Generation and interaction of shear inflow turbulence with a scaled horizontal axis tidal turbine

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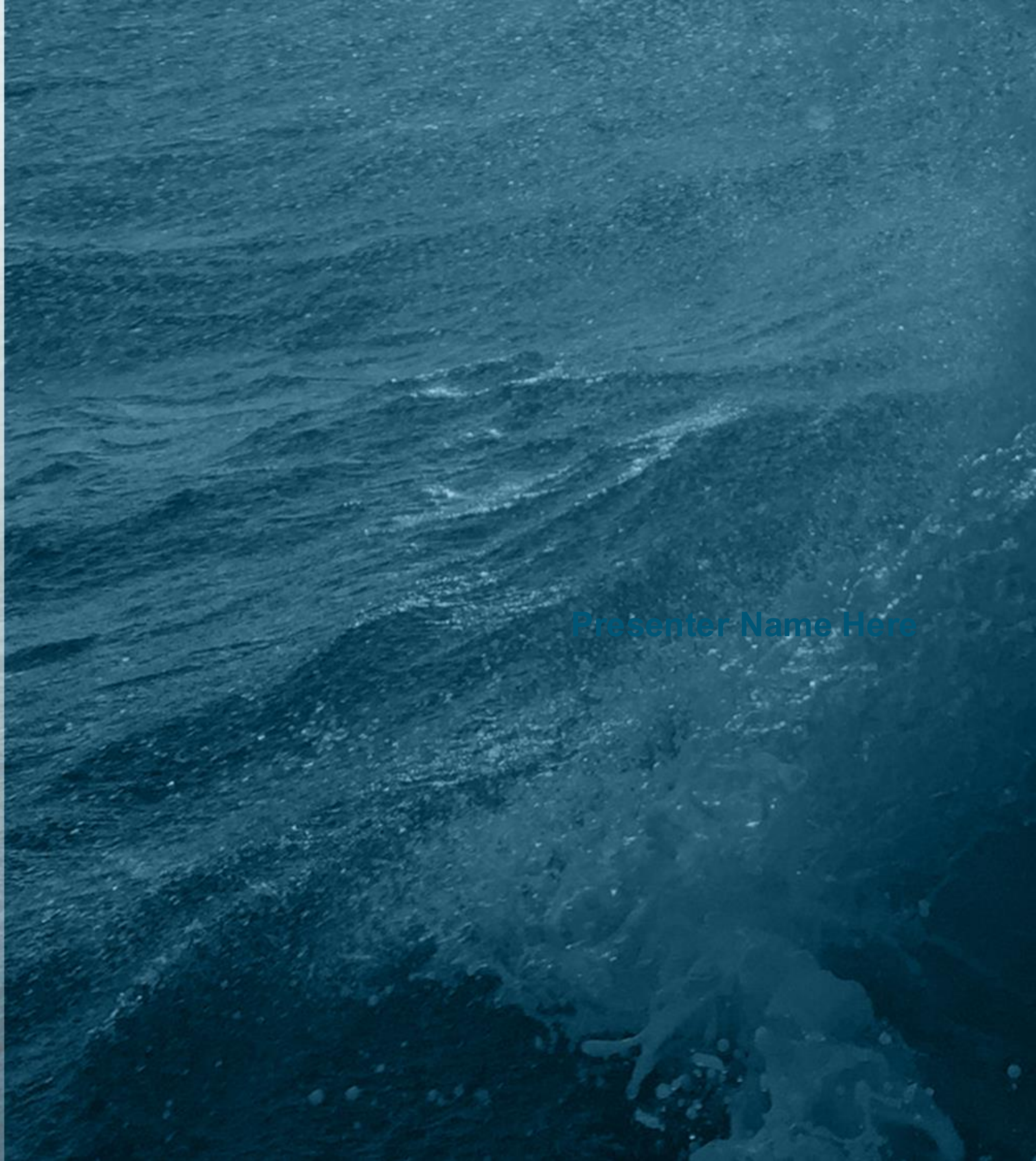
This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Water Power Technologies Office (WPTO) Award Number DE-EE0009450



