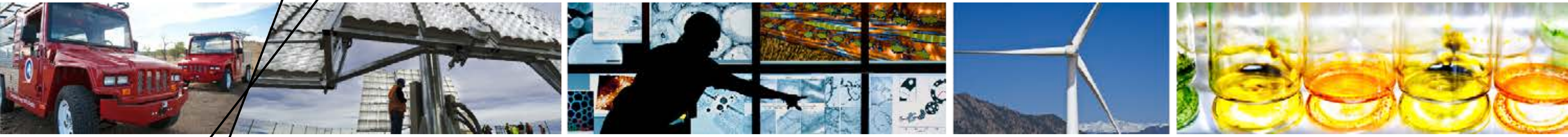
The Role of Design Standards in Wind Plant Optimization



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International Conference on Future Technologies for Wind Energy

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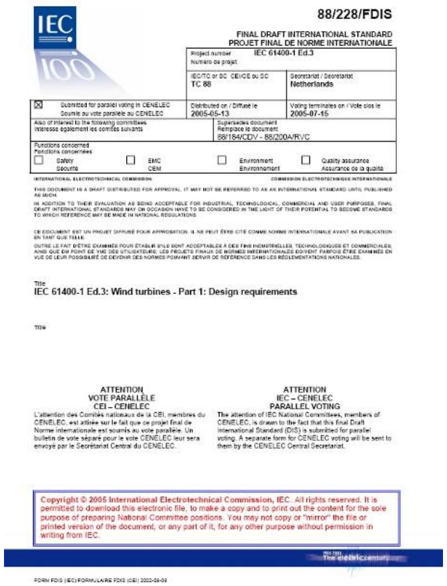
Outline

- **Standards for wind turbine design**
  - Stand-alone wind turbine
  - Wind-farm conditions
- **Wake models**
  - Production
  - Loading and production
- **Statistical properties of wind plant flow fields**
  - Mean
  - Variance, power spectral density (PSD), and coherence
- **Proper orthogonal decomposition of wind plant flow fields**
- **Conclusion**

Requirements and Consequences of Standards

- **The design standards used across the entire industry will drive the reliability across all suppliers … "uniform" safety margin.**
  - Modeling and simulation tools and component testing capabilities must be able to demonstrate ability to meet the standard.
  - A well-written standard is therefore well fitted to the modeling and testing capabilities of the industry.
- ***Any single innovation that does not keep loads within margins across all design load cases might not be an improvement.***

Turbine *Specifications* – Design Standards



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FINAL DRAFT INTERNATIONAL STANDARD
PROJET FINAL DE NORME INTERNATIONALE

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IEC/TC or SC CEI/CE ou SC: TC 88
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Supersedes document / Remplace le document: 88/184/CDV - 88/200A/RVC
Functions concerned / Fonctions concernées
☐ Safety / Sécurité ☐ EMC / CEM ☐ Environment / Environnement ☐ Quality assurance / Assurance de la qualité

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OUTRE LE FAIT D'ÊTRE EXAMINÉS POUR ÉTABLIR S'ILS SONT ACCEPTABLES À DES FINS INDUSTRIELLES, TECHNOLOGIQUES ET COMMERCIALES, AINSI QUE DU POINT DE VUE DES UTILISATEURS, LES PROJETS FINAUX DE NORMES INTERNATIONALES DOIVENT PARFOIS ÊTRE EXAMINÉS EN VUE DE LEUR POSSIBILITÉ DE DEVENIR DES NORMES POUVANT SERVIR DE RÉFÉRENCE DANS LES RÉGLEMENTATIONS NATIONALES.

Title
IEC 61400-1 Ed.3: Wind turbines - Part 1: Design requirements

Titre

ATTENTION
VOTE PARALLÈLE
CEI – CENELEC

L'attention des Comités nationaux de la CEI, membres du CENELEC, est attirée sur le fait que ce projet final de Norme internationale est soumis au vote parallèle. Un bulletin de vote séparé pour le vote CENELEC leur sera envoyé par le Secrétariat Central du CENELEC.

ATTENTION
IEC – CENELEC
PARALLEL VOTING

The attention of IEC National Committees, members of CENELEC, is drawn to the fact that this final Draft International Standard (DIS) is submitted for parallel voting. A separate form for CENELEC voting will be sent to them by the CENELEC Central Secretariat.

The electric century

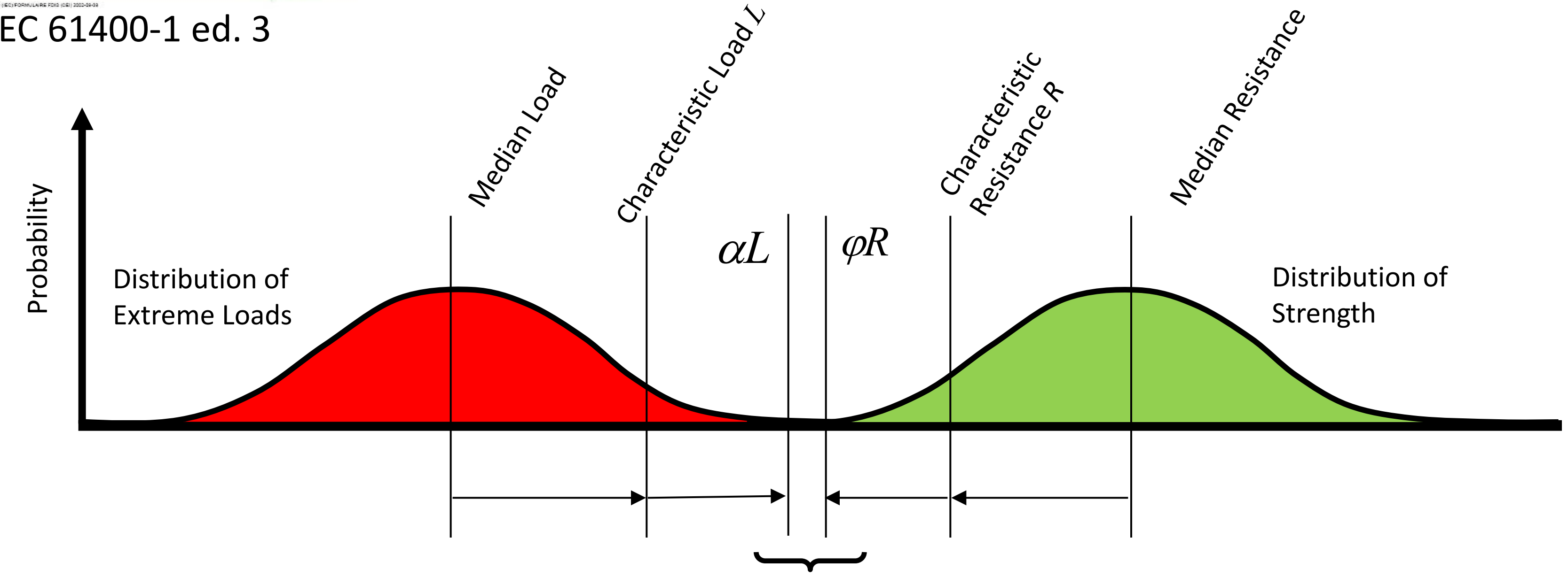
FORM FDIS (IEC)/FORMULAIRE FDIS (CEI) 2002-09-09

IEC 61400-1 ed. 3

- Characteristic Loads (e.g., 95% quantile)
  - Suite of design load cases (DLCs)
  - Uses aeroelastic model to apply atmospheric conditions to the dynamic structure
- Characteristic Strength (e.g., 95% quantile)
  - Material properties
  - Damage rules
  - Statistical variation

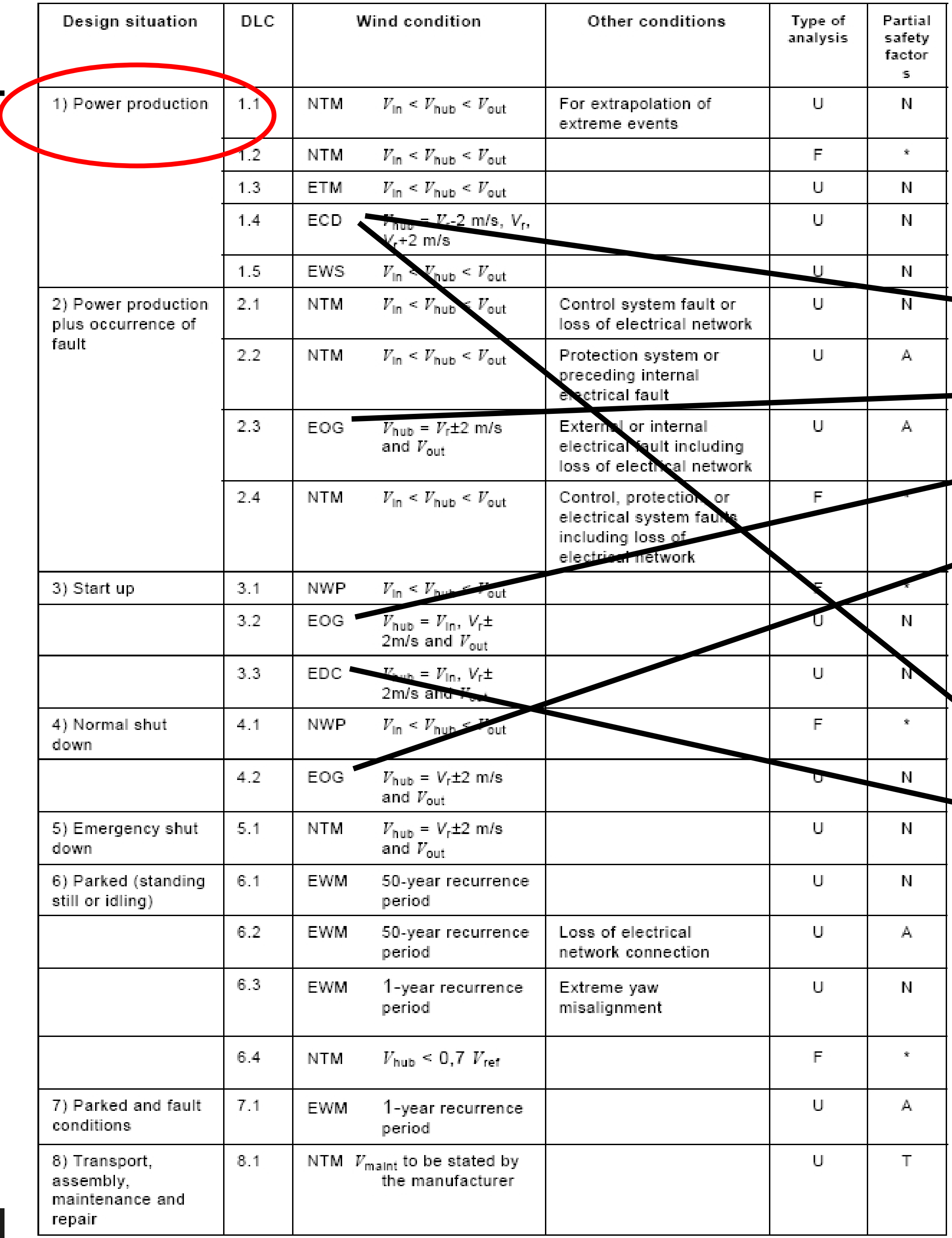
Design Criteria

$$\alpha L < \varphi R$$



IEC Standards have a suite of DLCs… including fatigue and ultimate loading

Table 2 – Design load cases



Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r$-2 m/s, V_r, V_r+2 m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm$ 2m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0,7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T

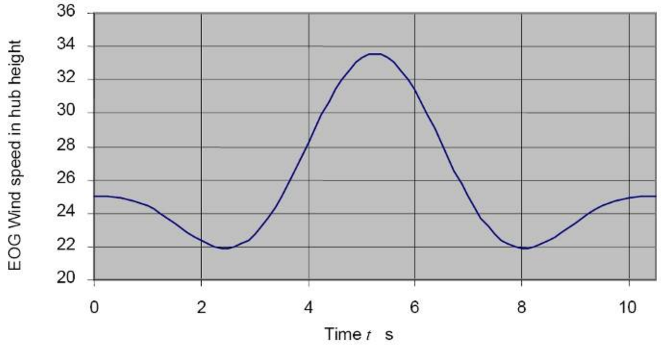


Figure 2 – Example of extreme operating gust

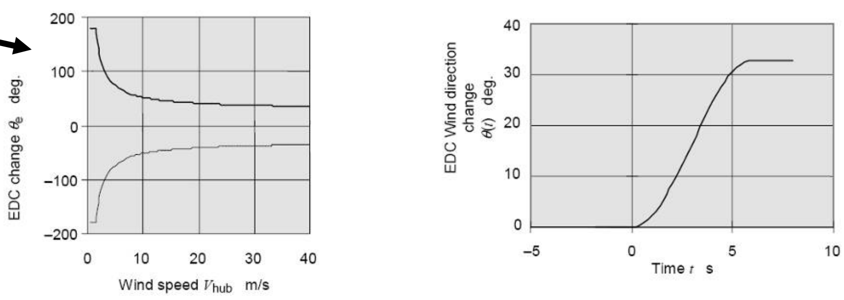


Figure 3 – Example of extreme direction change magnitude

Figure 4 – Example of extreme direction change

Operating under Normal Conditions

IEC Class	Reference Wind Speed
I	50 m/s
II	42.5 m/s
III	37.5 m/s

Atmospheric turbulence is defined by the following statistical properties for simulation purposes:

