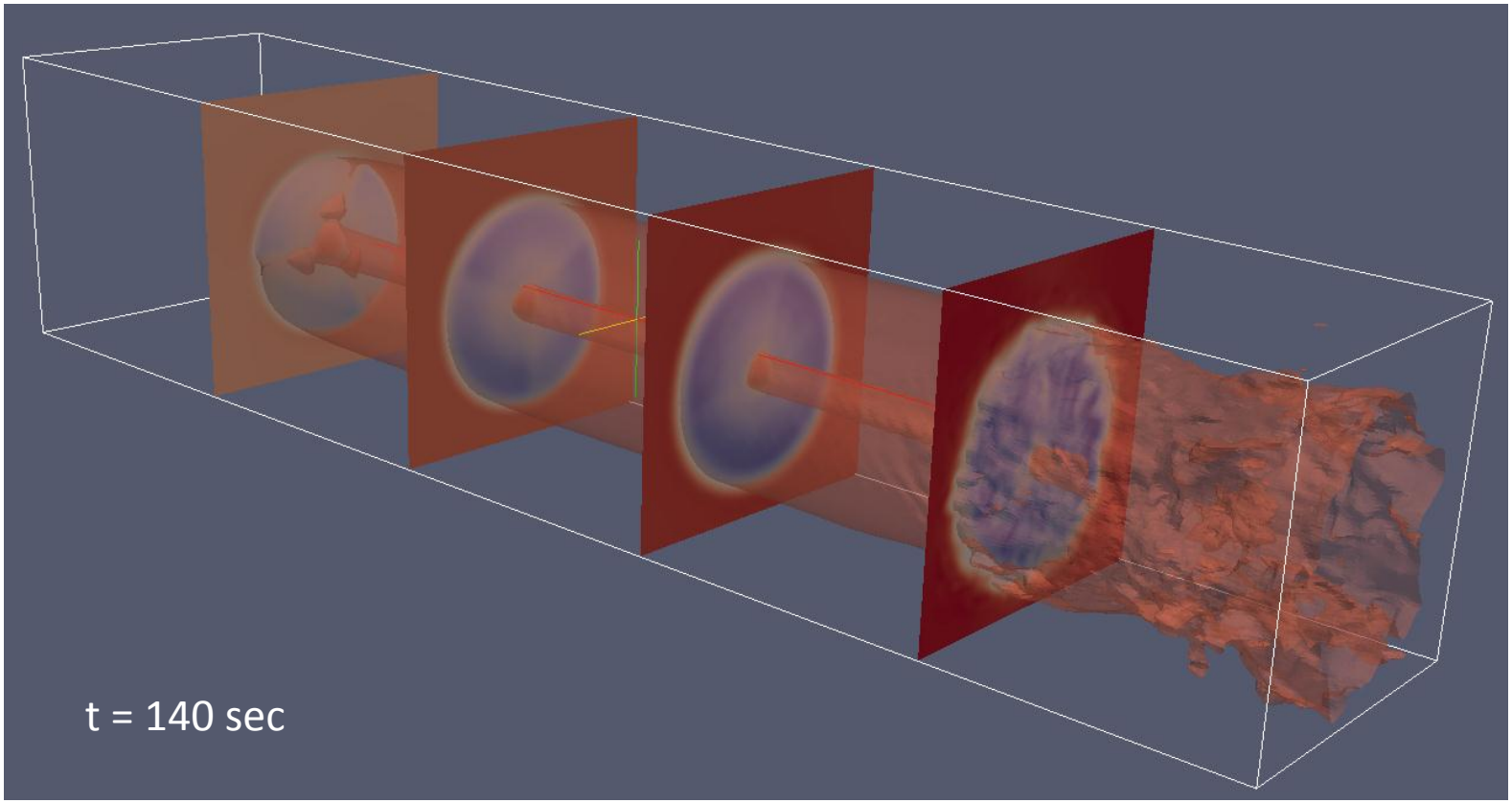
- In ../fastDuct/ execute “Allrun” script
  - currently set to run on a single node with 8 CPU cores
  - generates uniform mesh
  - decomposes the domain into nodes x cores
  - runs fastPisoSolver in parallel

- Once finished running:
  - execute “reconstructPar –time 140 (any desired saved time)
  - execute “foamToVTK –time 140
  - use ParaView for visualization
  - examine loads data from primary*.out using Excel/MatLab

