Characterization of Turbulence Anisotropy, Coherence, and Intermittency at a Prospective Tidal Energy Site

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Questions and Method

How do we describe the turbulence that a tidal turbine will experience, with only a time series of observations at one location in space?

What are the physical characteristics – size, shape, frequency – of the turbulence?

Can we parameterize, or simply classify, turbulence without doing the full analysis of physical characteristics?

How well can we model these turbulent properties with a stochastic turbulence generator?

Using data from an acoustic Doppler velocimeter in Puget Sound, WA, we perform a detailed characterization of the turbulent flow encountered by a turbine in a tidal strait. These results will be useful for improved realism in modeling the performance and loading of turbines in realistic ocean environments.

Observations

Dates	Feb 17-21, 2011
Depth	22m
Sampling Frequency	32 Hz
Hub Height	4.7m
Hub Height Max. Velocity	1.8 m/s

The data used in this analysis were collected from an acoustic Doppler velocimeter (ADV) off Nodule Point in the Puget Sound (Thomson et al. 2012). For a more in-depth description of the sites and the data collection details, see Thomson et al. (2012).

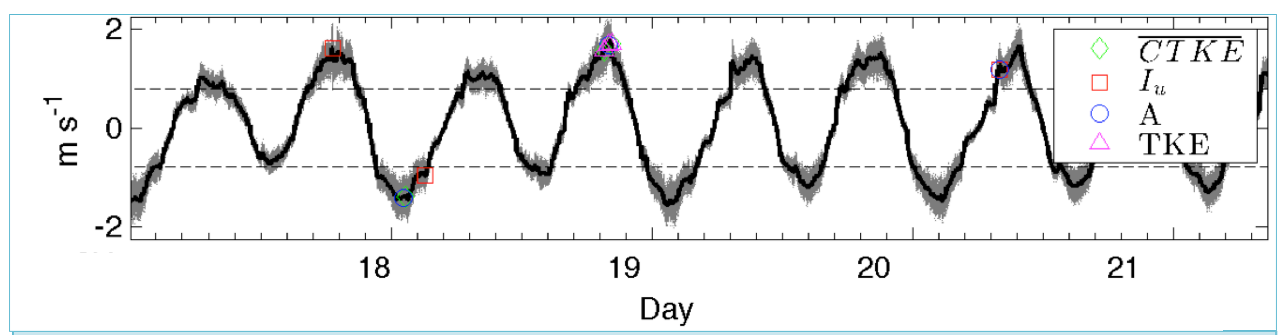

Figure 1: Horizontal component of velocity for the 4-day observation campaign.

Turbulence Metrics

Turbulence Intensity:

$$I_u = \frac{\sigma_u}{\langle u \rangle} = \frac{\sqrt{\overline{u'^2} - n^2}}{\bar{u}}$$

Coherent Turbulent Kinetic Energy:

$$CTKE = \frac{1}{2}\sqrt{\left(u'v'\right)^2 + \left(u'w'\right)^2 + \left(v'w'\right)^2}$$

Turbulent Kinetic Energy:

$$TKE = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

Anisotropy Tensor:

$$a_{ij} = \frac{\overline{u'_i u'_j}}{2k} - \frac{\delta_{ij}}{3}, \quad k = \frac{\overline{u'_i u'_i}}{2}$$

Anisotropy Magnitude

A new and improved metric for turbulence characterization and classification (McCaffrey et al, submitted):

1. Coordinate-system invariant
2. Units of energy
3. Built to be like CTKE which correlates with loads (Kelley et al 2000)
4. Includes anisotropy from shear stresses (from invariant, *II* – Lumley and Newman, 1977) *and* normal stresses (from *k*)

Anisotropy Magnitude:

$$A = k\sqrt{a_{ij}a_{ji}}$$

Physical Descriptors

Coherence – Autocorrelation, and Taylor and Integral Scales: Average Integral scale is ~10 sec, but some intervals stay correlated up to ~100 sec.

$$\rho(\tau) = \frac{\overline{u'(t)u'(t+\tau)}}{\overline{u'^2}}$$

$$\lambda = \sqrt{-2\left[\frac{\partial^2 \rho}{\partial \tau^2}\right]^{-1}}$$

$$\Lambda = \int_0^\infty \rho(\tau)d\tau$$

Intermittency – Probability density function: Flow is more intermittent at time scales of ~30-60 sec, which correlate to ~3-6m by Taylor's hypothesis

Anisotropy – Barycentric Map from eigenvalues (λ_i) of the anisotropy tensor (Banerjee et al. 2007): Flow is not isotropic!

$$C_{1c} = \lambda_1 - \lambda_2$$
$$C_{2c} = 2(\lambda_2 - \lambda_3)$$
$$C_{3c} = 3\lambda_3 + 1$$