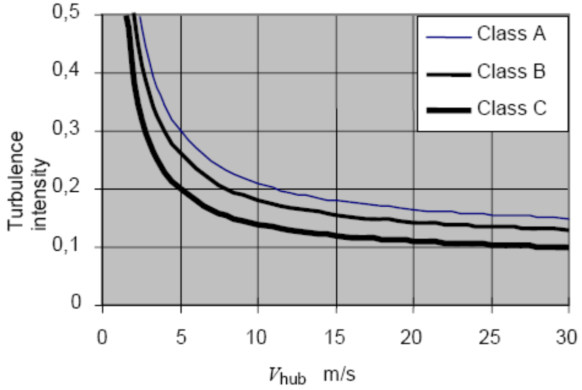
Wind-Speed Probability of Occurrence

$$P_R(V_{hub}) = 1 - \exp\left[-\pi\left(V_{hub}/2V_{ave}\right)^2\right]$$

Turbulence Frequency Content

$$\frac{f S_k(f)}{\sigma_k^2} = \frac{4 f\, L_k / V_{hub}}{\left(1+6 f\, L_k / V_{hub}\right)^{5/3}}$$

Turbulence Intensity



Coherence

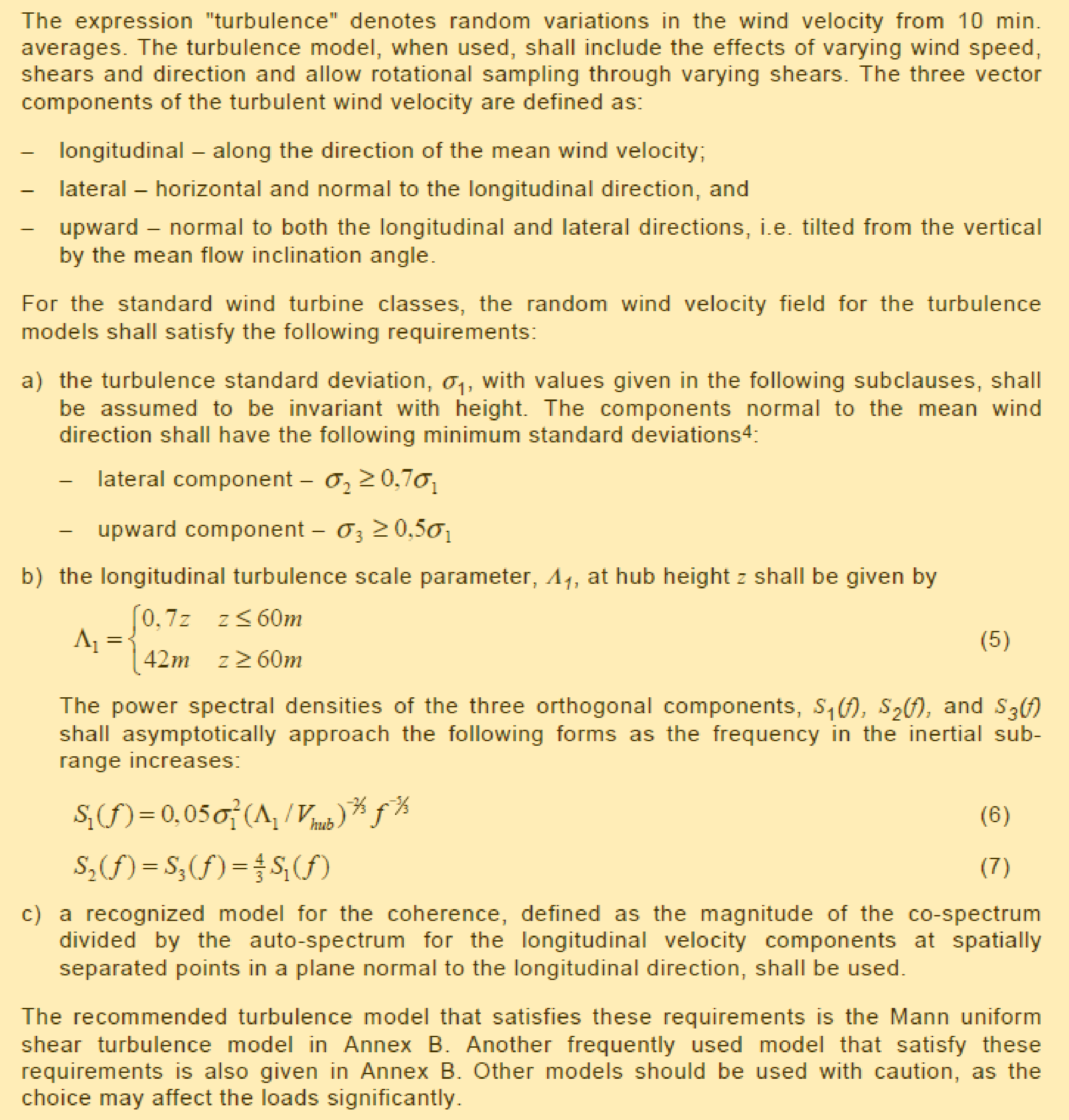
$$Coh(r,f) = \exp\left[-12\left(\left(f\cdot r/V_{hub}\right)^2 + \left(0{,}12 r/L_c\right)^2\right)^{0,5}\right]$$

Parameters are defined for an individual turbine in each wind-speed class.

NREL's TurbSim turns these descriptors into wind inputs – FAST turns them into turbine loads

IEC 61400-1 Defines the Models That Are Allowed

- Magnitude of the turbulence intensity
- Relative variance in each component
- PSD shape
- Coherence must be a “recognized model”
- The “Mann” model is the recommended turbulence model
- Other turbulence simulation techniques are allowed



The expression "turbulence" denotes random variations in the wind velocity from 10 min. averages. The turbulence model, when used, shall include the effects of varying wind speed, shears and direction and allow rotational sampling through varying shears. The three vector components of the turbulent wind velocity are defined as:

- longitudinal – along the direction of the mean wind velocity;
- lateral – horizontal and normal to the longitudinal direction, and
- upward – normal to both the longitudinal and lateral directions, i.e. tilted from the vertical by the mean flow inclination angle.

For the standard wind turbine classes, the random wind velocity field for the turbulence models shall satisfy the following requirements:

a) the turbulence standard deviation, σ_1, with values given in the following subclauses, shall be assumed to be invariant with height. The components normal to the mean wind direction shall have the following minimum standard deviations[4]:

  - lateral component – $\sigma_2 \geq 0{,}7\sigma_1$
  - upward component – $\sigma_3 \geq 0{,}5\sigma_1$

b) the longitudinal turbulence scale parameter, Λ_1, at hub height z shall be given by

$$\Lambda_1 = \begin{cases} 0,7z & z \leq 60m \\ 42m & z \geq 60m \end{cases} \quad (5)$$

The power spectral densities of the three orthogonal components, $S_1(f)$, $S_2(f)$, and $S_3(f)$ shall asymptotically approach the following forms as the frequency in the inertial sub-range increases:

$$S_1(f) = 0,05\sigma_1^2(\Lambda_1 / V_{hub})^{-2/3} f^{-5/3} \quad (6)$$

$$S_2(f) = S_3(f) = \tfrac{4}{3} S_1(f) \quad (7)$$

c) a recognized model for the coherence, defined as the magnitude of the co-spectrum divided by the auto-spectrum for the longitudinal velocity components at spatially separated points in a plane normal to the longitudinal direction, shall be used.

The recommended turbulence model that satisfies these requirements is the Mann uniform shear turbulence model in Annex B. Another frequently used model that satisfy these requirements is also given in Annex B. Other models should be used with caution, as the choice may affect the loads significantly.

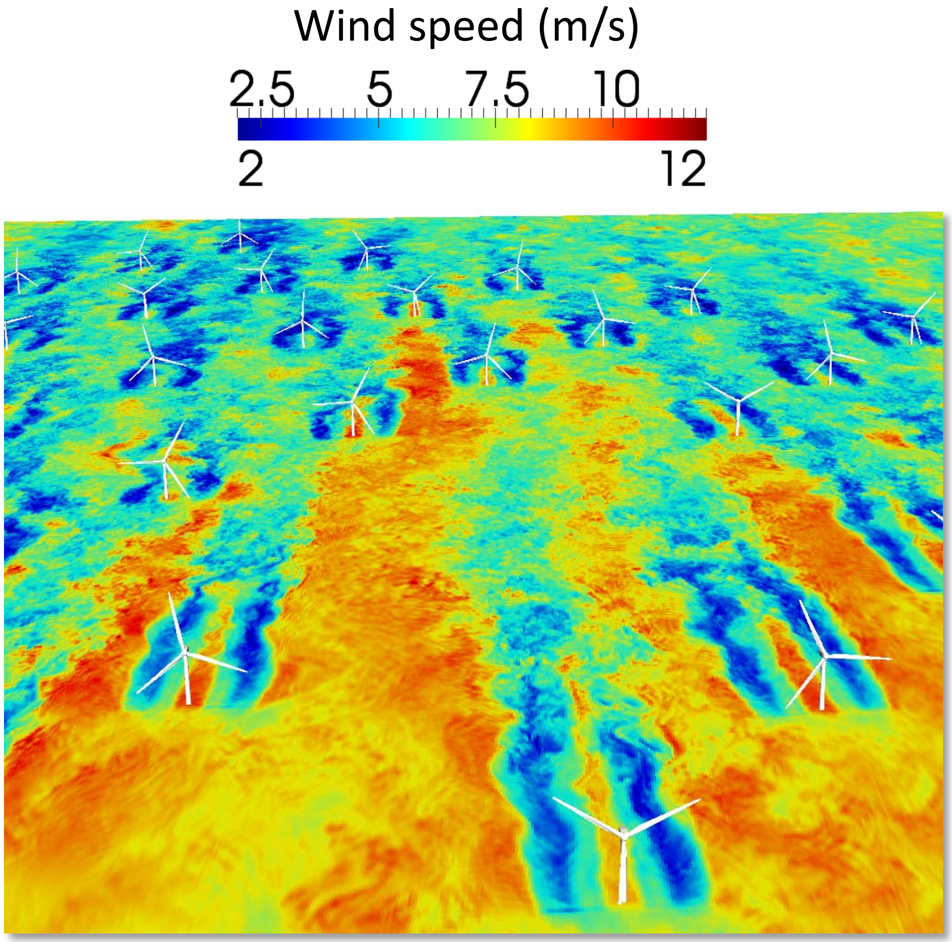
Wake Effects on Design Loads (1)

Design process:

1. Design loads are estimated for stand-alone operation.
2. Optimal turbine system design is achieved for turbines of a certain class.
3. The turbine is selected for use in a particular wind plant.
4. A site assessment check is done for wake loads on the specific turbine location in the plant layout.
5. If the loads are increased to where the design is inadequate, then re-design to increase load-carrying capacity.

Result:

- Initial turbine system design may no longer be optimal.
- The ability to conduct design optimization does not exist for turbines within a wind plant.



Contours of instantaneous wind speed in simulated flow through the Lillgrund wind plant

Wake Effects on Design Loads (2)

- **IEC 61400-1 says (after the turbine has been designed according to external conditions defined in Clause 6):**

11 Assessment of a wind turbine for site-specific conditions

11.4 Assessment of wake effects from neighboring wind turbines

> "The increase in loading generally assumed to result from wake effects may be accounted for by the use of an effective turbulence intensity, which shall include adequate representation of the effect on loading of ambient turbulence and discrete and turbulent wake effects.
>
> For fatigue calculations, the effective turbulence intensity, I_{eff}, may be derived according to Annex D.
>
> For ultimate loads, I_{eff}, may be assumed to be the maximum of the wake turbulence intensity from neighbouring wind turbines as defined in Annex D."

- **This refers to the model of Frandsen (2005).**

Wake Effects on Design Loads (3)

- **Turbulence is increased based on the distance and angle between turbines (relative to mean flow).**
- **The increase is uniform over the entire turbine rotor.**
- **Influences from nearby turbines are summed over all machines in the array.**

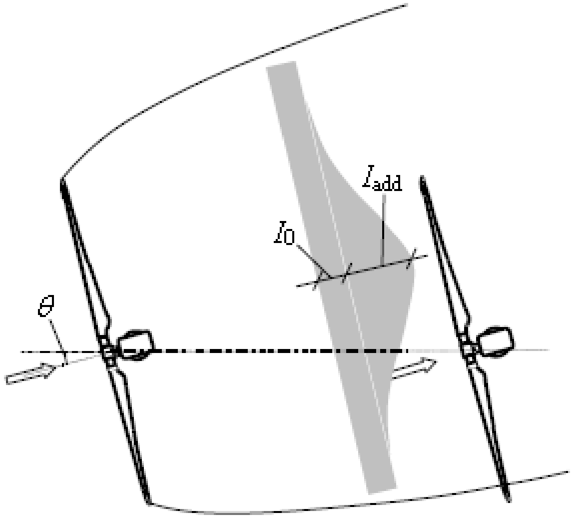


Figure 3.8 *Illustration of wake turbulence as experienced by downwind turbine.*

if $\min\{d_i\} < 10\,D$:

$$I_{eff} = \frac{\hat{\sigma}_{eff}}{V_{hub}} = \frac{1}{V_{hub}}\left[(1 - N\,p_w)\hat{\sigma}^m + p_w\sum_{i=1}^{N}\hat{\sigma}_T^m(d_i)\right]^{\frac{1}{m}};\ p_w = 0,06 \qquad \text{(D.3)}$$

where

$\hat{\sigma}$ is the ambient estimated turbulence standard deviation;