- Run “AllClean” to remove saved flow data, loads, and the grid

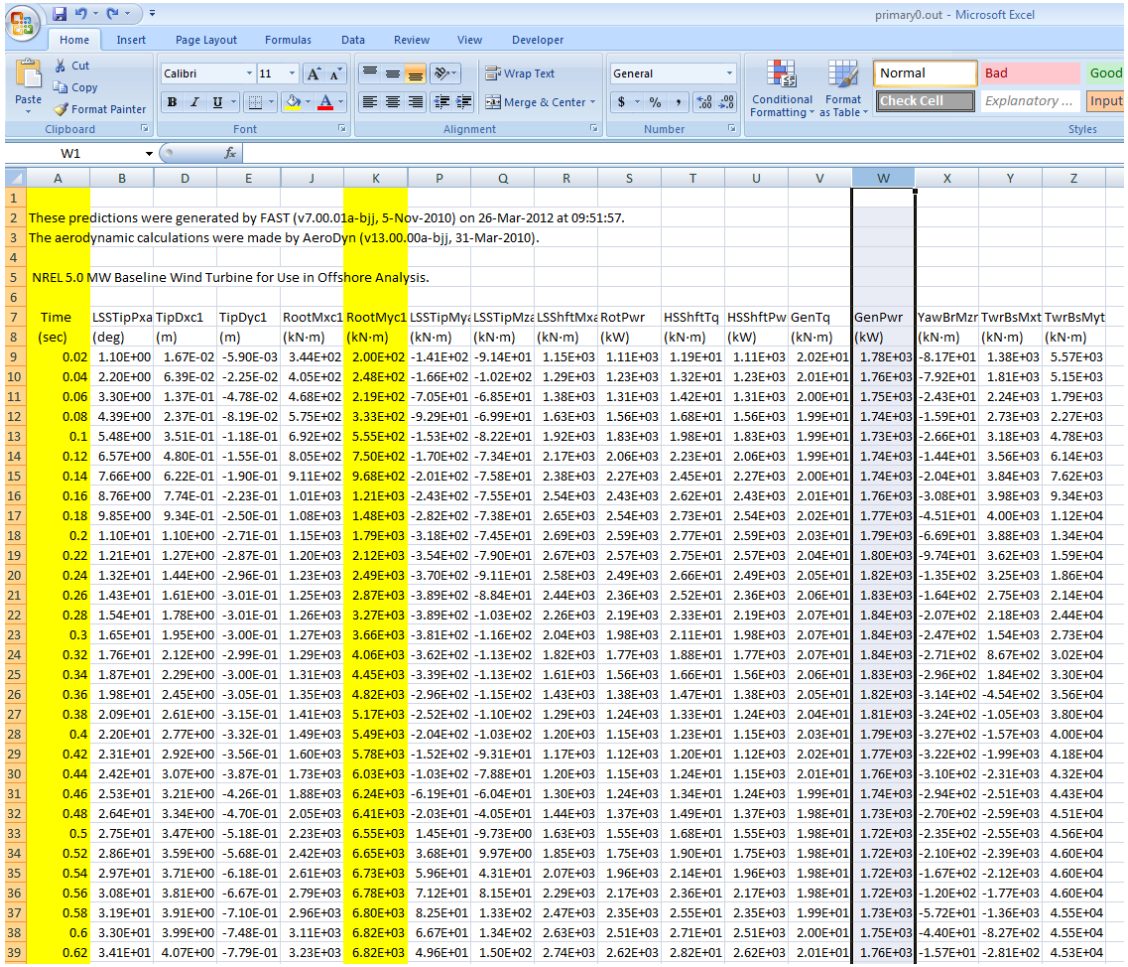
Sample Run

Streamwise Velocity Contours and iso-surface



Downstream turbine is being approached with wake structures

Out-of-plane Blade Loadings and Power Output from FAST



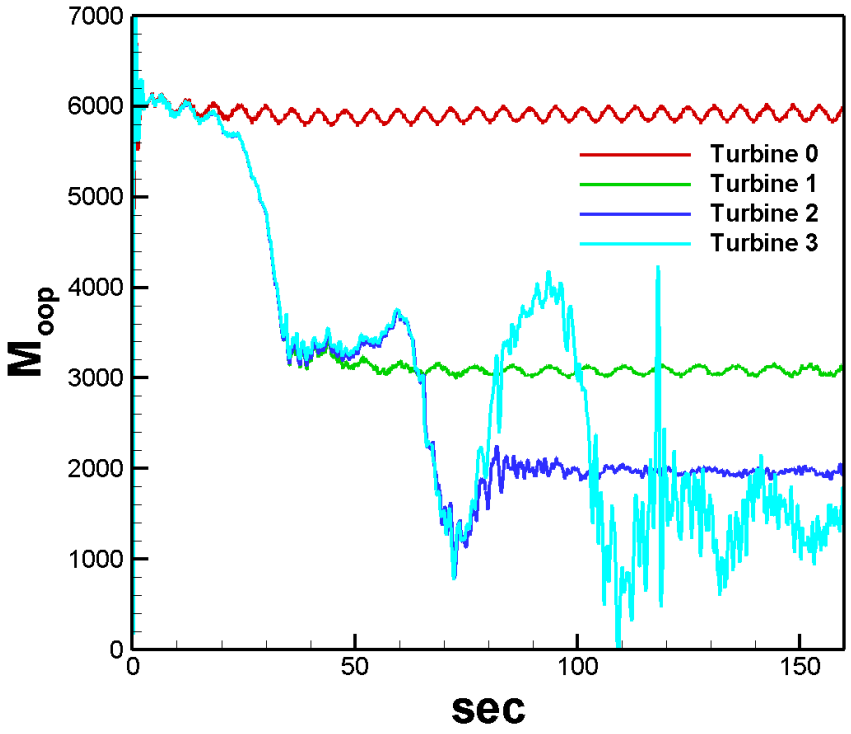
	A	B	D	E	J	K	P	Q	R	S	T	U	V	W	X	Y	Z
1																	
2	These predictions were generated by FAST (v7.00.01a-bjj, 5-Nov-2010) on 26-Mar-2012 at 09:51:57.																
3	The aerodynamic calculations were made by AeroDyn (v13.00.00a-bjj, 31-Mar-2010).																
4																	
5	NREL 5.0 MW Baseline Wind Turbine for Use in Offshore Analysis.																
6																	
7	Time	LSSTipPxa	TipDxc1	TipDyc1	RootMxc1	RootMyc1	LSSTipMy	LSSTipMza	LSShftMxa	RotPwr	HSShftTq	HSShftPw	GenTq	GenPwr	YawBrMzr	TwrBsMxt	TwrBsMyt
8	(sec)	(deg)	(m)	(m)	(kN·m)	(kN·m)	(kN·m)	(kN·m)	(kN·m)	(kW)	(kN·m)	(kW)	(kN·m)	(kW)	(kN·m)	(kN·m)	(kN·m)
9	0.02	1.10E+00	1.67E-02	-5.90E-03	3.44E+02	2.00E+02	-1.41E+02	-9.14E+01	1.15E+03	1.11E+03	1.19E+01	1.11E+03	2.02E+01	1.78E+03	-8.17E+01	1.38E+03	5.57E+03
10	0.04	2.20E+00	6.39E-02	-2.25E-02	4.05E+02	2.48E+02	-1.66E+02	-1.02E+02	1.29E+03	1.23E+03	1.32E+01	1.23E+03	2.01E+01	1.76E+03	-7.92E+01	1.81E+03	5.15E+03
11	0.06	3.30E+00	1.37E-01	-4.78E-02	4.68E+02	2.19E+02	-7.05E+01	-6.85E+01	1.38E+03	1.31E+03	1.42E+01	1.31E+03	2.00E+01	1.75E+03	-2.43E+01	2.24E+03	1.79E+03
12	0.08	4.39E+00	2.37E-01	-8.19E-02	5.75E+02	3.33E+02	-9.29E+01	-6.99E+01	1.63E+03	1.56E+03	1.68E+01	1.56E+03	1.99E+01	1.74E+03	-1.59E+01	2.73E+03	2.27E+03
13	0.1	5.48E+00	3.51E-01	-1.18E-01	6.92E+02	5.55E+02	-1.53E+02	-8.22E+01	1.92E+03	1.83E+03	1.98E+01	1.83E+03	1.99E+01	1.73E+03	-2.66E+01	3.18E+03	4.78E+03
14	0.12	6.57E+00	4.80E-01	-1.55E-01	8.05E+02	7.50E+02	-1.70E+02	-7.34E+01	2.17E+03	2.06E+03	2.23E+01	2.06E+03	1.99E+01	1.74E+03	-1.44E+01	3.56E+03	6.14E+03