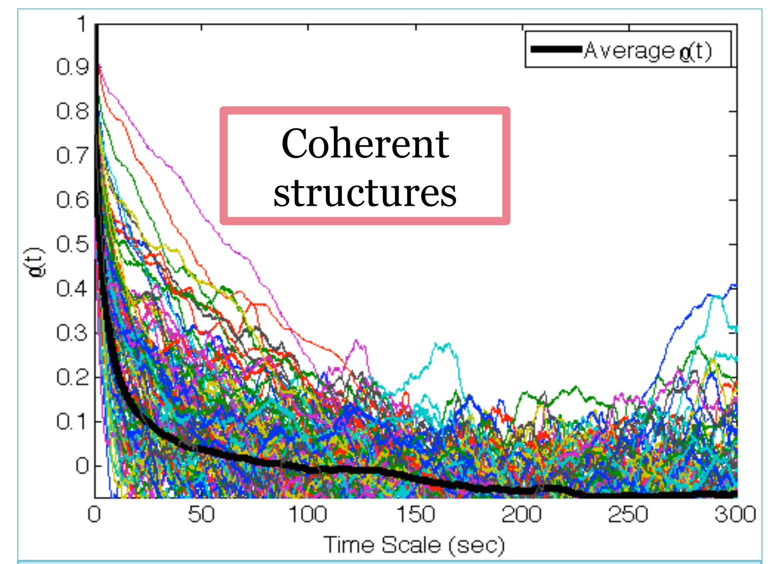

Figure 2: Autocorrelation function from ADV data at Nodule Point, with the average.

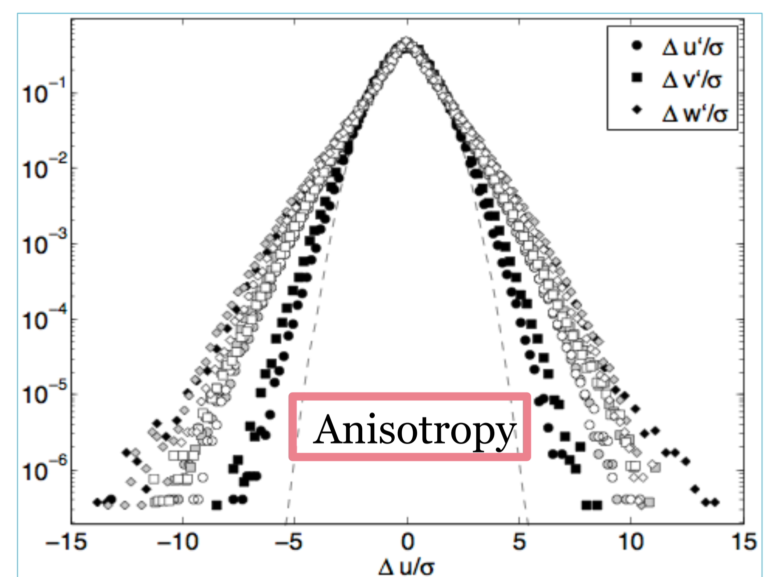

Figure 3: Probability density function of velocity differences from ADV data at Δt=1/32s (black), and 3m (gray) and 6m (white) rotor diameters.

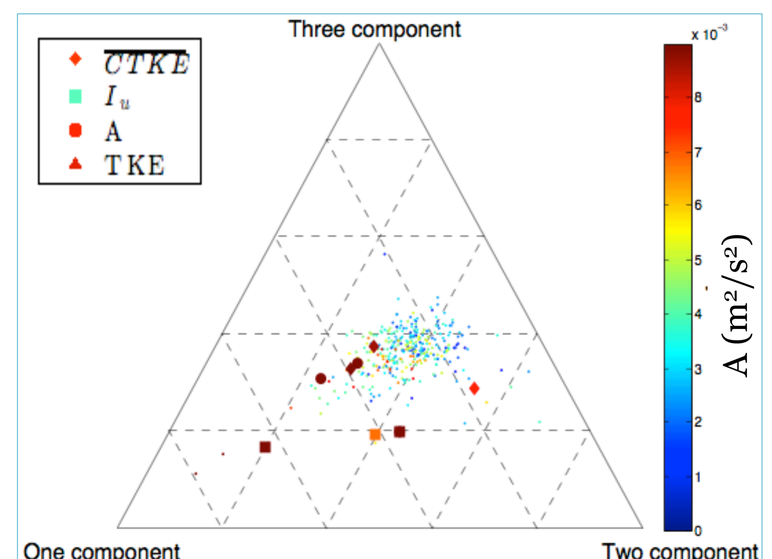

Figure 4: Barycentric map based on eigenvalues colored by A for the ADV data at Nodule Point.

Parameterization

How do we represent how "turbulent" a location is?