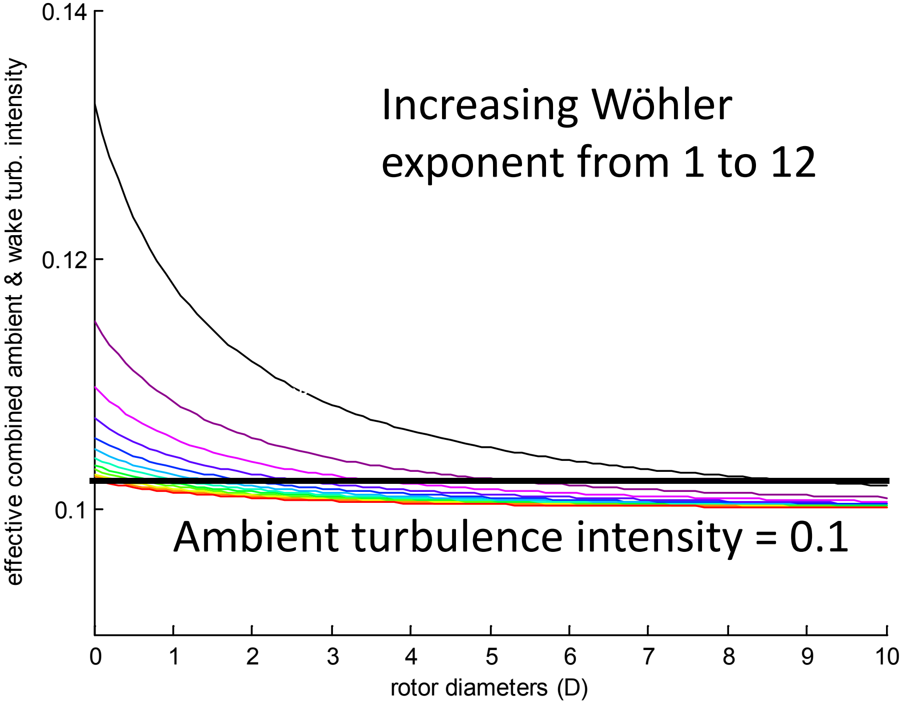
$\hat{\sigma}_T = \sqrt{\dfrac{0,9\,V_{hub}^2}{\left(1,5 + 0,3\,d_i\sqrt{V_{hub}/c}\right)^2} + \hat{\sigma}^2}$ is the maximum centre-wake, hub height turbulence standard deviation;

d_i is the distance, normalised by rotor diameter, to neighbouring wind turbine no. i;

The Frandsen Model is called out in IEC 61400-1 Ed. 3 (not prescriptive)

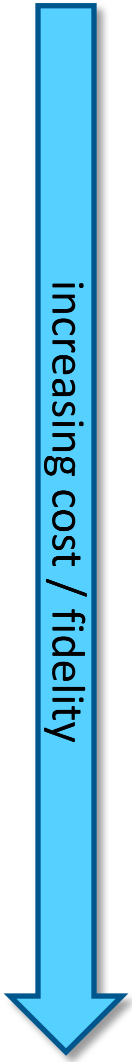
Wake Effects on Design Loads (4)

- **Frandsen I_{eff} depends on material fatigue characteristics (i.e., the Wöhler exponent)…and turbulence structure being maintained**



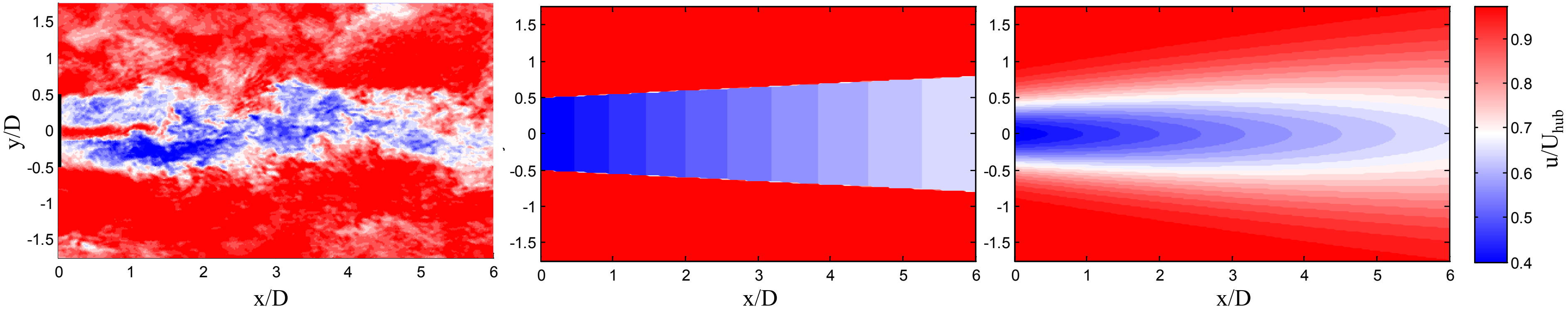
Hierarchy of Wake Models

Type	Example
Empirical	Jensen (1983)/Katíc (1986) (Park) & Frandsen
Linearized Reynolds-averaged Navier-Stokes (RANS)	Ainslie (1985) (Eddy-viscosity) Ott et al. (2011) (Fuga)
Phenomenological	Larsen et al. (2007) (Dynamic Wake Meandering)
Statistical	None now in place
Nonlinear RANS	k-ω with actuator disk, line, fully resolved
Large-eddy simulation (LES)	Dynamic Smagorinsky with actuator disk, line



Wake Models for Power Production (1)

- **There are many…some of the more popular include:**
  - Jensen (1983)/Katíc (1986) – Park model
  - Ainslie (1985) – Eddy-viscosity model
  - Fuga



LES snapshot of full unsteady wake

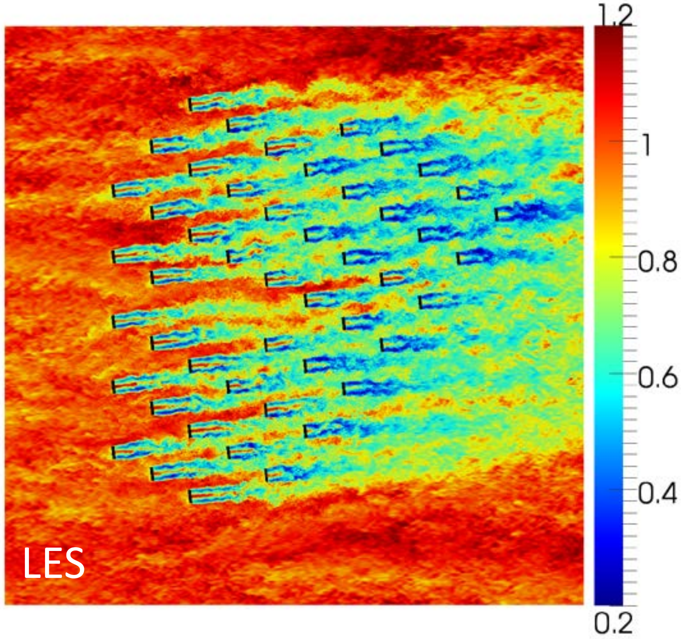
Park

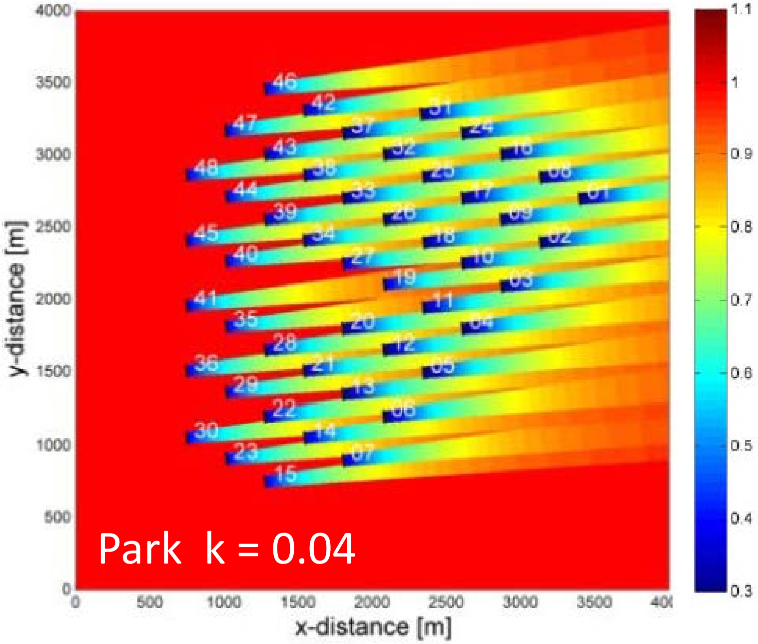
Eddy-Viscosity

The value of the wake model depends heavily on the spatial and time scales of the application: Energy production averages over both space and time, whereas loads are determined by instantaneous values in both time and space.

Wake Models for Power Production (2)

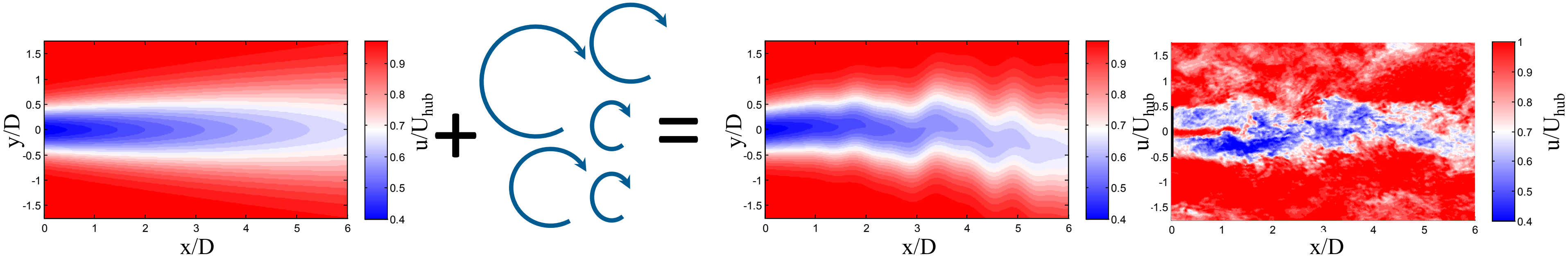
Full wind-farm example: Lillgrund (48 turbines)





Wake Models for Mechanical Loads

- **Dynamic Wake Meandering (DWM) model, Larsen et al. (2007)**
- **Idea: The wake is a passive tracer in a turbulent atmospheric flow field**
  - Can inherently include atmospheric stability effects through turbulent field
  - Turbulent field can be stochastically generated using spectra/coherence from model spectrum or field measurements
- **Procedure:**
  - Create a base wake with eddy-viscosity model
  - Obtain a turbulent field with smallest scales on order of rotor diameter
  - Use turbulent field to meander sequences of base wake “releases”



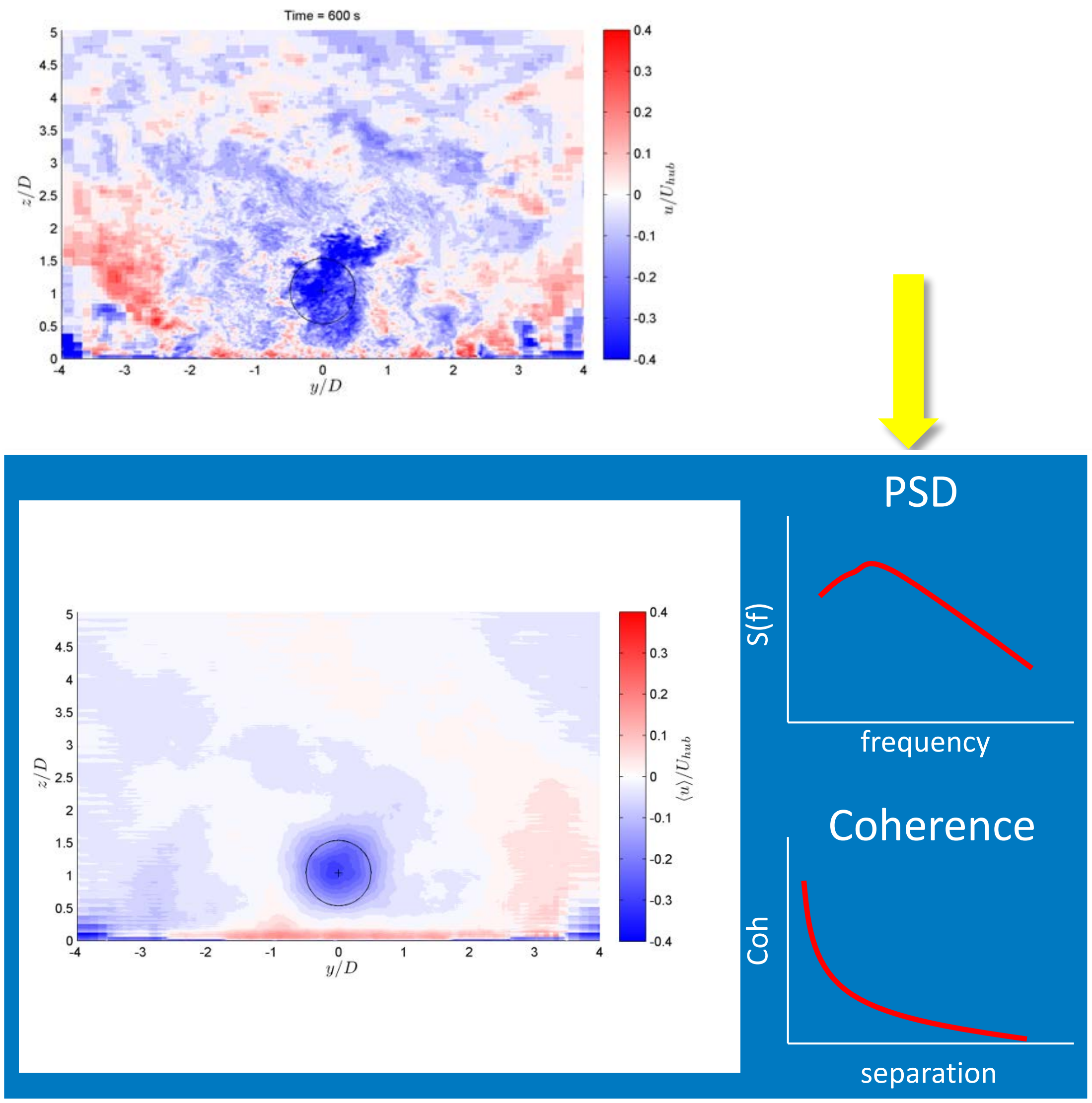
Base Wake

DWM (snapshot)