15	0.14	7.66E+00	6.22E-01	-1.90E-01	9.11E+02	9.68E+02	-2.01E+02	-7.58E+01	2.38E+03	2.27E+03	2.45E+01	2.27E+03	2.00E+01	1.74E+03	-2.04E+01	3.84E+03	7.62E+03
16	0.16	8.76E+00	7.74E-01	-2.23E-01	1.01E+03	1.21E+03	-2.43E+02	-7.55E+01	2.54E+03	2.43E+03	2.62E+01	2.43E+03	2.01E+01	1.76E+03	-3.08E+01	3.98E+03	9.34E+03
17	0.18	9.85E+00	9.34E-01	-2.50E-01	1.08E+03	1.48E+03	-2.82E+02	-7.38E+01	2.65E+03	2.54E+03	2.73E+01	2.54E+03	2.02E+01	1.77E+03	-4.51E+01	4.00E+03	1.12E+04
18	0.2	1.10E+01	1.10E+00	-2.71E-01	1.15E+03	1.79E+03	-3.18E+02	-7.45E+01	2.69E+03	2.59E+03	2.77E+01	2.59E+03	2.03E+01	1.79E+03	-6.69E+01	3.88E+03	1.34E+04
19	0.22	1.21E+01	1.27E+00	-2.87E-01	1.20E+03	2.12E+03	-3.54E+02	-7.90E+01	2.67E+03	2.57E+03	2.75E+01	2.57E+03	2.04E+01	1.80E+03	-9.74E+01	3.62E+03	1.59E+04
20	0.24	1.32E+01	1.44E+00	-2.96E-01	1.23E+03	2.49E+03	-3.70E+02	-9.11E+01	2.58E+03	2.49E+03	2.66E+01	2.49E+03	2.05E+01	1.82E+03	-1.35E+02	3.25E+03	1.86E+04
21	0.26	1.43E+01	1.61E+00	-3.01E-01	1.25E+03	2.87E+03	-3.89E+02	-8.84E+01	2.44E+03	2.36E+03	2.52E+01	2.36E+03	2.06E+01	1.83E+03	-1.64E+02	2.75E+03	2.14E+04
22	0.28	1.54E+01	1.78E+00	-3.01E-01	1.26E+03	3.27E+03	-3.89E+02	-1.03E+02	2.26E+03	2.19E+03	2.33E+01	2.19E+03	2.07E+01	1.84E+03	-2.07E+02	2.18E+03	2.44E+04
23	0.3	1.65E+01	1.95E+00	-3.00E-01	1.27E+03	3.66E+03	-3.81E+02	-1.16E+02	2.04E+03	1.98E+03	2.11E+01	1.98E+03	2.07E+01	1.84E+03	-2.47E+02	1.54E+03	2.73E+04
24	0.32	1.76E+01	2.12E+00	-2.99E-01	1.29E+03	4.06E+03	-3.62E+02	-1.13E+02	1.82E+03	1.77E+03	1.88E+01	1.77E+03	2.07E+01	1.84E+03	-2.71E+02	8.67E+02	3.02E+04
25	0.34	1.87E+01	2.29E+00	-3.00E-01	1.31E+03	4.45E+03	-3.39E+02	-1.13E+02	1.61E+03	1.56E+03	1.66E+01	1.56E+03	2.06E+01	1.83E+03	-2.96E+02	1.84E+02	3.30E+04
26	0.36	1.98E+01	2.45E+00	-3.05E-01	1.35E+03	4.82E+03	-2.96E+02	-1.15E+02	1.43E+03	1.38E+03	1.47E+01	1.38E+03	2.05E+01	1.82E+03	-3.14E+02	-4.54E+02	3.56E+04
27	0.38	2.09E+01	2.61E+00	-3.15E-01	1.41E+03	5.17E+03	-2.52E+02	-1.10E+02	1.29E+03	1.24E+03	1.33E+01	1.24E+03	2.04E+01	1.81E+03	-3.24E+02	-1.05E+03	3.80E+04