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Introduction

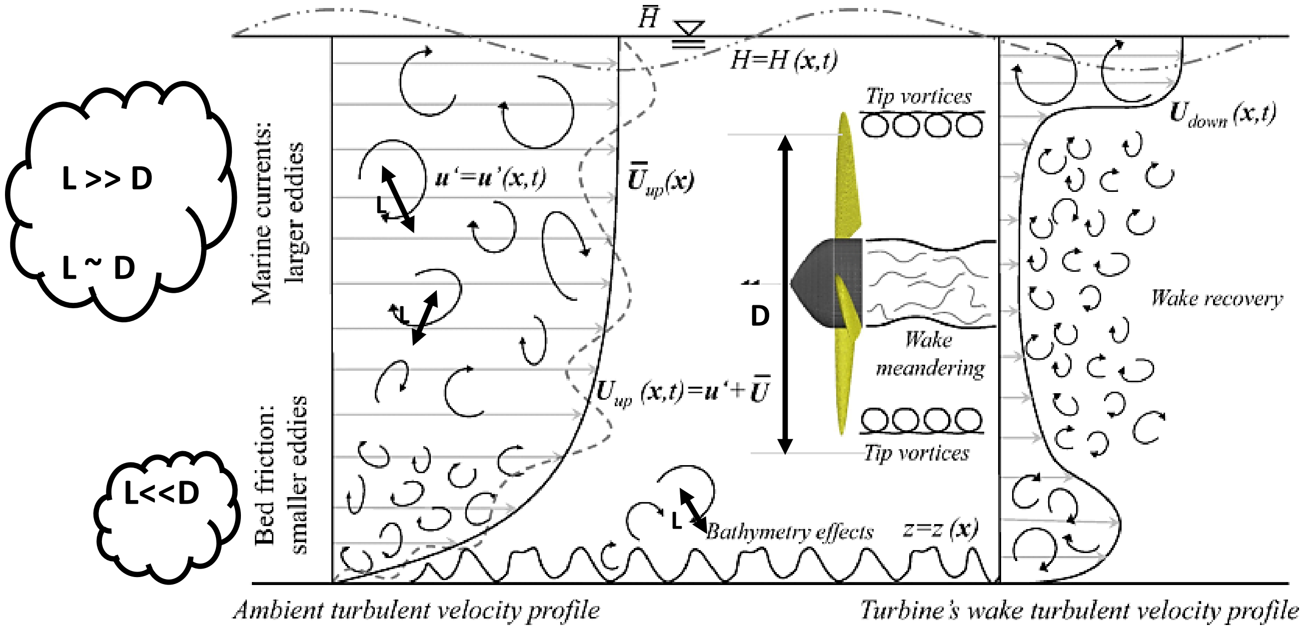
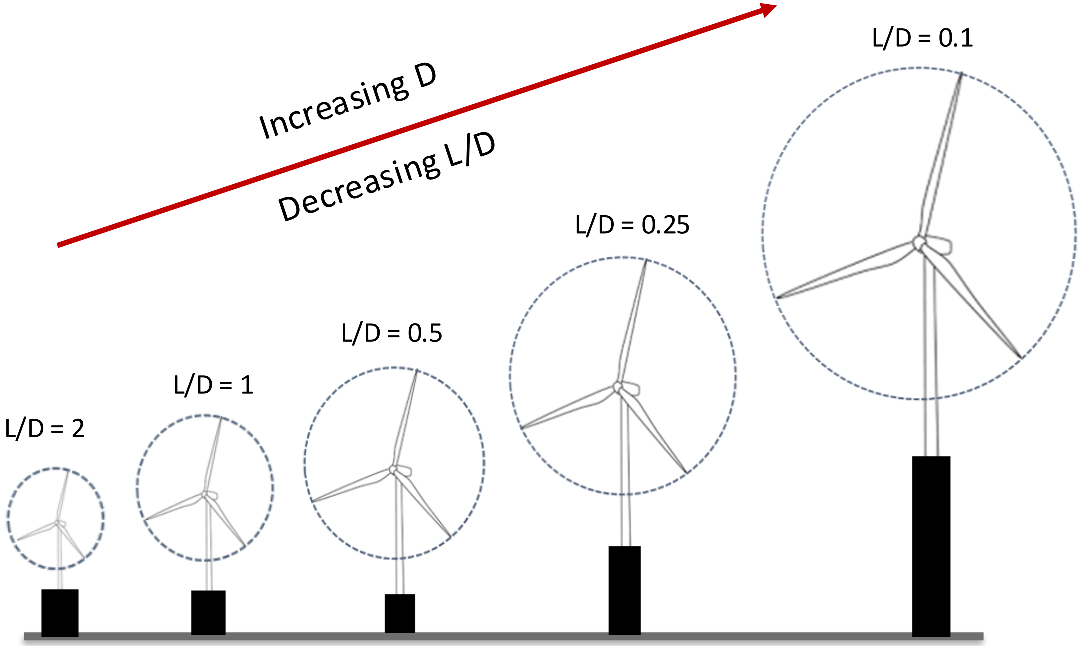