LES (for comparison)

Study Statistical Properties of the Wake for Design Purposes

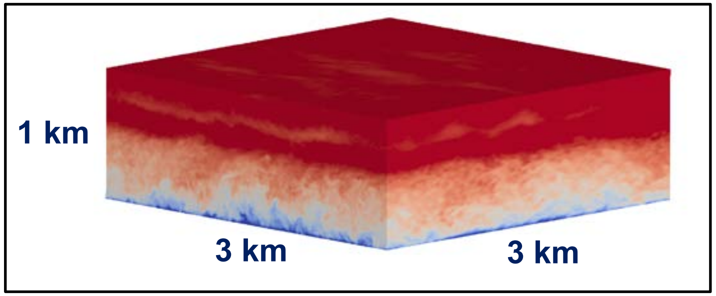
- **Work with an large-eddy simulation (LES) at near-rated conditions**
- **Estimate PSD and coherence within the wake at several downwind locations**
- **Reconstruct the inflow using empirical PSD and coherence definitions**
- **Look for a generic description that envelops various potential waked statistics within an array**

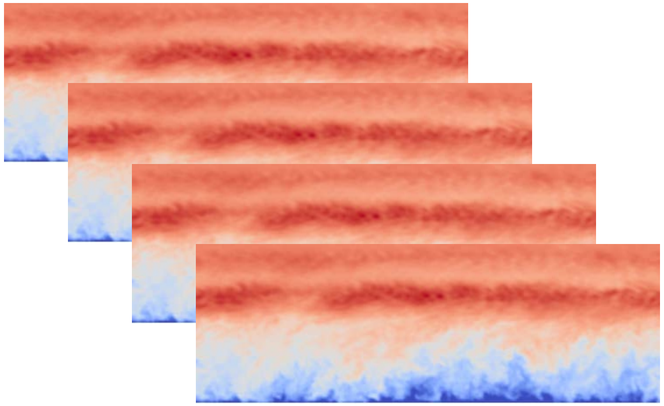


Simulation Method

- 600-second simulation with wake
- The highest resolution is 1.25 m
- The background mesh is 10 m

"Precursor" atmospheric large-eddy simulation (run for 18,000 s to reach quasi-equilibrium)



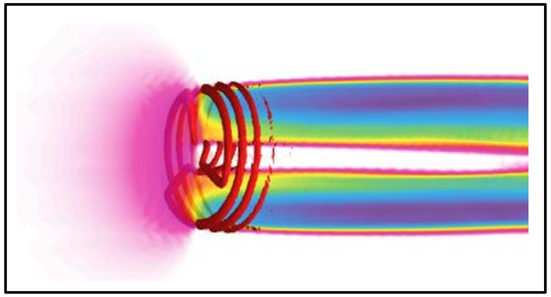


Save planes of data at every time steps

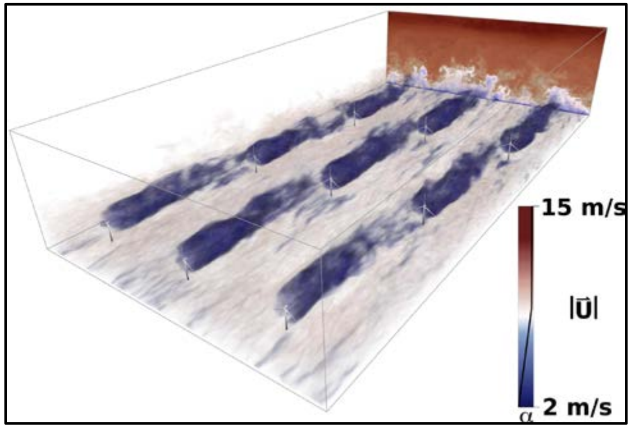
Initialize wind-farm domain with precursor volume field

Use saved precursor data as inflow boundary conditions

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

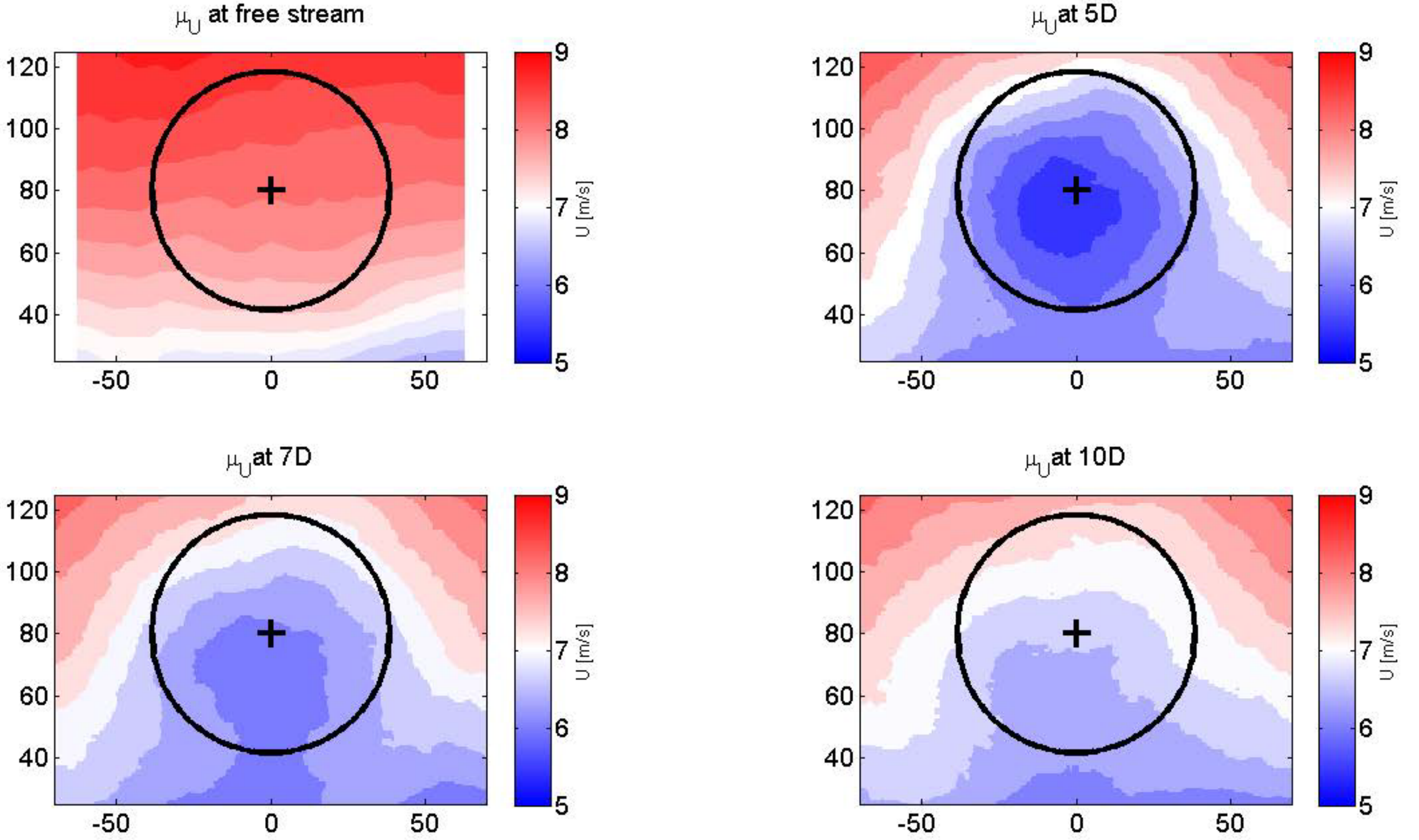


Wind-farm large-eddy simulation



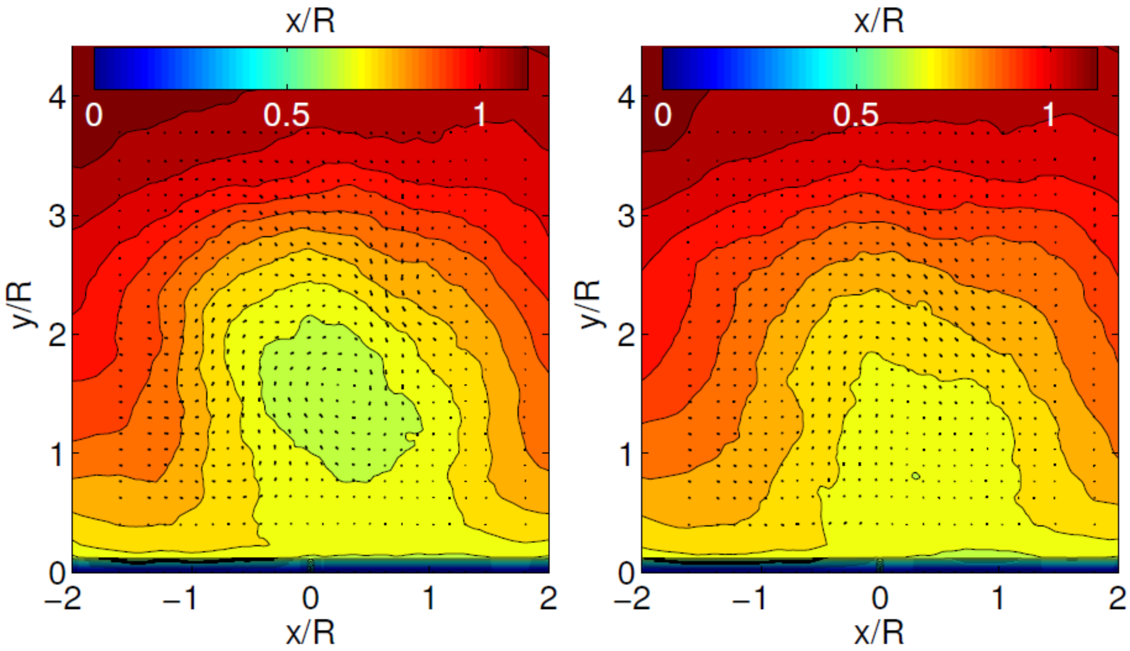
Mean Wake Field from LES

- **Results are typical of historic wake studies**



Average Wake Matches Estimate by Troldborg

- **The shape of the average velocity deficit field is quite similar for two independent LES-based calculations**
- **Troldborg's decays a bit faster … due to different turbulence?**
- **Overall, great agreement**



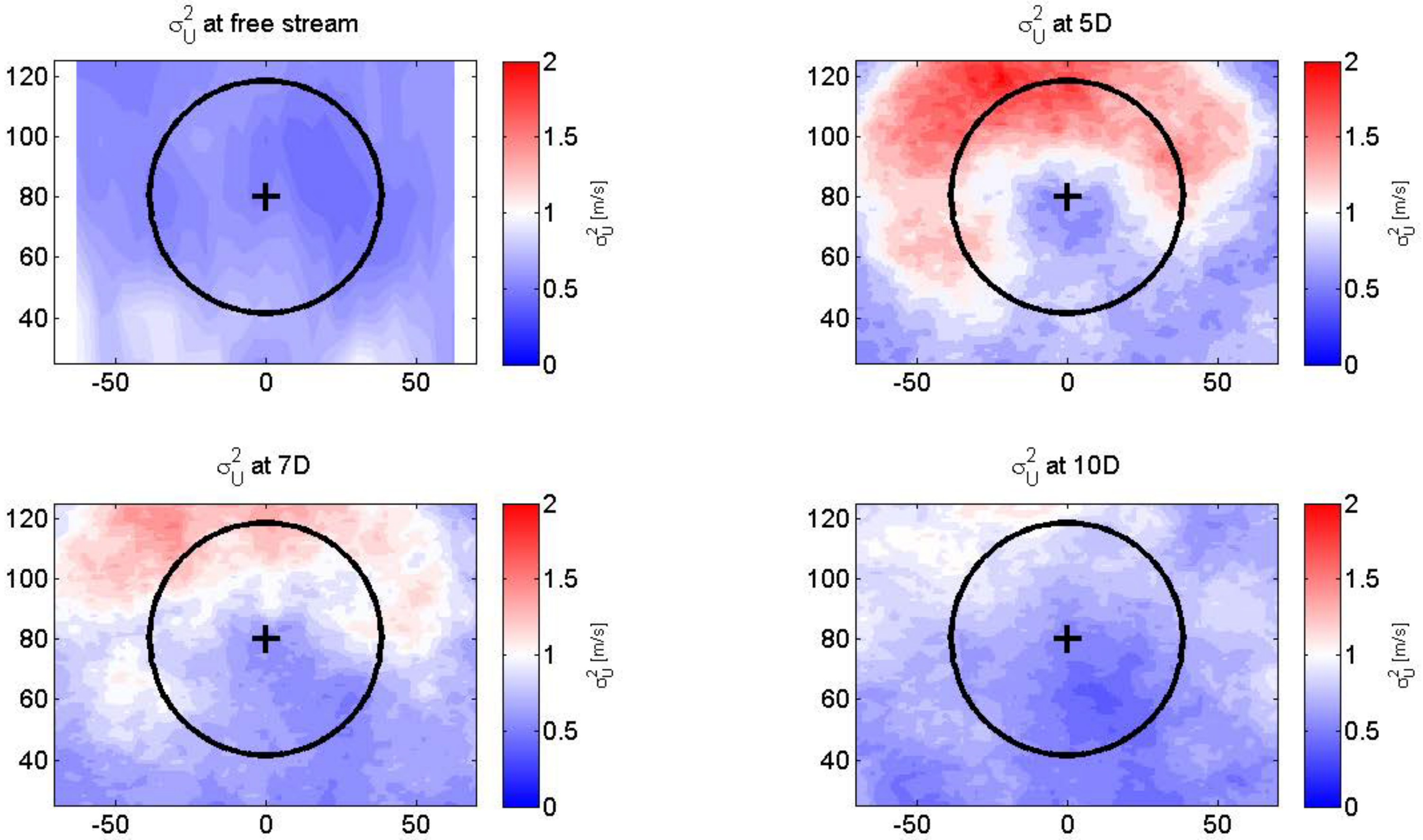
Average velocity field at 5D and 7D from Troldborg

Niels Troldborg, "Actuator Line Modeling of Wind Turbine Wakes," DTU Mechanical Engineering, Ph.D. thesis, June 2008.