28	0.4	2.20E+01	2.77E+00	-3.32E-01	1.49E+03	5.49E+03	-2.04E+02	-1.03E+02	1.20E+03	1.15E+03	1.23E+01	1.15E+03	2.03E+01	1.79E+03	-3.27E+02	-1.57E+03	4.00E+04
29	0.42	2.31E+01	2.92E+00	-3.56E-01	1.60E+03	5.78E+03	-1.52E+02	-9.31E+01	1.17E+03	1.12E+03	1.20E+01	1.12E+03	2.02E+01	1.77E+03	-3.22E+02	-1.99E+03	4.18E+04
30	0.44	2.42E+01	3.07E+00	-3.87E-01	1.73E+03	6.03E+03	-1.03E+02	-7.88E+01	1.20E+03	1.15E+03	1.24E+01	1.15E+03	2.01E+01	1.76E+03	-3.10E+02	-2.31E+03	4.32E+04
31	0.46	2.53E+01	3.21E+00	-4.26E-01	1.88E+03	6.24E+03	-6.19E+01	-6.04E+01	1.30E+03	1.24E+03	1.34E+01	1.24E+03	1.99E+01	1.74E+03	-2.94E+02	-2.51E+03	4.43E+04
32	0.48	2.64E+01	3.34E+00	-4.70E-01	2.05E+03	6.41E+03	-2.03E+01	-4.05E+01	1.44E+03	1.37E+03	1.49E+01	1.37E+03	1.98E+01	1.73E+03	-2.70E+02	-2.59E+03	4.51E+04
33	0.5	2.75E+01	3.47E+00	-5.18E-01	2.23E+03	6.55E+03	1.45E+01	-9.73E+00	1.63E+03	1.55E+03	1.68E+01	1.55E+03	1.98E+01	1.72E+03	-2.35E+02	-2.55E+03	4.56E+04
34	0.52	2.86E+01	3.59E+00	-5.68E-01	2.42E+03	6.65E+03	3.68E+01	9.97E+00	1.85E+03	1.75E+03	1.90E+01	1.75E+03	1.98E+01	1.72E+03	-2.10E+02	-2.39E+03	4.60E+04
35	0.54	2.97E+01	3.71E+00	-6.18E-01	2.61E+03	6.73E+03	5.96E+01	4.31E+01	2.07E+03	1.96E+03	2.14E+01	1.96E+03	1.98E+01	1.72E+03	-1.67E+02	-2.12E+03	4.60E+04
36	0.56	3.08E+01	3.81E+00	-6.67E-01	2.79E+03	6.78E+03	7.12E+01	8.15E+01	2.29E+03	2.17E+03	2.36E+01	2.17E+03	1.98E+01	1.72E+03	-1.20E+02	-1.77E+03	4.60E+04
37	0.58	3.19E+01	3.91E+00	-7.10E-01	2.96E+03	6.80E+03	8.25E+01	1.33E+02	2.47E+03	2.35E+03	2.55E+01	2.35E+03	1.99E+01	1.73E+03	-5.72E+01	-1.36E+03	4.55E+04
38	0.6	3.30E+01	3.99E+00	-7.48E-01	3.11E+03	6.82E+03	6.67E+01	1.34E+02	2.63E+03	2.51E+03	2.71E+01	2.51E+03	2.00E+01	1.75E+03	-4.40E+01	-8.27E+02	4.55E+04
39	0.62	3.41E+01	4.07E+00	-7.79E-01	3.23E+03	6.82E+03	4.96E+01	1.50E+02	2.74E+03	2.62E+03	2.82E+01	2.62E+03	2.01E+01	1.76E+03	-1.57E+01	-2.81E+02	4.53E+04