Figure taken from Ouro & Stoesser (2019)

- **L << D :** Structures forming from sea bed with integral length scale (L) smaller than turbine diameter (D)
- **L ≥ D** : Structures from the marine current and wave interaction having spatial correlation of D and larger
- **Turbulence** : Ambient turbulence is non-homogeneous and anisotropic with varying length scales
- **Velocity Profile** : Ambient inflow is non-uniform or shear profile

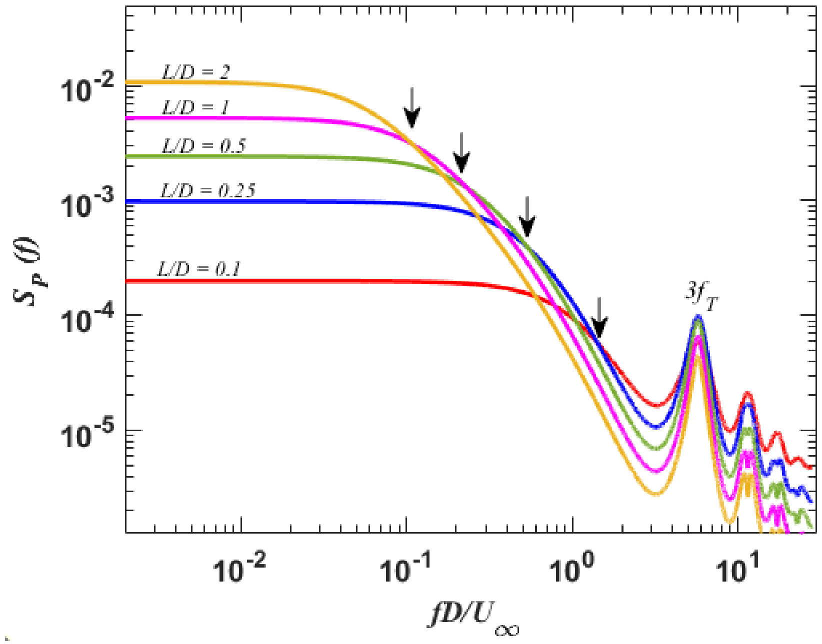
Ouro, P., Stoesser, T. Impact of Environmental Turbulence on the Performance and Loadings of a Tidal Stream Turbine. *Flow Turbulence Combust* **102**, 613–639 (2019)

Open Question Addressed



Turbine Power Spectral Model for HIT (Deskos et al. 2020)

$$S_P(f) = \left(\frac{3}{2}\rho(1-a)^2 \frac{dC_L}{d\alpha} U^2\right)^2 \int_{-\infty}^{\infty} \iint_0^R R_{11}(r_1, r_2, \tau) \exp(-i2\pi f\tau)\, c(r_1) c(r_2) \sqrt{\lambda^*(r_1)^2 + 1}\sqrt{\lambda^*(r_2)^2 + 1}\, dr_1 dr_2 d\tau$$