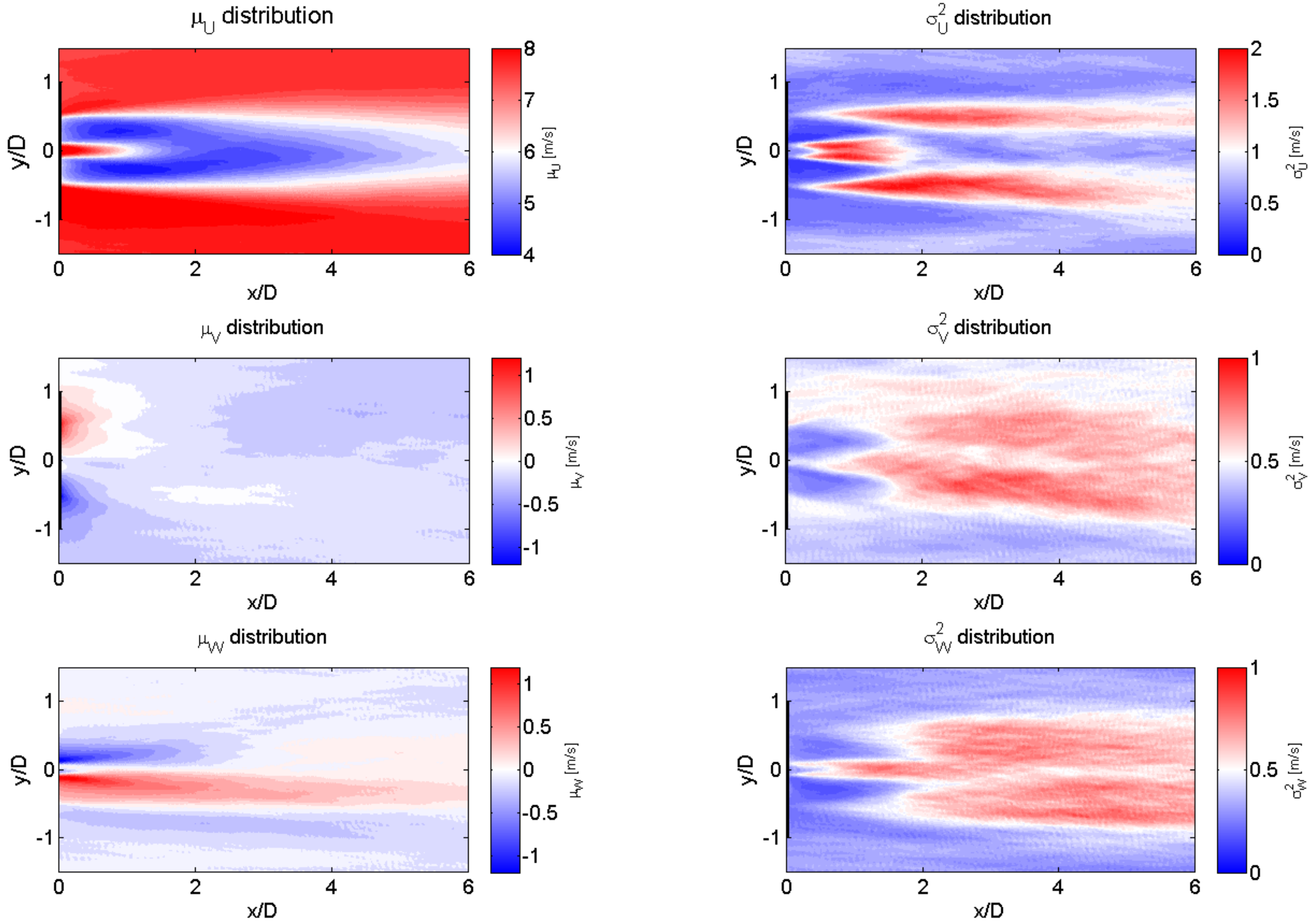
http://orbit.dtu.dk/services/downloadRegister/5289075/niels_troldborg.pdf

Variance in the Wake Field from LES

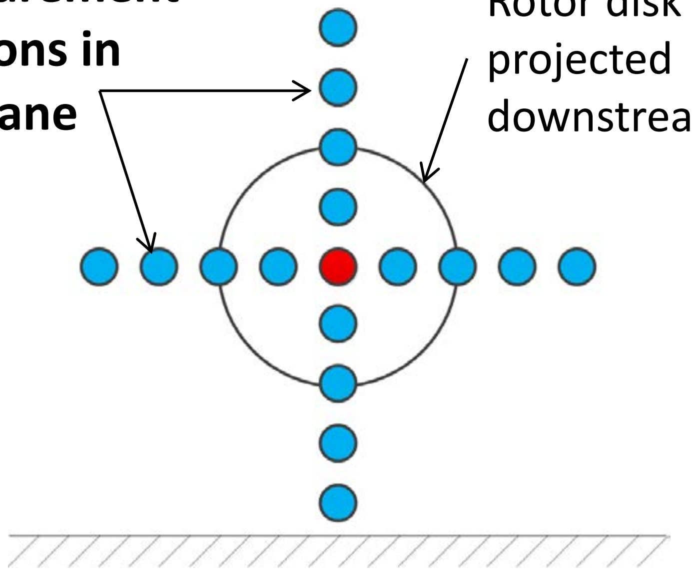
- **Variance is not evenly distributed across the rotor… i.e., inhomogeneous wake turbulence field**



Mean Vertical and Cross-Wind Wake Flows



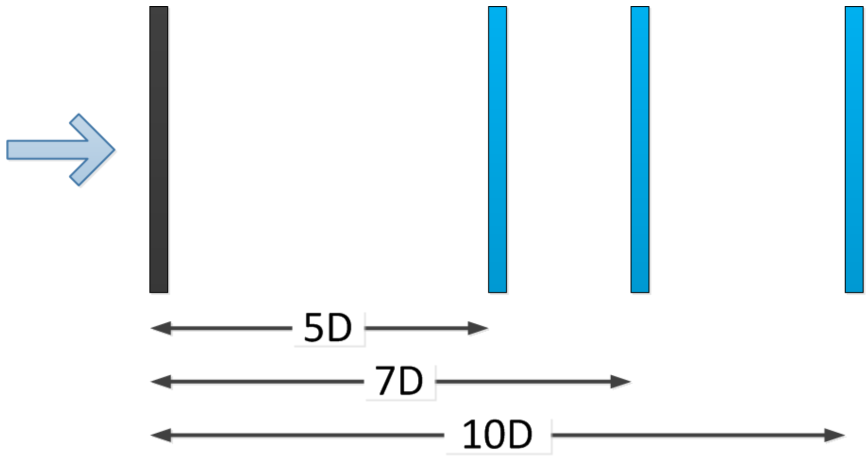
PSD and Coherence Statistics Estimated in LES