Example: primary0.out

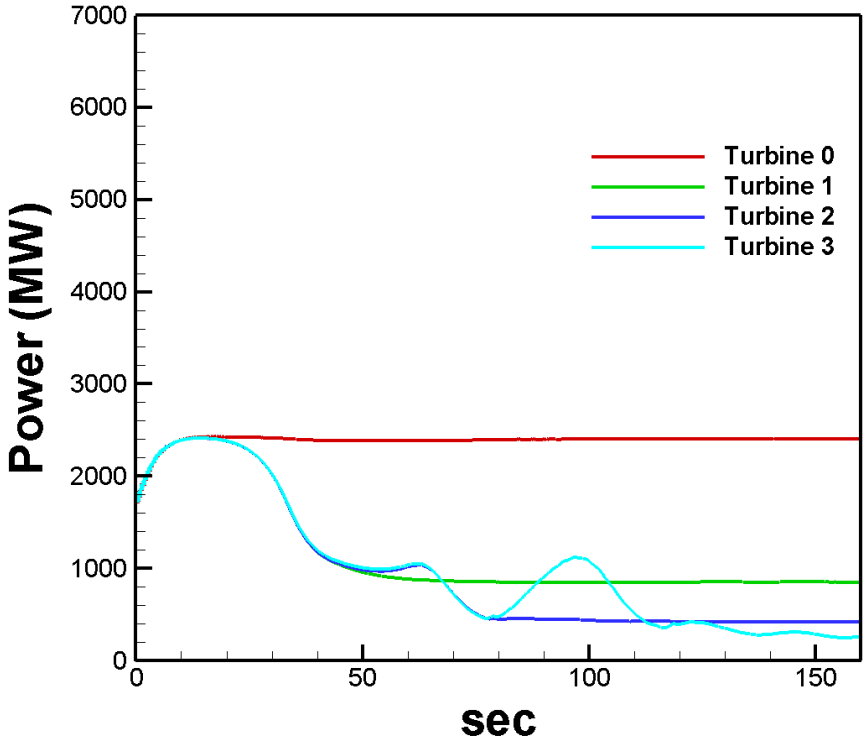
- loads data primary*out can be opened using Excel with "tab delimited" options

