Wind farm-wide aggregated turbulence modeling

- An open-source medium-fidelity ambient wind input to NREL's tool FAST.farm
- A step toward frequency-domain modeling of offshore wind farms

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Motivation State-of-the-art ambient wind modeling not appropriate for medium-fidelity wind farm modeling

Individual turbines

Stochastic inflow simulator (e.g. TurbSim for OpenFAST)

Point-based PSD (wind spectrum) → Coherence → IFFT → Frozen wake → Time series

- Frozen wake not valid at wind farm scale: the ambient wind of a point downstream is not a delayed copy of the ambient wind of a point upstream
- Grid size covering a farm requires exceedingly large active memory and computational time resources

Wind farms

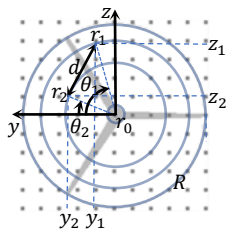
Atmospheric boundary layer solver (e.g. ABLSolver for SOWFA)

Time-domain CFD: Convection, Coriolis force, pressure gradients, viscous/SGS stresses, buoyancy, … → Finite volumes → Time series

- Exceedingly large computational time and disk memory resources required
- Steep learning curve
- Overly high fidelity considering uncertainties in medium-fidelity wake model

Step 1 Turbine level [1]

- **Objective:** Reducing wind field to a hub-based 3-component vector
- **Method:** Averaging coherence over all pairs of points on the rotor disc
- **Outcome:** Frequency-domain transfer function from point-based to aggregated PSD



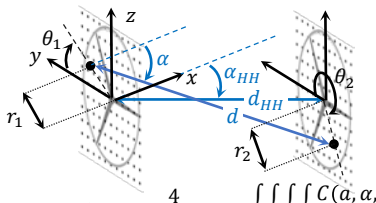
$$H^2(f) = 4\frac{\int_{r_0}^{R}\int_{r_0}^{R}\int_{0}^{2\pi}\int_{0}^{2\pi} C(d,f)\; r_1 r_2 d\theta_1 d\theta_2 dr_1 dr_2}{(R^2 - r_0^2)^2}$$

$$S_{agg}(f) = H^2(f)\; S_{point}\,(f)$$

- Load-equivalent agg. wind may be included by weighted averaging, 3p harmonics by azimuthal expansion
- Farm-coherent full-field realizations may be post-generated from agg. ones

Step 2 Farm level

1. Use as input wind farm-wide coherence and PSD point-based models derived from measurements in offshore farms [3,4]
2. Aggregate coherence by averaging over all pairs of points between 2 virtual rotor discs with hub located at grid points



$$C_{agg}(d_{HH},\alpha_{HH},f) = \frac{4}{(R^2 - r_0^2)^2}\frac{\int\int\int\int C(a,\alpha,f)}{H_{rotor\,1}(f)\,H_{rotor\,2}(f)}$$

3. Add a phase offset in coherence before IFFT to model time lag due to convection [2,4]

$$\varphi = 2\pi\frac{d_{HH}\cos\alpha_{HH}}{U_\infty}f$$

4. Compute a realization of the aggregated wind field satisfying

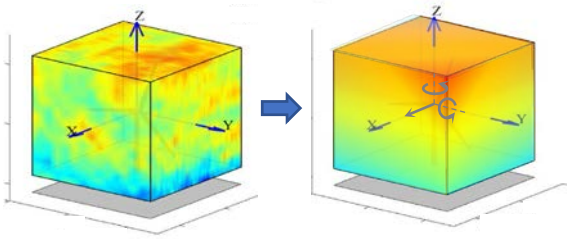
Diagonal matrix of agg. PSDs; Statistical averaging

$$\sqrt{\boldsymbol{S}_{agg}}\,\mathbf{C}_{agg}\sqrt{\boldsymbol{S}_{agg}} = \langle UU^H\rangle$$

Agg. coherence matrix (complex); Fourier transform of wind speeds at grid points

Step 3 Refinement

- **Motivation:** Rotor-scale spatial variations affect loads and possibly wake modeling
- **Objective:** Adding linear shear components, equivalent to rotational speeds around normal axes to each wind component



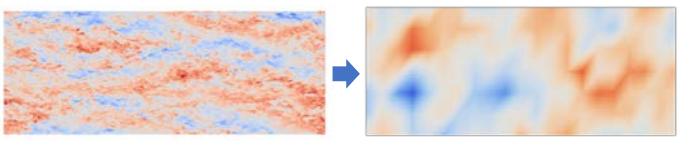
- **Method:** As in step 1 and 2 by weighting coherence with projected distance from hub, e.g. for horizontal shear in x comp.:

$$H^2(f) = \frac{\int\int\int\int C(d,f)\; y_1 y_2\; r_1 r_2}{\int\int\int\int\; {y_1}^2 {y_2}^2 r_1 r_2}$$

- **Outcome:** Augmented system in Step 2 with shear-specific agg. PSDs, agg. coherence and cross-coherence with mean component

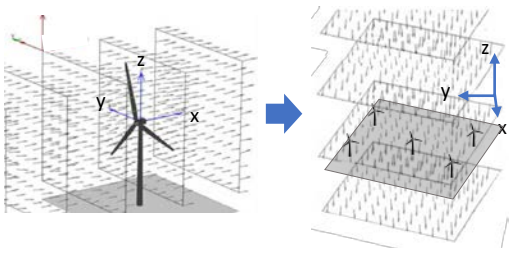
Turbulence aggregation

- **Number of grid points reduced by ~20^3, number of time steps by ~20**
- **Limited error induced on further wind farm modeling:**
  - ✓ **turbine loads and response**
  - ✓ **wake and wake interactions (ambient wind is anyway averaged [7])**



Step 4 Open-source implementation in NREL's TurbSim

- Keep using Veer's method with frozen-wake assumption (TurbSim's core [8,9])
  - ✓ Only 1 agg. vertical point (hub height) → convect pre-computed aggregated turbulence box through the XY (farm) plane instead of the YZ (rotor) plane
  - ✓ Deal with complex, anisotropic coherence by decoupling complex phase and modulus [5] and computing nearest positive-definite coherence matrix [6]
- Add grid points for each turbine location given a layout, write output in FAST.farm- and OpenFAST-compatible file formats



Case study: CPU cores: 8, area: 5 km², sim. time: 3 hrs

	ABLSolver	TurbSim
Grid res.	10 m	200 m
Time res.	1 s	20 s
CPU time	3 days*	1.5 hrs
File size	180 GB*	20 MB

*Derived from example cases given by NREL

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