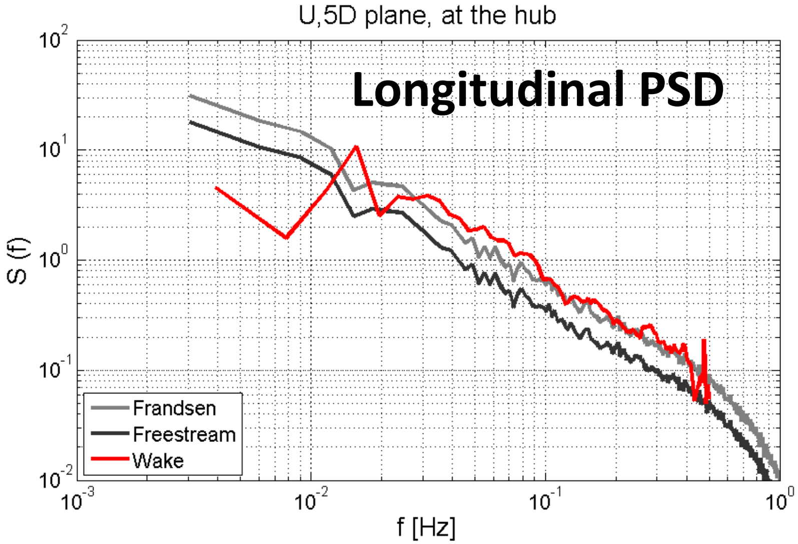
Measurement locations in the plane

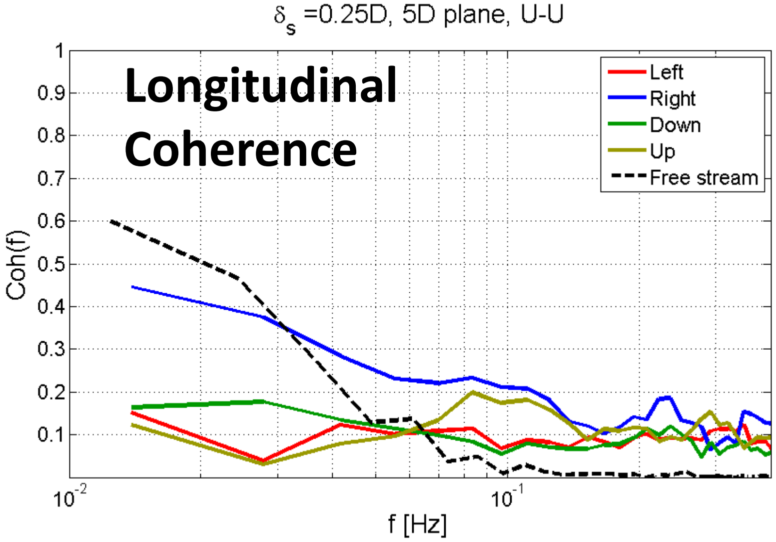
Rotor disk projected downstream

Downstream locations



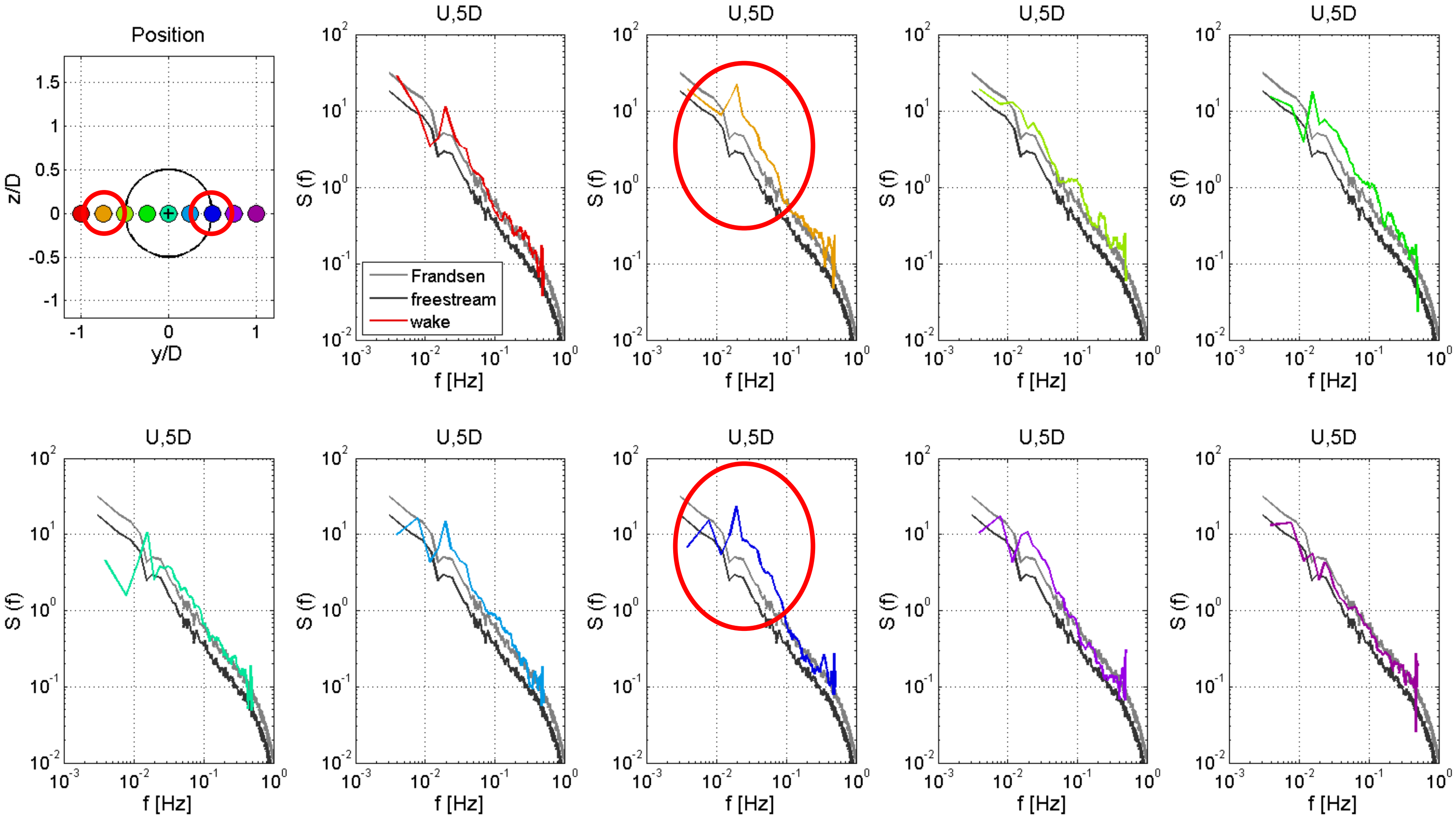
Hub location 5D downstream



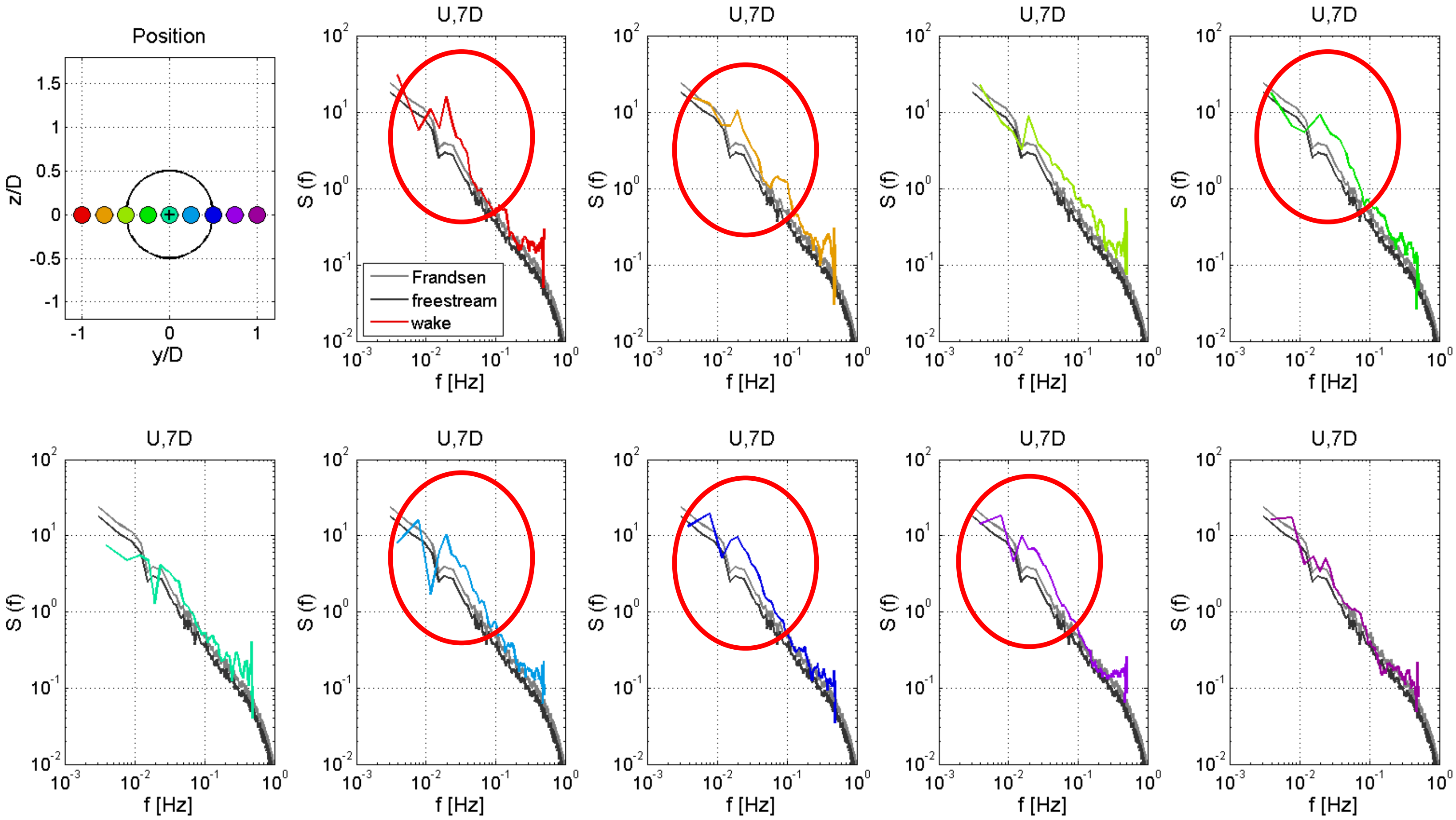


PSD at Each Point Compared with Freestream and Frandsen Correction

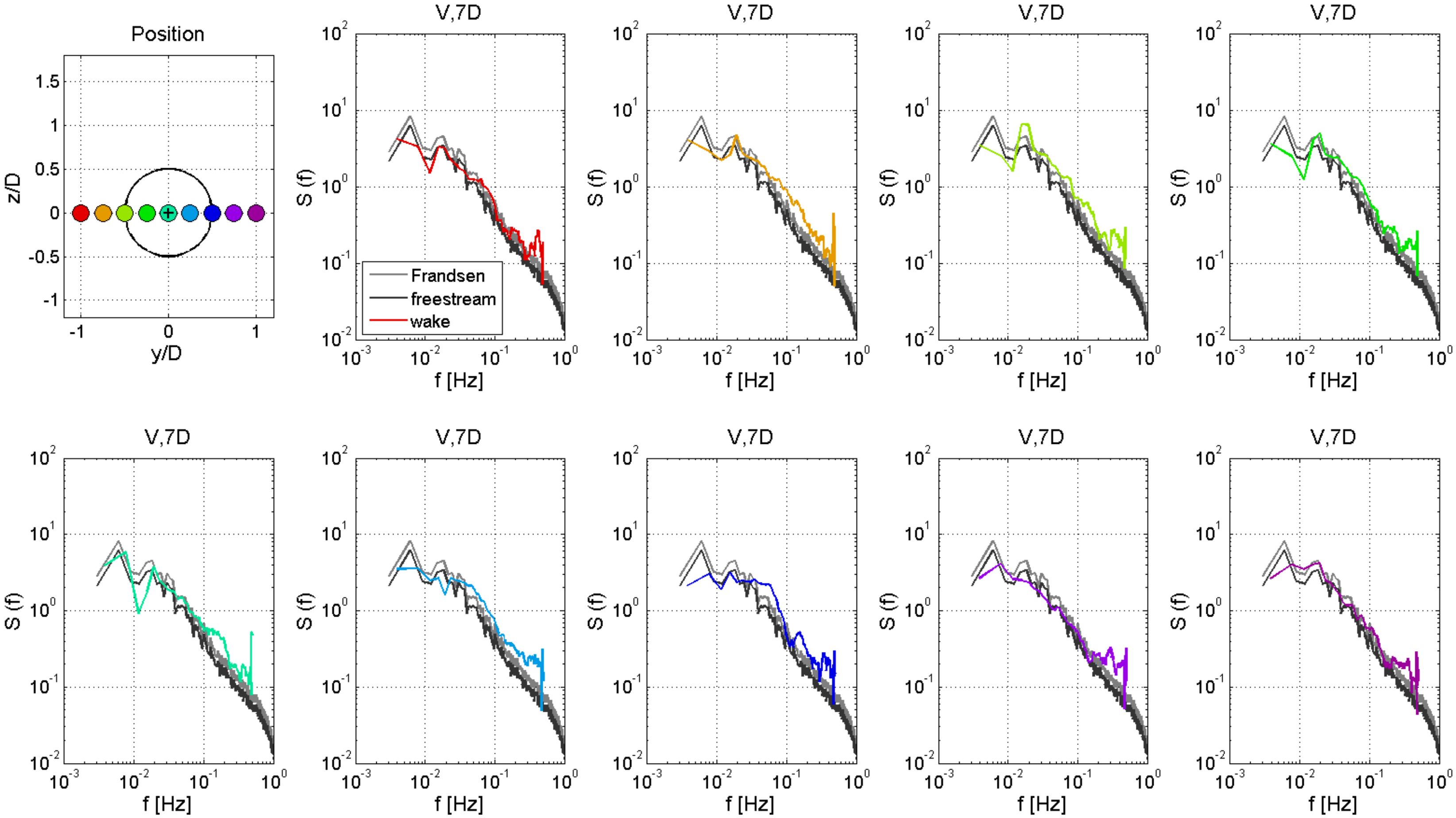
- **Increased frequency content can be seen at the edges of the wake in a low-frequency band between 0.02 and 0.10 Hz (@5D)**