- columns of data can be selected to generate figures

Out-of-plane Blade Loadings and Power Output from FAST



Blade root out-of-plane bending moment



Power generation

Example Cases:
Wind Farm Simulation

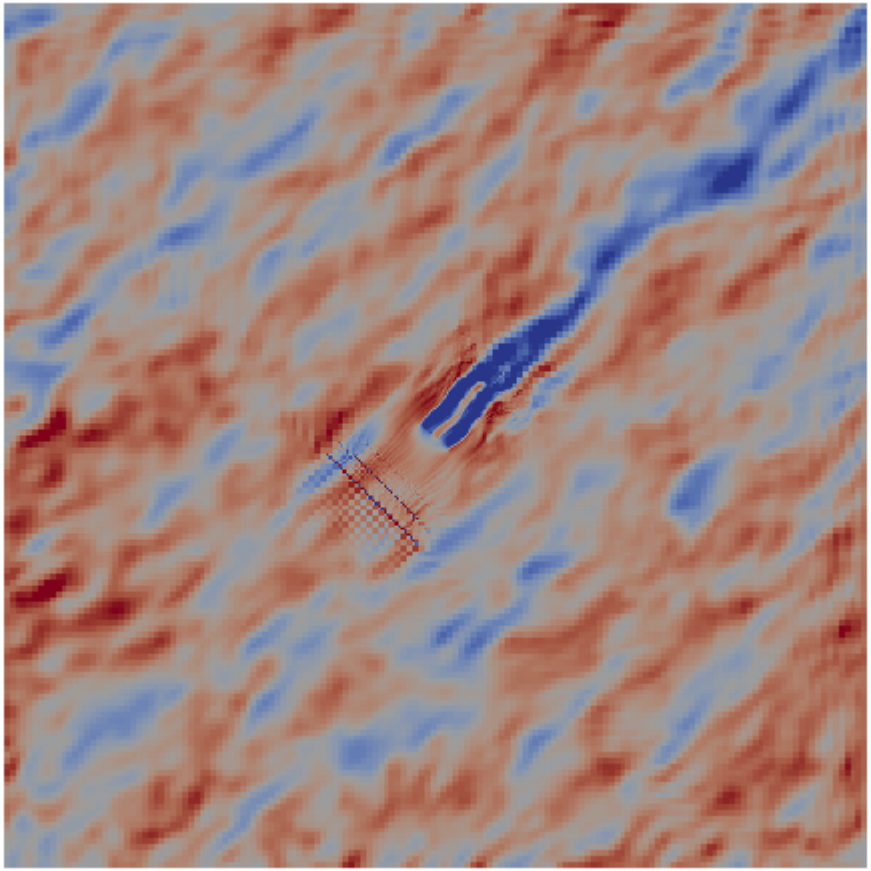
Wind Farm Simulation

- **See “tutorials/windPlant”**
- **Uses the solver windPlantPisoSolver**
- **2 cases: Neutral and unstable ($-z_i/L \approx 4$)**
- **Wind: 9 m/s from 225 deg at 90 m**
- **Domain size: 3km × 3km × 1 km (x × y × z)**
- **Grid size:**
  - Background grid is same as ABL precursor
  - Locally refined down to 2.5 m around single 5MW turbine in horizontal center of domain with 90 m hub height
- **Run on 64 processors**
  - Took 21 hrs for 750 s of simulation time
  - Much smaller time step than precursor (dt = 0.015s)