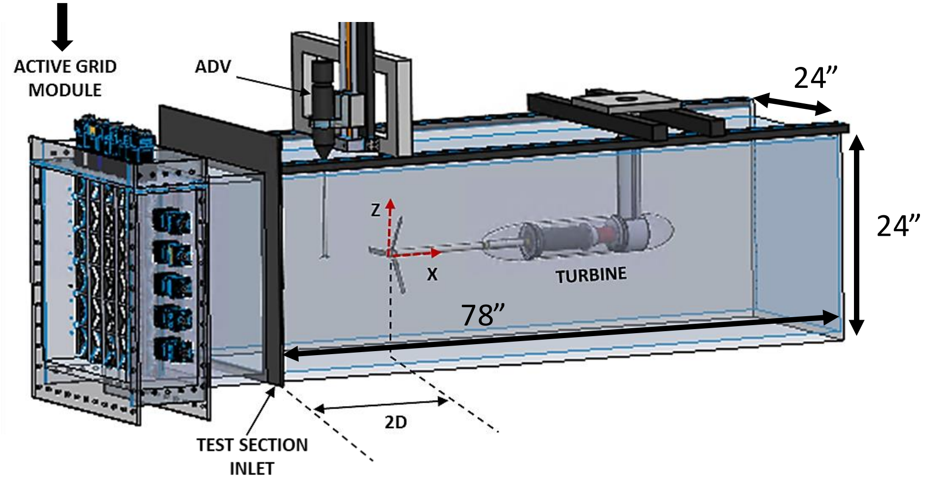


- **Open Question**
  How does integral length scale in non-homogeneous/shear inflow drives power fluctuations?

Deskos, G., Payne, G. S., Gaurier, B., & Graham, M. (2020). On the spectral behaviour of the turbulence-driven power fluctuations of horizontal-axis turbines. *Journal of Fluid Mechanics*, *904*, A13.

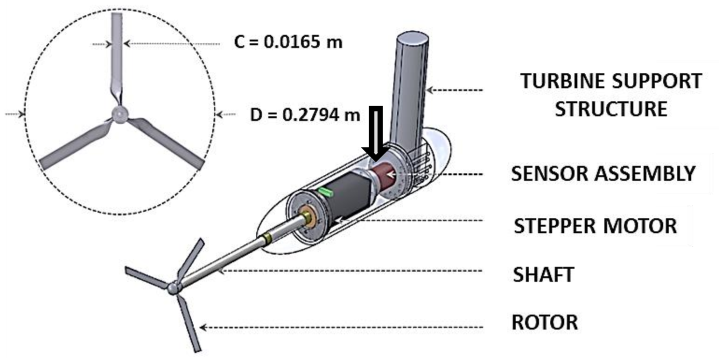
Tidal Turbulence Testing Facility (T^3F)

- **Water Tunnel with Active Grid**
  - The water tunnel test-section has a cross-section of 24'' x 24'' and 78" in length (~2m)
  - Equipped with Makita-style active grid for turbulence generation and shear inflow



Recirculating Water Tunnel equipped with Active Grid

- **Tidal Turbine Model**
  - A 1:20 scaled of 5m diameter Verdant power turbine
  - The turbine diameter is 11" (0.28m)
  - Turbine blade profile of SG6043 with chord = 16.5mm
  - Turbine is equipped with Torque and Thrust sensors
  - The sampling frequency of sensors is 200Hz



1:20 scaled Tidal Turbine having D = 0.28m

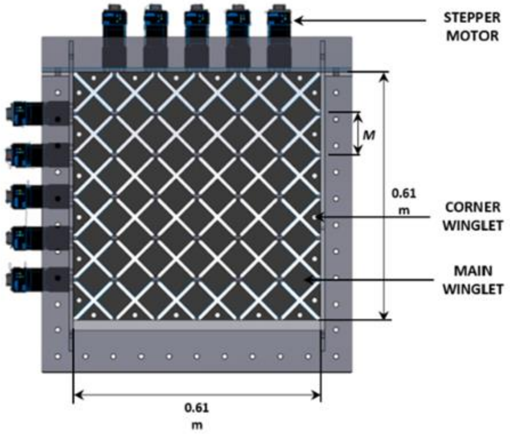
Acoustic Doppler Velocimeter (ADV, 50Hz)