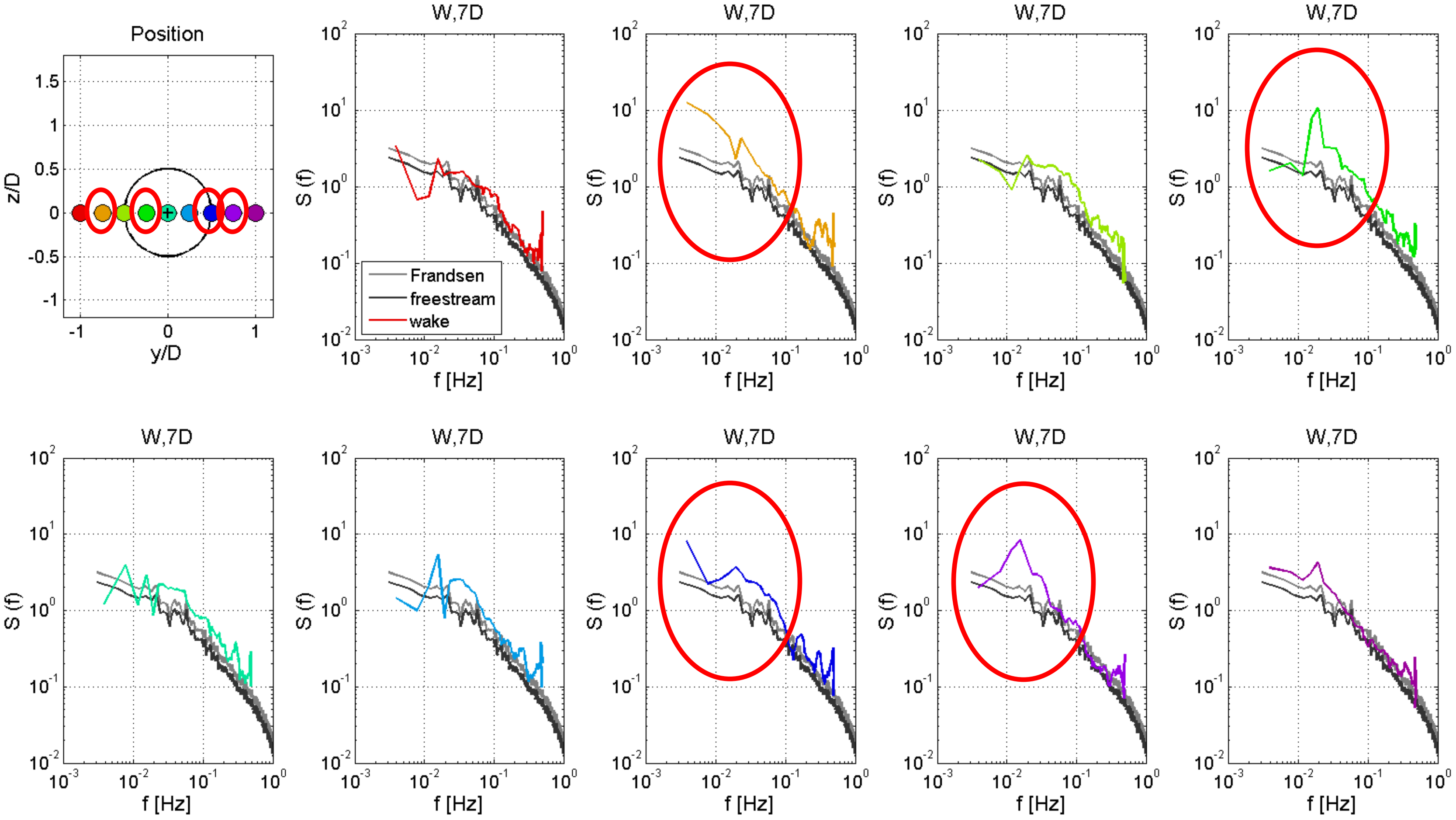
Longitudinal-Component PSDs at 7D



Lateral-Component PSDs at 7D

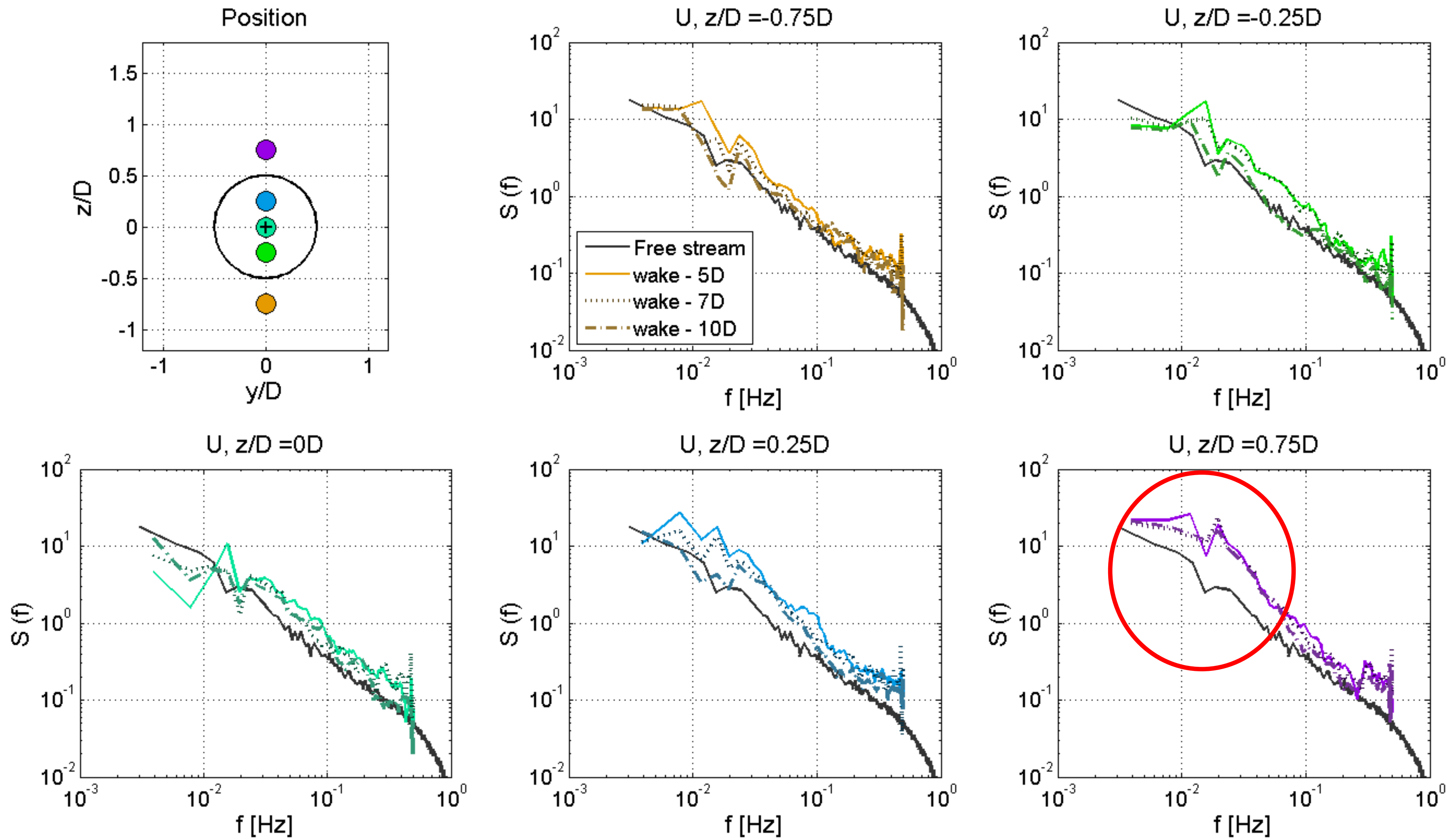


Vertical-Component PSDs at 7D



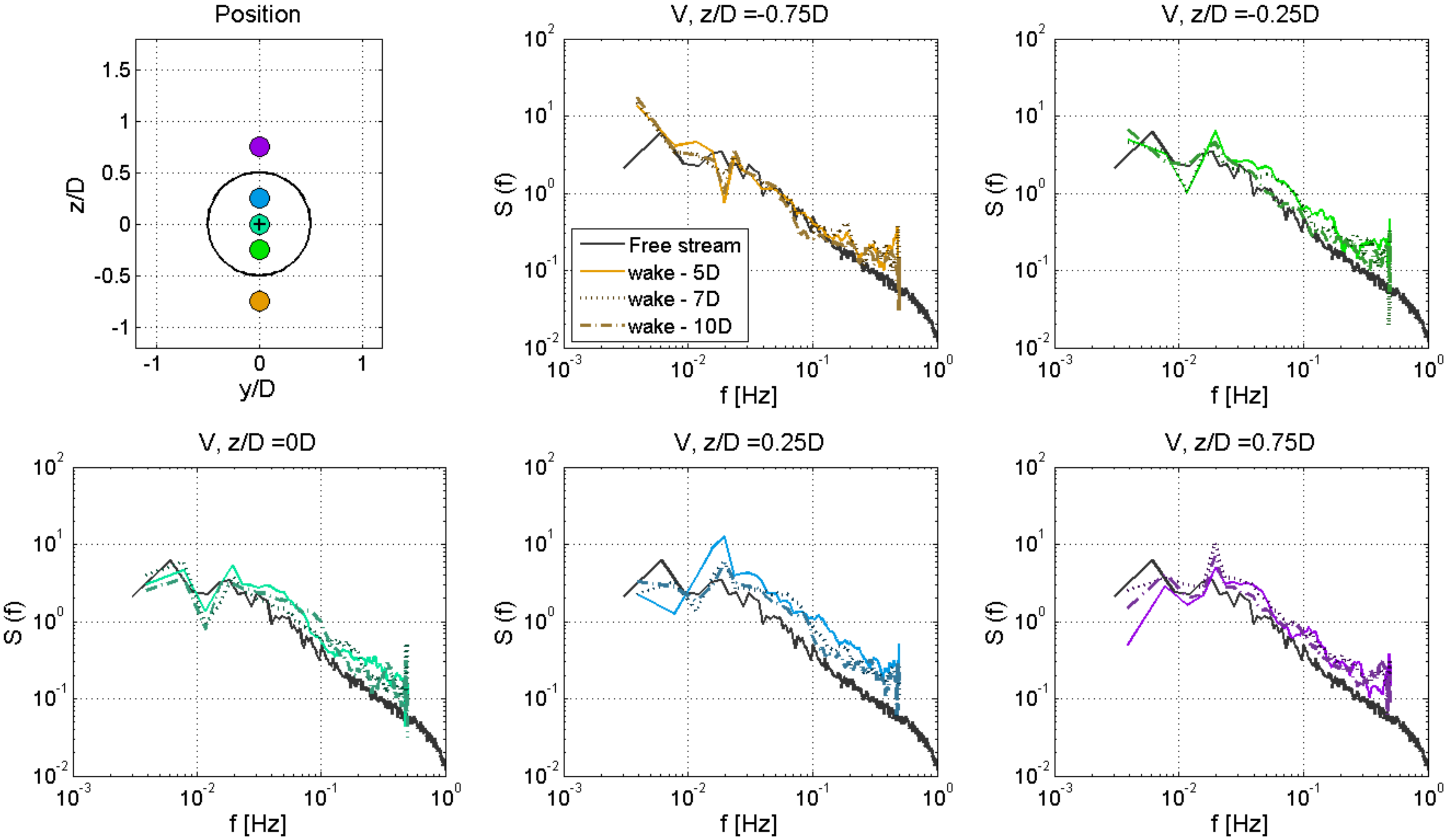
Longitudinal Turbulence Content Does Not Entirely Decay, Even at 10D, at the Top of the Rotor

Along-wind turbulence PSDs as they evolve downstream at 5D, 7D, and 10D



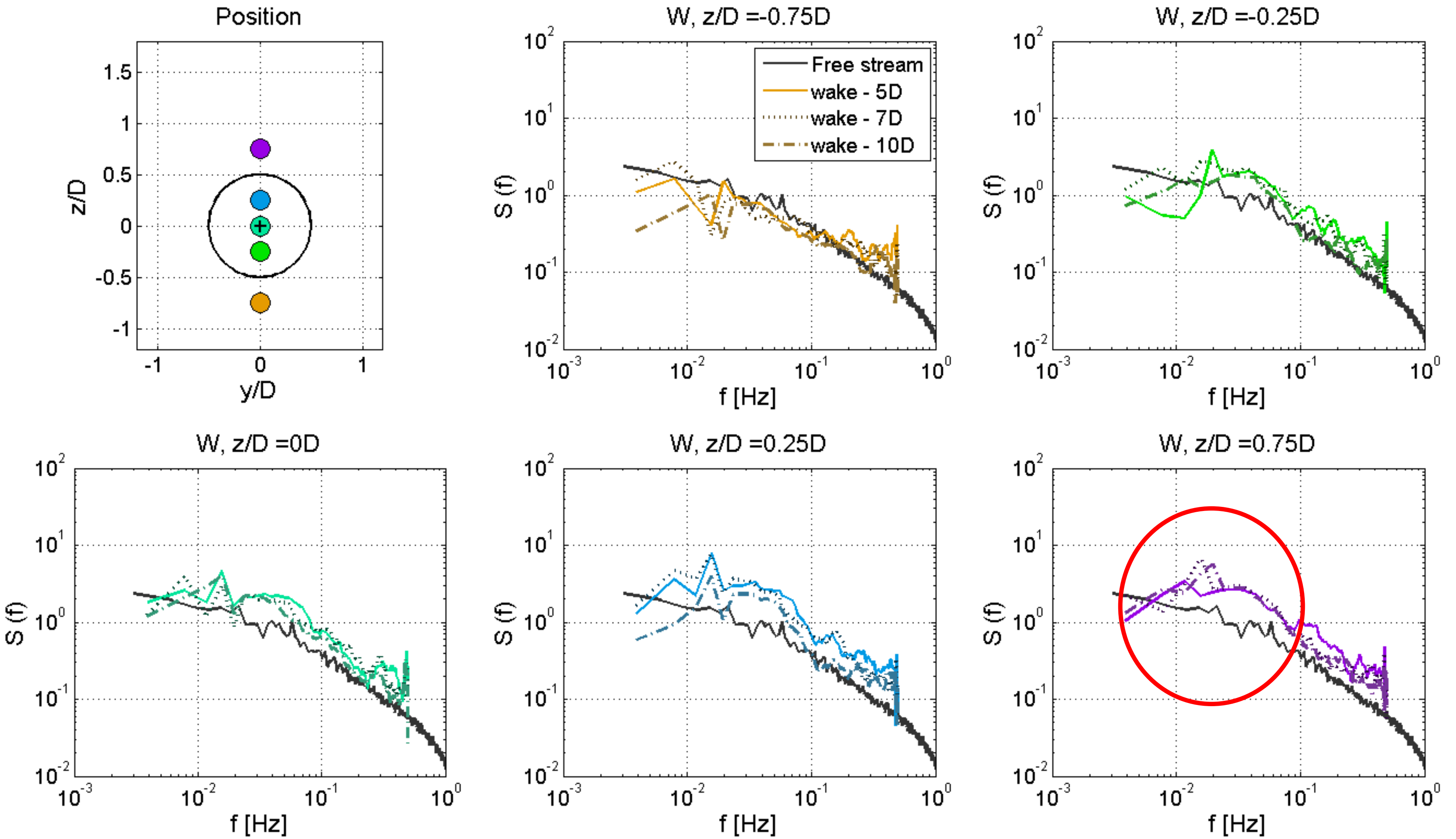
Lateral Component is Not Greatly Changed from the Freestream

Lateral-turbulence PSDs as they evolve downstream at 5D, 7D, and 10D



Vertical-Component PSD Remains High, and Even Grows, at 10D at the Top of the Rotor

Vertical-turbulence PSDs as they evolve downstream at 5D, 7D, and 10D



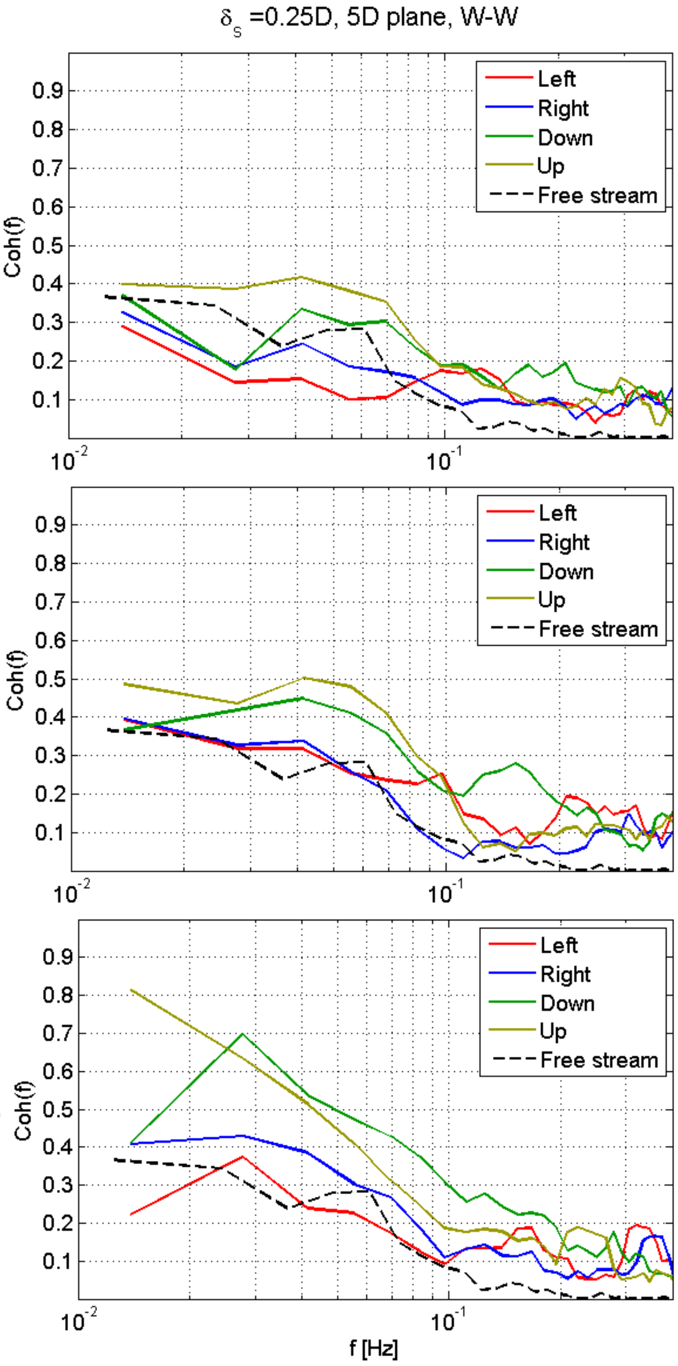
Coherence: Vertical Component

- **The coherence at 5D is decreased relative to the freestream (more mixed flow).**
- **It gradually increases until, at 10D, it is significantly greater than freestream (more organized) – especially for vertical separations.**
- **This hints at horizontal waves or horizontal vortices developing as the wake mixes in the vertical direction.**
- **No such pattern is evident in the longitudinal or lateral components.**

5D

7D

10D

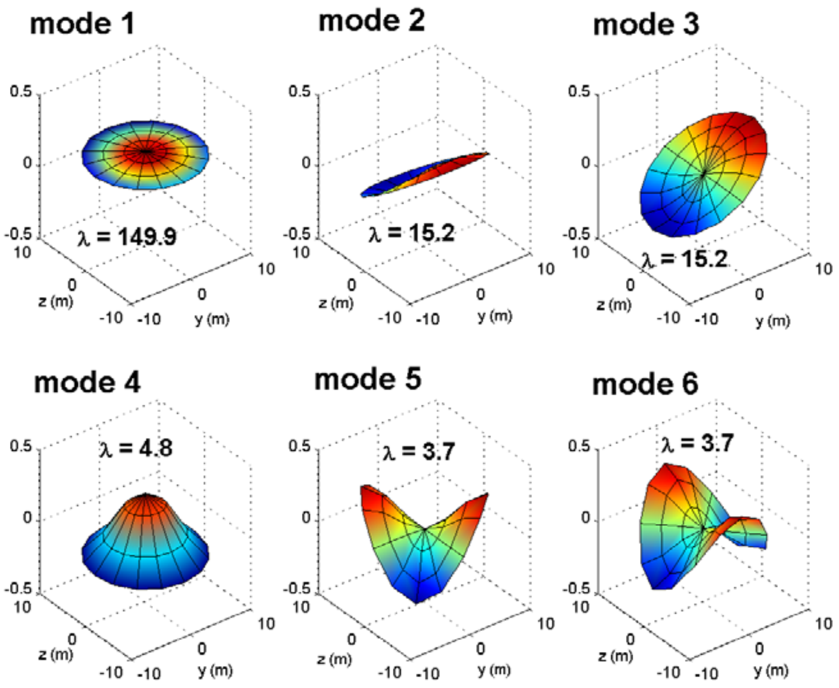


Observations of Wind Farm Effect on Rotor Inflow

- A mixing layer at the top elevation of the wind plant will contain higher shears and increased turbulence.
- Both longitudinal and vertical wind-speed components have enhanced low-frequency content at and above the downwind projection of the rotor edges … a meandering effect??
- At higher separations (~10D) the mixing has become increased in scale, as shown by increases in coherence with distance downstream.
- Modest up-flows are generated as low-velocity air near the surface expands outward.
- Point-to-point statistics are a bit cumbersome at representing these wake structures embedded in the flow field – spatial representations should be investigated.