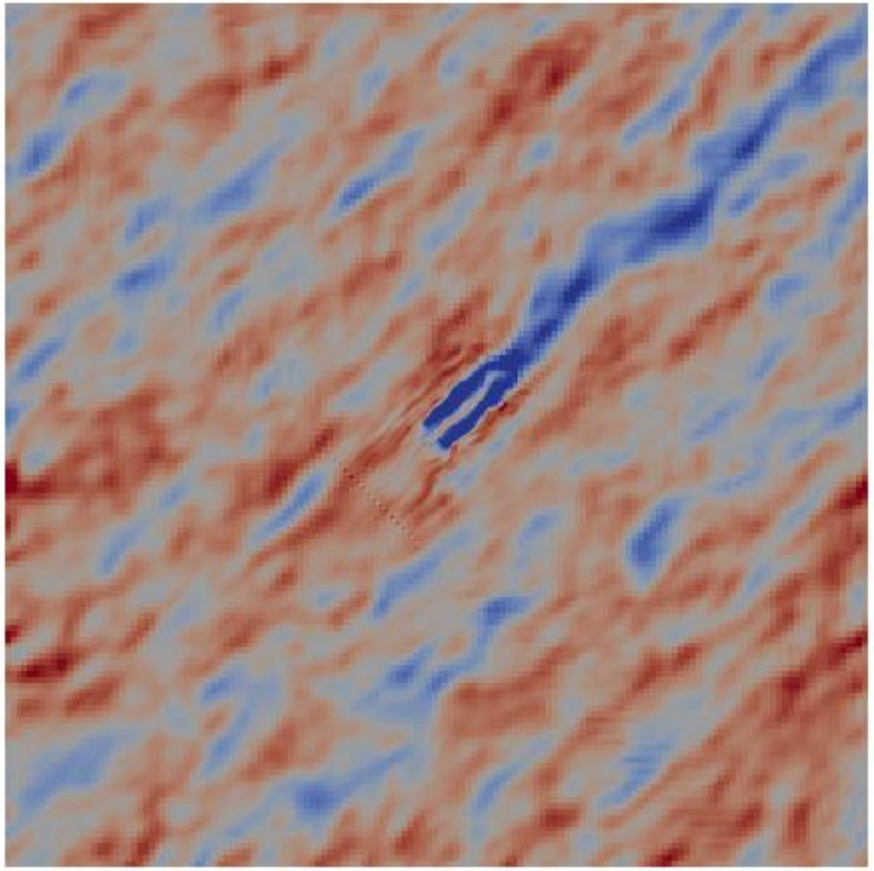
The Process (see the “Allrun” script)

- **Build a coarse mesh with blockMesh (serial)**
  - Builds a hexahedral mesh
- **Locally refine with topoSet (serial) and refineMesh (serial)**
- **Use refineMesh (serial) to globally refine mesh to desired resolution**
  - Splits hexahedral cells in half in each direction
- **Use initial field files from precursor simulation, but change the periodic boundaries to inflow/outflow (timeVaryingFixedMapped) to use saved boundary data from precursor using changeDictionary (serial)**
- **Renumber the cells to get better matrix banding with renumberMesh (serial)**
- **Decompose the domain with decomposePar (serial)**
- **Initialize solution with precursor field using mapFields (serial)**
- **Run the solver**