M. Hanzla & A. Banerjee, Spectral behavior of a horizontal axis tidal turbine in elevated levels of homogeneous turbulence, Applied Energy, Volume 380, 2025, 124842, ISSN 0306-2619

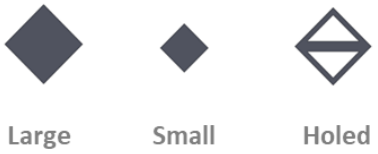
Freestream Turbulence Generation Capabilities

- Active Grid Configurations
  - 10-shaft configurations – 5 horizontal and 5-vertical
  - Each shaft is equipped with 6 diamond shape winglets
  - Each shaft is separately controlled with stepper motor
  - The stepper motor is programmed using LabVIEW
  - There are 24 half winglets attached on the walls

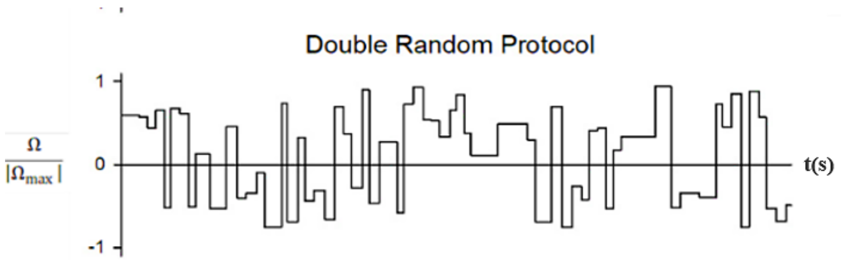
10-shafts configuration



Winglet Types



- Active Grid Operating Protocols
  - Stepper motor are programmed to operate in control
  - Double random allows randomized shaft direction and angular speed



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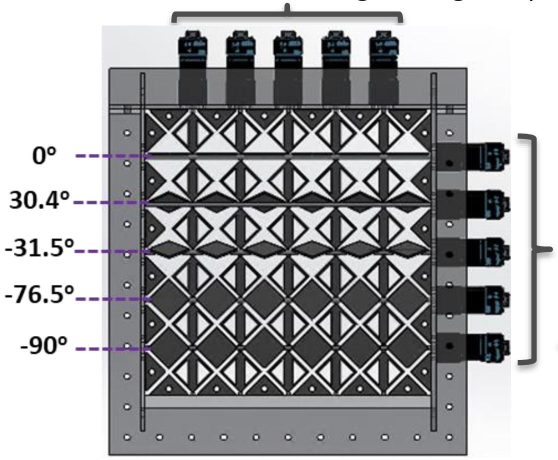
Shear Inflow Turbulence Generation

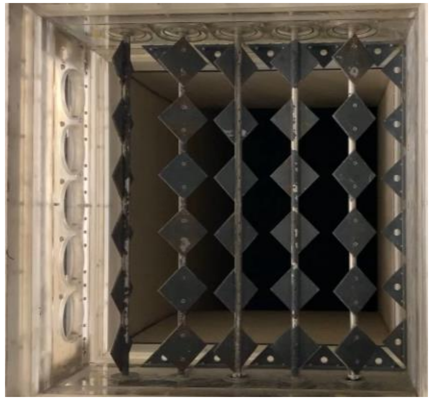
Dynamic Shafts
(Turbulence Generating Winglets)

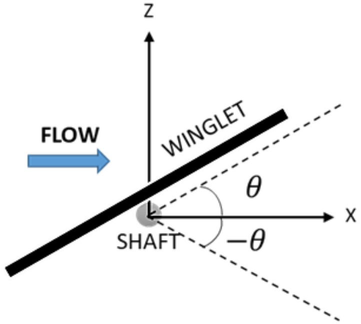
Static Shafts
(Shear Generating Winglets)