Is I_u, CTKE, or A better at representing intermittency, coherence, and anisotropy?

	λ(sec)	Λ (sec)
I_u	0.596	0.450
TKE	0.747	0.079
CTKE	0.680	0.017
A	**0.884**	0.317

A **best captures:**

- Anisotropy from barycentric maps
- Intermittency from pdfs
- Coherence from the Taylor scale

Parameterization methods:

- Barycentric maps colored by 4 metrics
- Pdfs separated by strength of 4 metrics
- Regression performed on Taylor and Integral scales versus 4 metrics

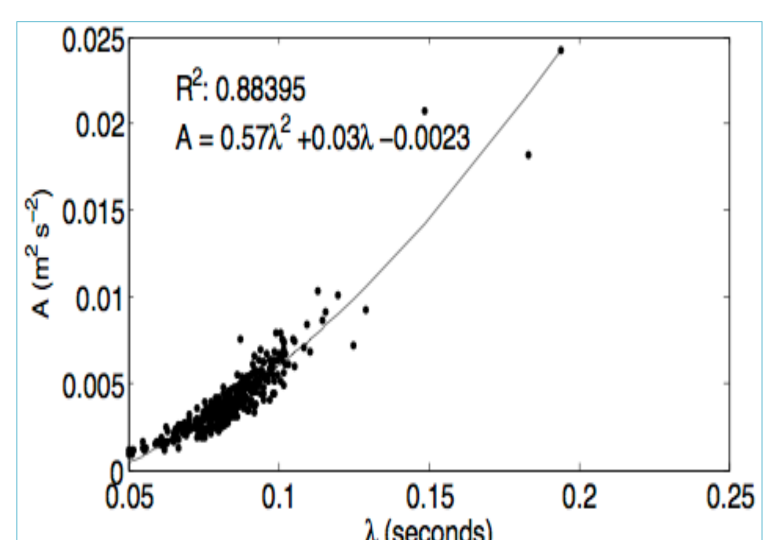

Figure 5: A versus Taylor scale, λ, with regrression for the ADV data at Nodule Point.

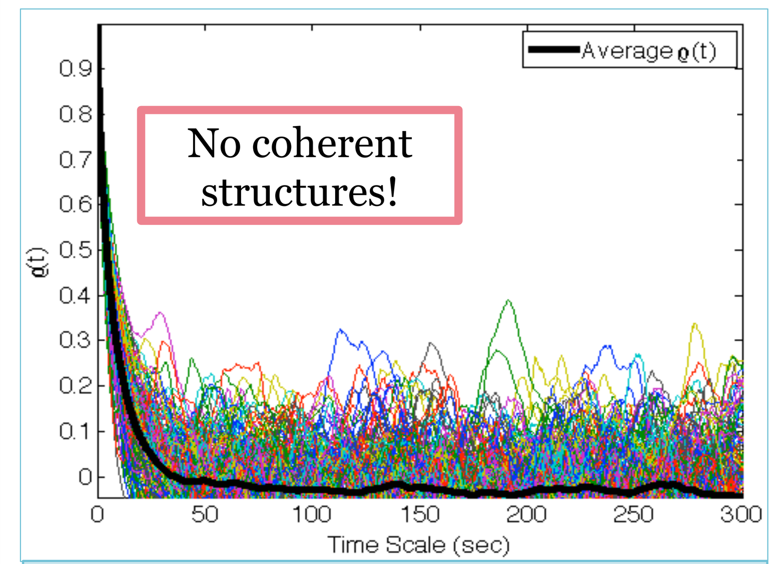

Figure 6: Autocorrelation from HydroTurbSim data, with the average.

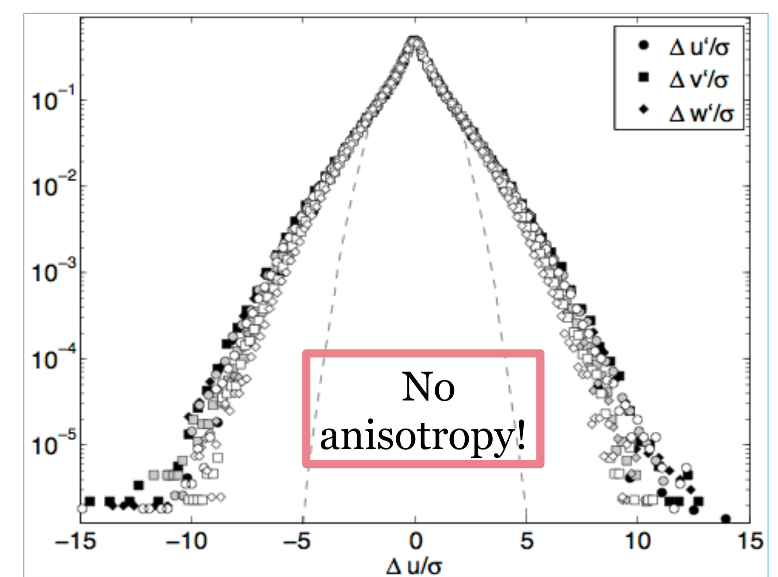

Figure 7: Probability density function of velocity differences from HydroTurbSim data for Δt=1/10s (black), and 3m (gray) and 6m (white) rotor diameters.