Results

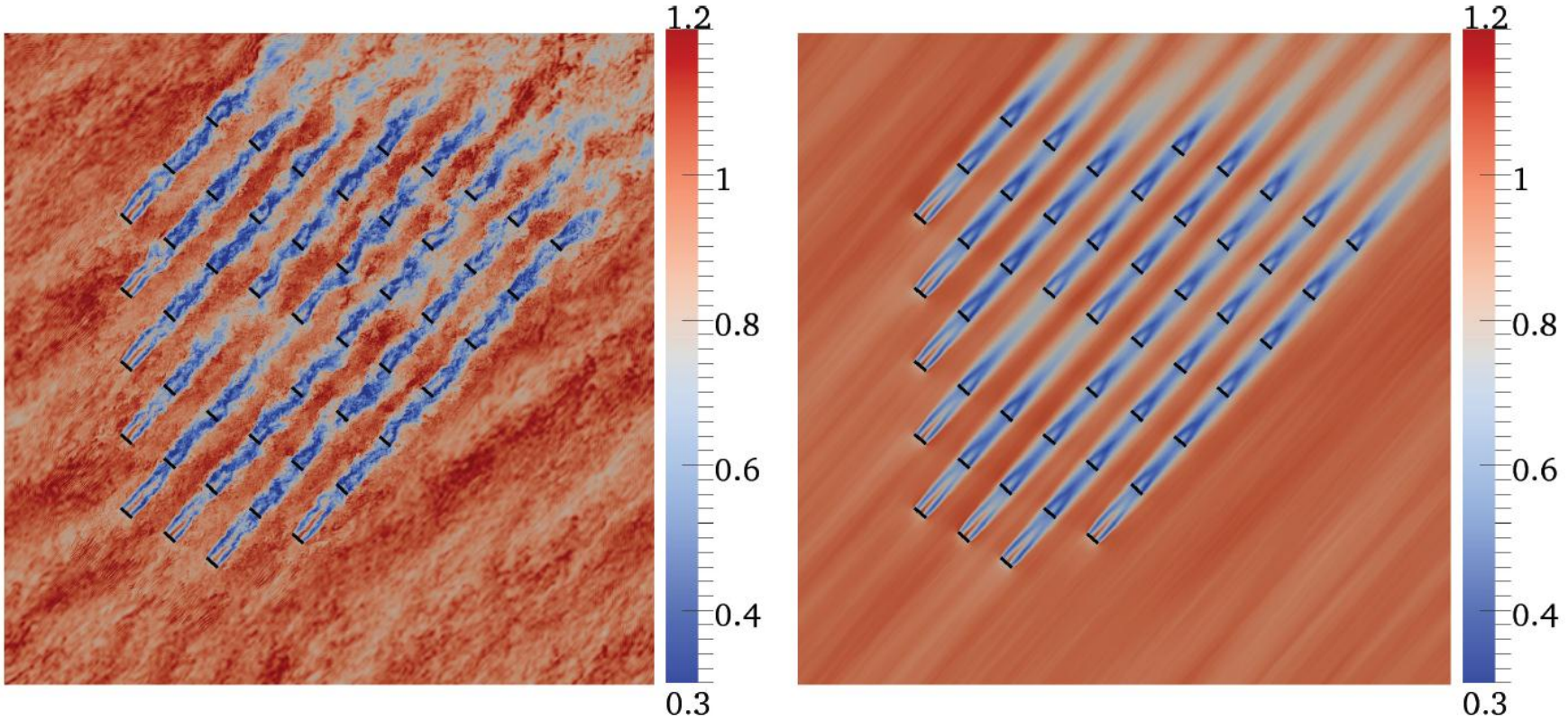


The effect of too rapid a transition in grid resolution



Increasing the filter width helped, but not the best fix

Results



Results from a 48 turbine simulation[1] of the Lillgrund offshore wind farm

[1] Churchfield, M. J., Lee, S., Michalakes, J., and Moriarty, P. J., "A Numerical Study of the Effects of Atmospheric and Wake Turbulence on Wind Turbine Dynamics," Journal of Turbulence, Vol. 13, No. 14, pp. 1-32, 2012.

Some References

Churchfield, M. J., Lee, S., Michalakes, J., and Moriarty, P. J., "A Numerical Study of the Effects of Atmospheric and Wake Turbulence on Wind Turbine Dynamics," Journal of Turbulence, Vol. 13, No. 14, pp. 1-32, 2012.

Churchfield, M. J., Lee, S., Moriarty, P. J., Martinez, L. A., Leonardi, S., Vijayakumar, G., and Brasseur, J. G., "A Large-Eddy Simulation of Wind-Plant Aerodynamics," AIAA Paper AIAA-2012-537, 2012.

Lee, S., Churchfield, M. J., Moriarty, P. J., Jonkman, J., "Atmospheric and Wake Turbulence Impacts on Wind Turbine Fatigue Loading," AIAA Paper AIAA-2012-540, 2012.

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Acknowledgements

- **Atmospheric Boundary Layer and OpenFOAM-related**
  - Jim Brasseur, Eric Patterson, Ganesh Vijayakumar, Adam Lavely, Mike Kinzel
- **Actuator Line Model**
  - Tony Martínez, Stefano Leonardi
- **NREL collaborators**
  - Pat Moriarty, Mike Sprague, Julie Lundquist, John Michalakes, Avi Purkayastha

Help

- **First check the NWTC Codes forum at: https://wind.nrel.gov/forum/wind/**

- **Then contact**
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  - Sang Lee (sang.lee@nrel.gov)