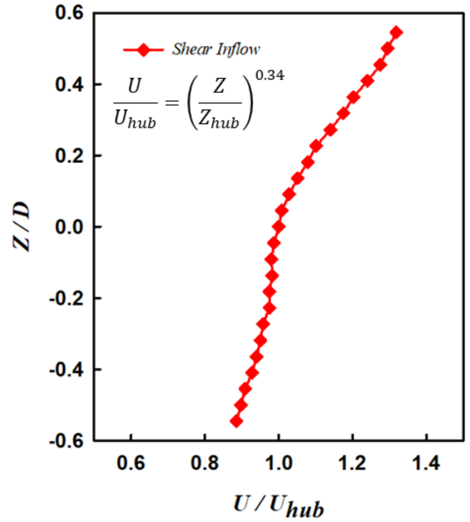
10-SHAFT CONFIGURATION

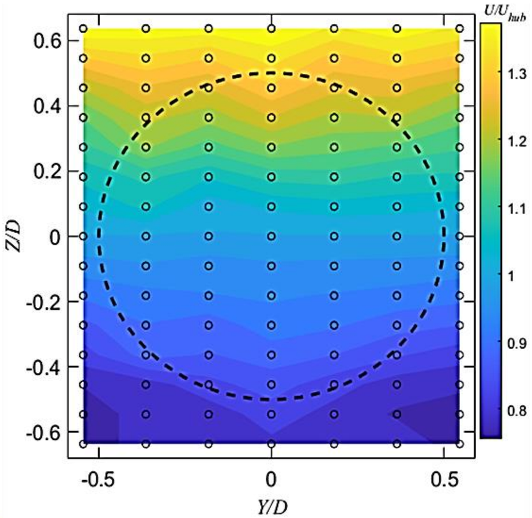
Vertical Shafts – Double Random (DR)





Side View of Horizontal Shafts





- Grid Configuration for Shear Inflow
  - Horizontal shafts are fixed at certain angles
  - Vertical shafts are operated using DR protocol
  - Horizontal shafts creates the non-uniformity
  - Vertical shafts add turbulence and uniformity

Cases Description And Characterization

Case Name	Active Grid	Protocol
Quasi-laminar (QL)	No Grid	-
Dynamic Shear-Ti	Yes	DR at 1 Hz
Dynamic Shear-Ti-High L	Yes	DR at 0.1Hz