Proper Orthogonal Decomposition

Saranyasoontorn and Manuel, 9th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability, Albuquerque, NM, 2004.



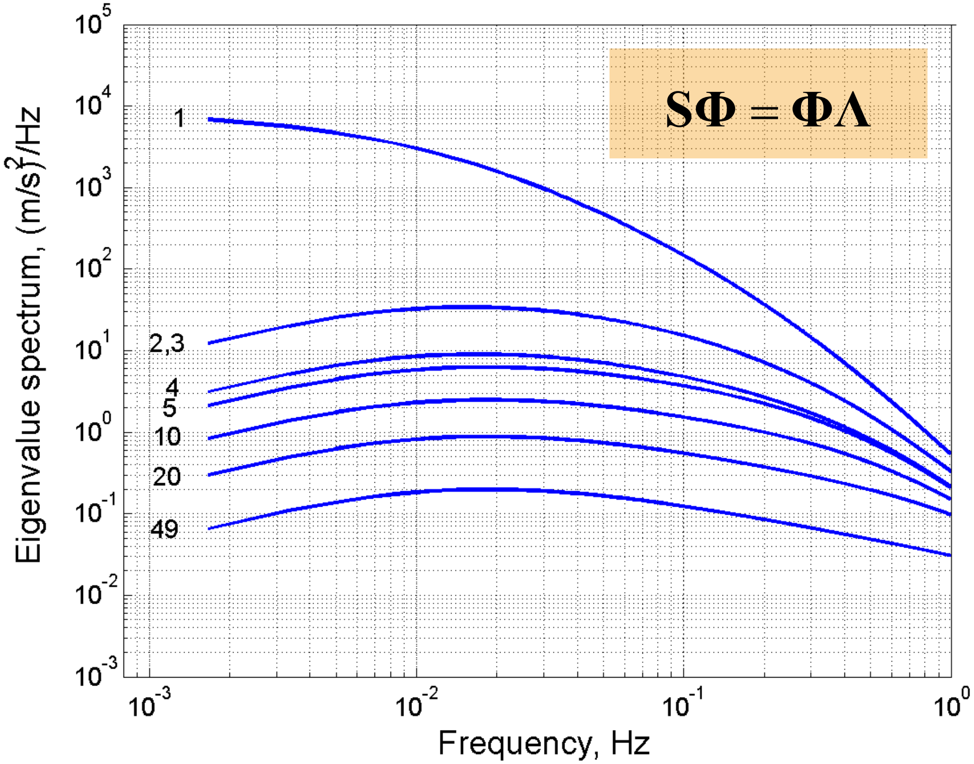
First six POD modes at 0.1 Hz and corresponding eigenvalues

Proper orthogonal decomposition (POD) describes the inflow as a summation of eigenmodes ...resulting in a low-order flow-field model.

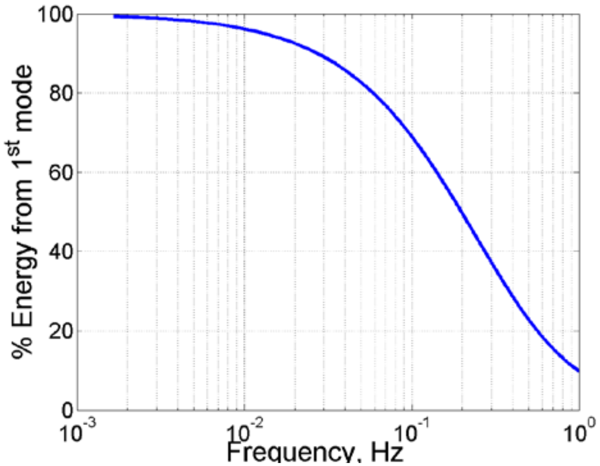
- **Mode 1 describes an almost uniform spatial inflow structure.**
- **Modes 2 and 3 describe spatial shear of the inflow structure.**
- **Higher eigenmodes have more complex spatial patterns.**

The POD approach offers the possibility of capturing structures from the wake embedded in the turbulence.

Eigenvalue Spectra



Eigenvalue spectra for different POD modes



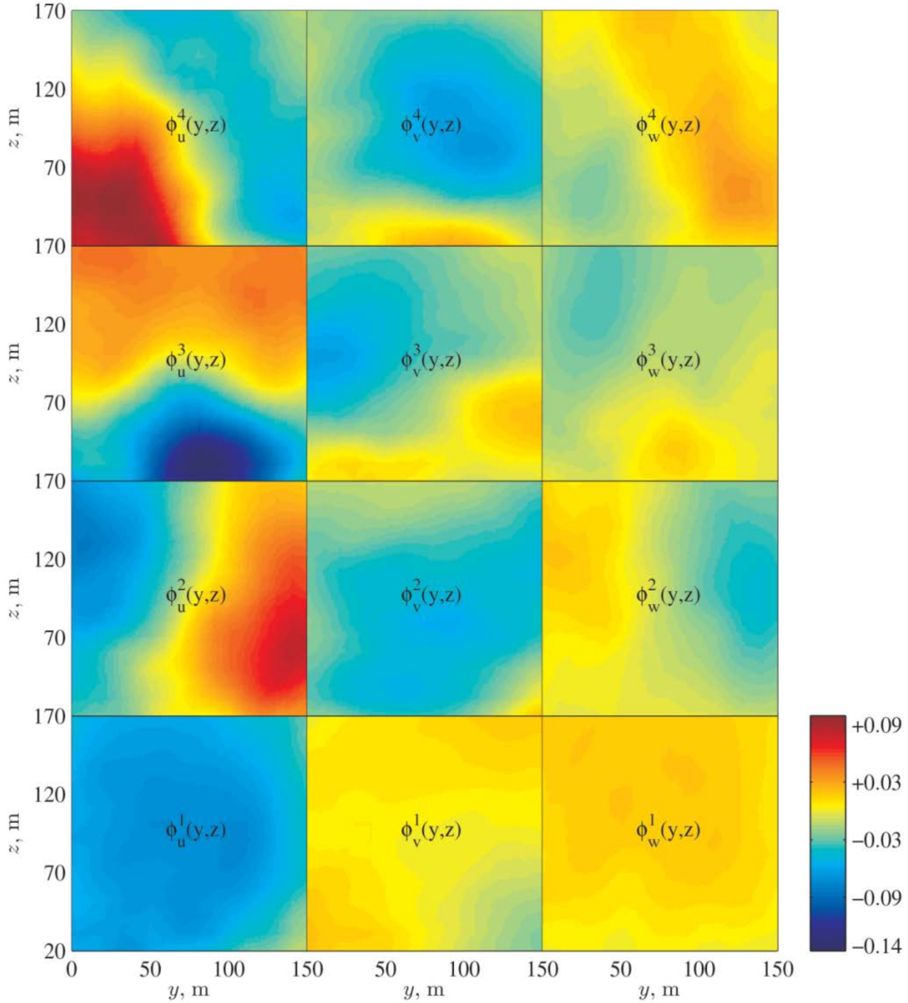
% Energy from 1st mode

- Mode 1 is considerably more energetic at low frequencies.
- Energy from all modes is comparable at higher frequencies.

Source: Saranyasoontorn and Manuel, 2004

POD Application

- **Another illustration of POD modeling**
- **POD can represent any generic random field.**
- **It should be feasible to model wake structures mixed into the turbulent flows of a wind plant.**

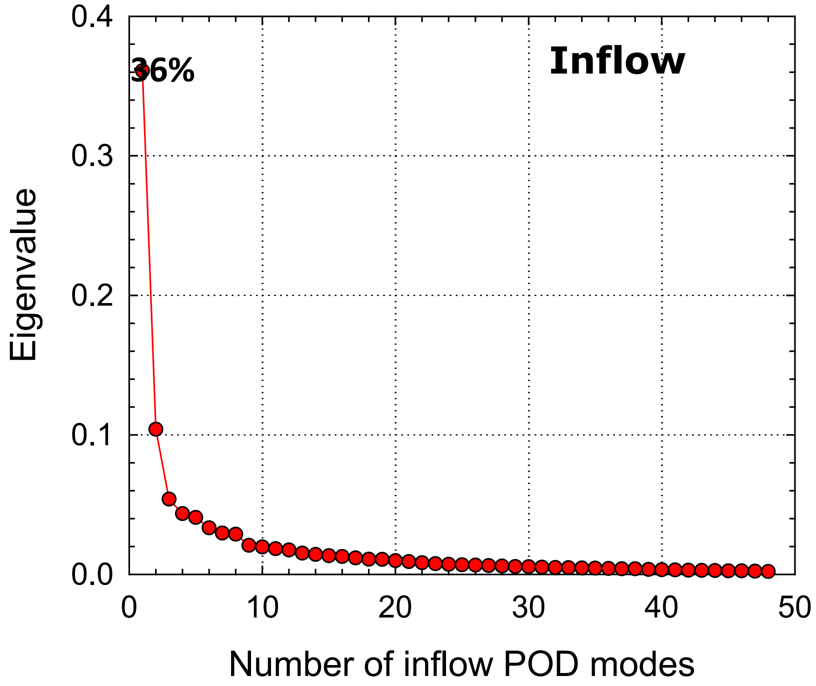


The first four POD modes of u, v, and w wind components

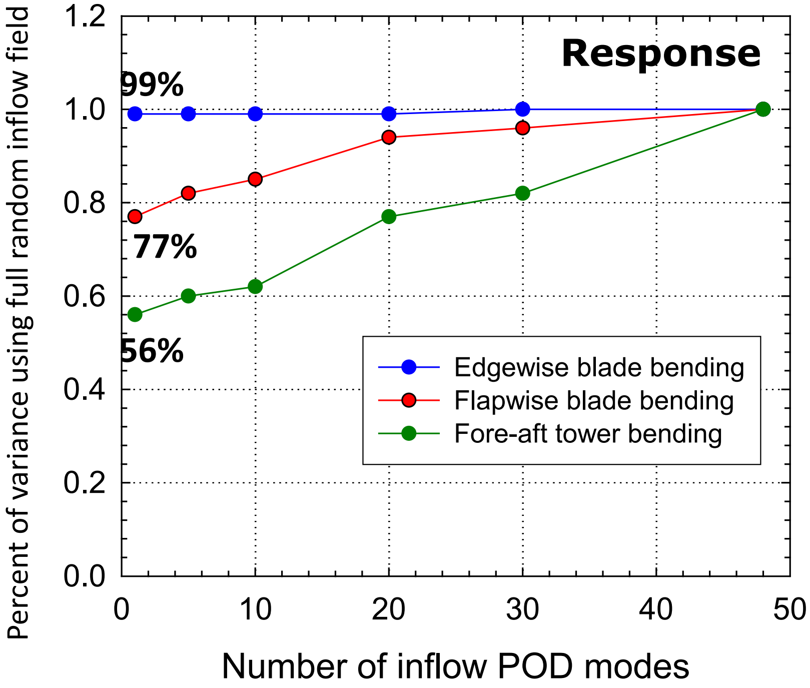
(Figure 5.3, from: Rai, Raj Kumar, “Estimation and Use of Wind Inflow for Wind Turbine Performance Prediction,” Ph.D., University of Wyoming Department of Mechanical Engineering, August, 2013.)

POD Mode Representation: Inflow vs. Turbine Response

Ratio of energy in each POD mode to total energy in full random field



Ratio of *approximate* variance of turbine response (based on number of POD modes) to *exact* variance



Conclusion: Turbine response can sometimes need fewer POD modes.

from Saranyasoontorn and Manuel, 2004

Conclusions

- Optimal design of turbines in a wind plant will have to consider wake effects from nearby machines.
- Current wake models that are useful for design are simplifications of the actual inflow field.
- The atmospheric flow that includes wakes has a statistical nature that describes its structure … but do second-order statistics suffice for resolving the intermittent behavior due to wake meandering?
- Statistical models of flow inside a wind plant hold promise of providing an objective set of criteria against which designs can be optimized.
- POD methods are worth examining for this purpose because of their ability to resolve wake structures – there is already some momentum in that direction.

Thank you.

Photo courtesy of Paul Veers, NREL