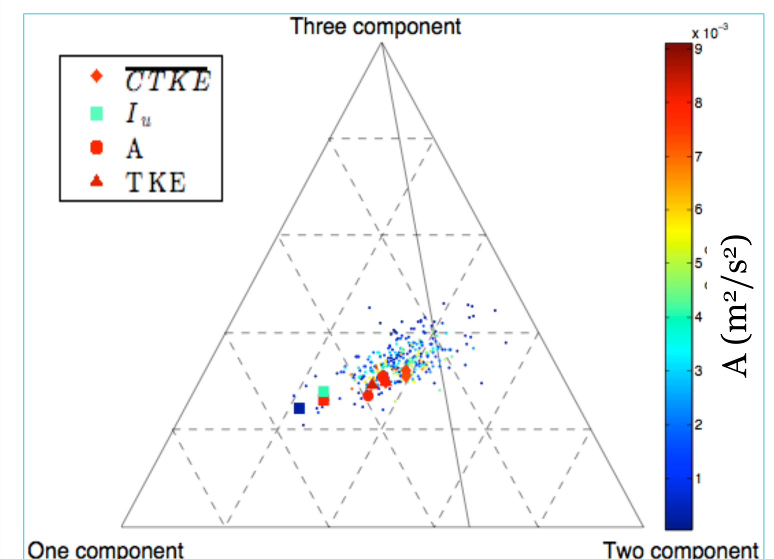

Figure 8: Barycentric map from HydroTurbSim data colored by A.

Stochastic Model

Output from the National Renewable Energy Laboratory's HydroTurbSim model was analyzed to determine which aspects of the realistic flow a stochastic turbulence generator captures.

Input:
- Background mean flow profile
- Turbulent spectral density curve based on observations
- Turbulence intensity standard
- Reynolds Stresses

Method:
- Inverse fast Fourier transform
- Spatial correlation function

Output:
- Two-dimensional snapshots of three velocity components in time (or, assuming Taylor's hypothesis, the third dimension in space)

HydroTurbSim creates turbulence with a set turbulence spectrum, and defines anisotropy based on random-phase correlations between Reynolds stresses, and proportions between normal stresses.

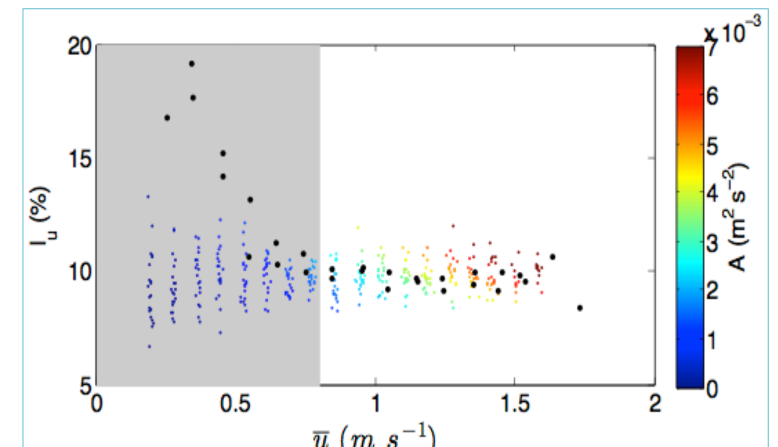

Figure 9: Turbulence intensity, I_u, versus mean speed, colored based on *A* for HydroTurbSim data. Black dots are average I_u from ADV data.

Conclusions

Observational data results:

- Coherence was measured through autocorrelations, intermittency was measured through probability density functions, and anisotropy was measured based on the eigenvalues of the anisotropy tensor.
- Physical characteristics were parameterized by the turbulence intensity, turbulent kinetic energy, coherent turbulent kinetic energy, and anisotropy magnitude, which was introduced.
- *A* was shown to be the best at parameterizing coherence and anisotropy.

HydroTurbSim results:

- No coherent events are seen in the autocorrelation functions.
- Anisotropy is only captured when defined by the input (Reynolds shear stresses), but not the normal stresses, as seen in the pdf.
- HydroTurbSim does what it is built to do, but doesn't capture coherent events.
- LES is expected to capture the coherent structures that HydroTurbSim cannot.

Acknowledgements

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