- Velocity Time Series – Reynolds Decomposition

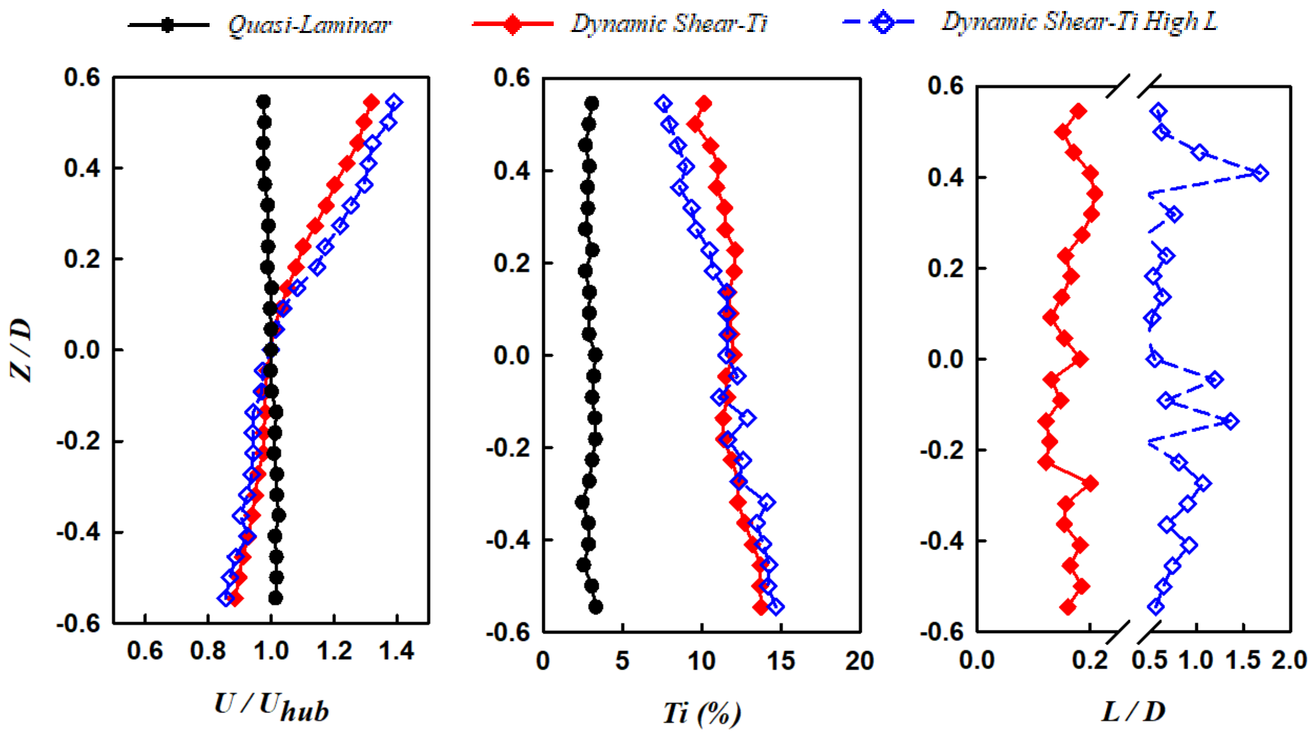
$$u(t) = U + u'(t)$$

- Turbulence Intensity

$$Ti(\%) = 100 \times \frac{\sqrt{u'^2}}{U}$$

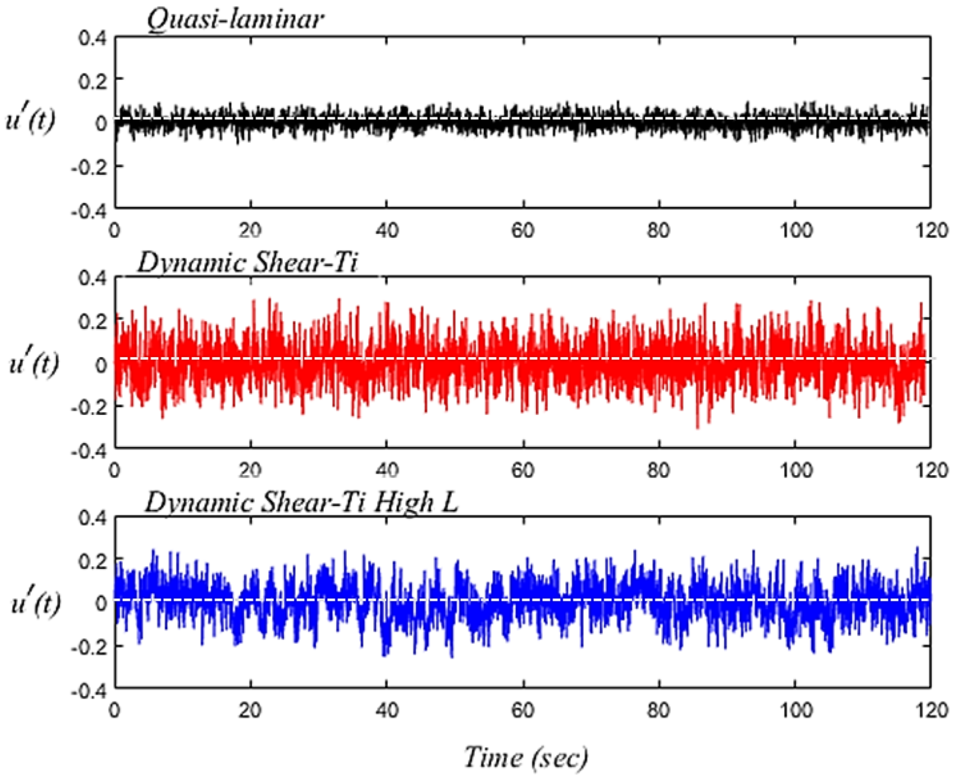
- Integral Length Scale

$$\mathrm{L/D} = U\left(\int_0^\infty \frac{\overline{u'(t)u'(t+\tau)}}{\overline{u'^2(t)}}\,d\tau\right)/D$$



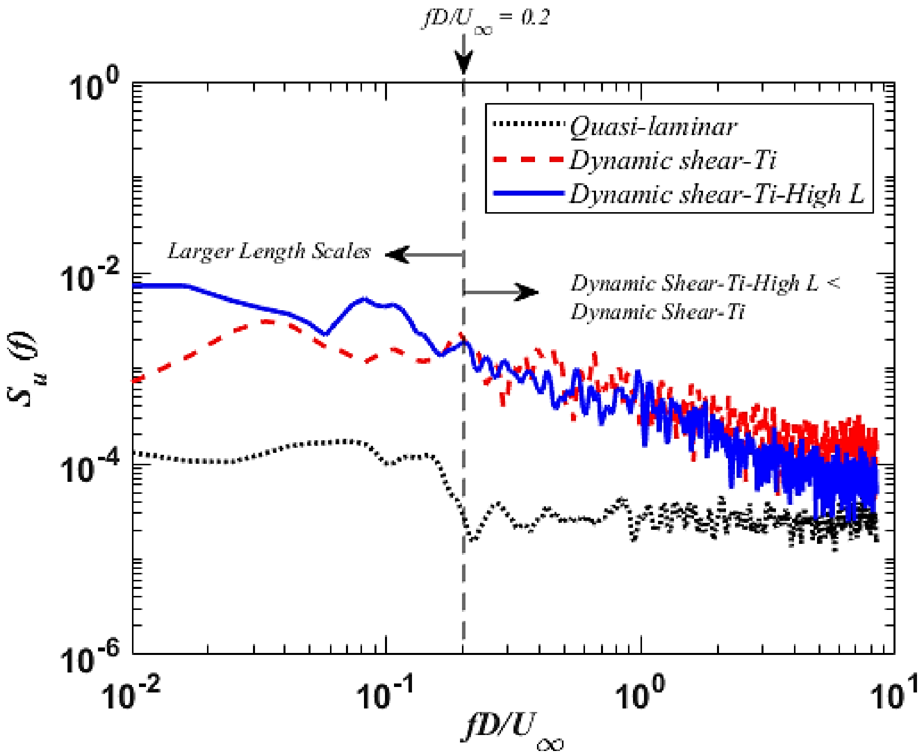
Comparison of Velocity Spectra

- Velocity Fluctuations Time Series



- Power Spectral Density (PSD)

$$S_u(f) = \int_{-\infty}^{\infty} \overline{u'(t)u'(t+\tau)}\, e^{-i2\pi f\tau} d\tau$$



Turbine Performance

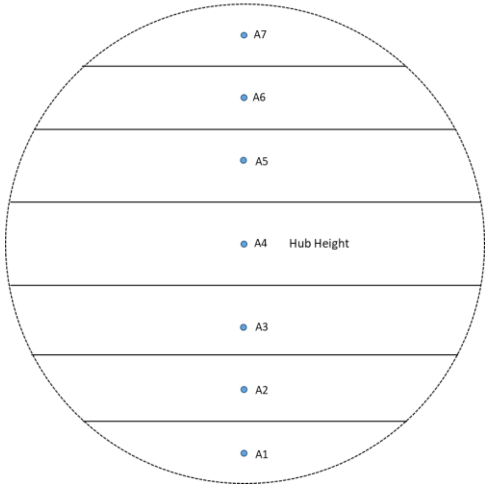
$$\lambda = \frac{\omega D}{2U_{eq}} \qquad C_P = \frac{Q\omega}{1/2\rho A_T U_{eq}^3} \qquad C_T = \frac{T}{1/2\rho A_T U_{eq}^2}$$

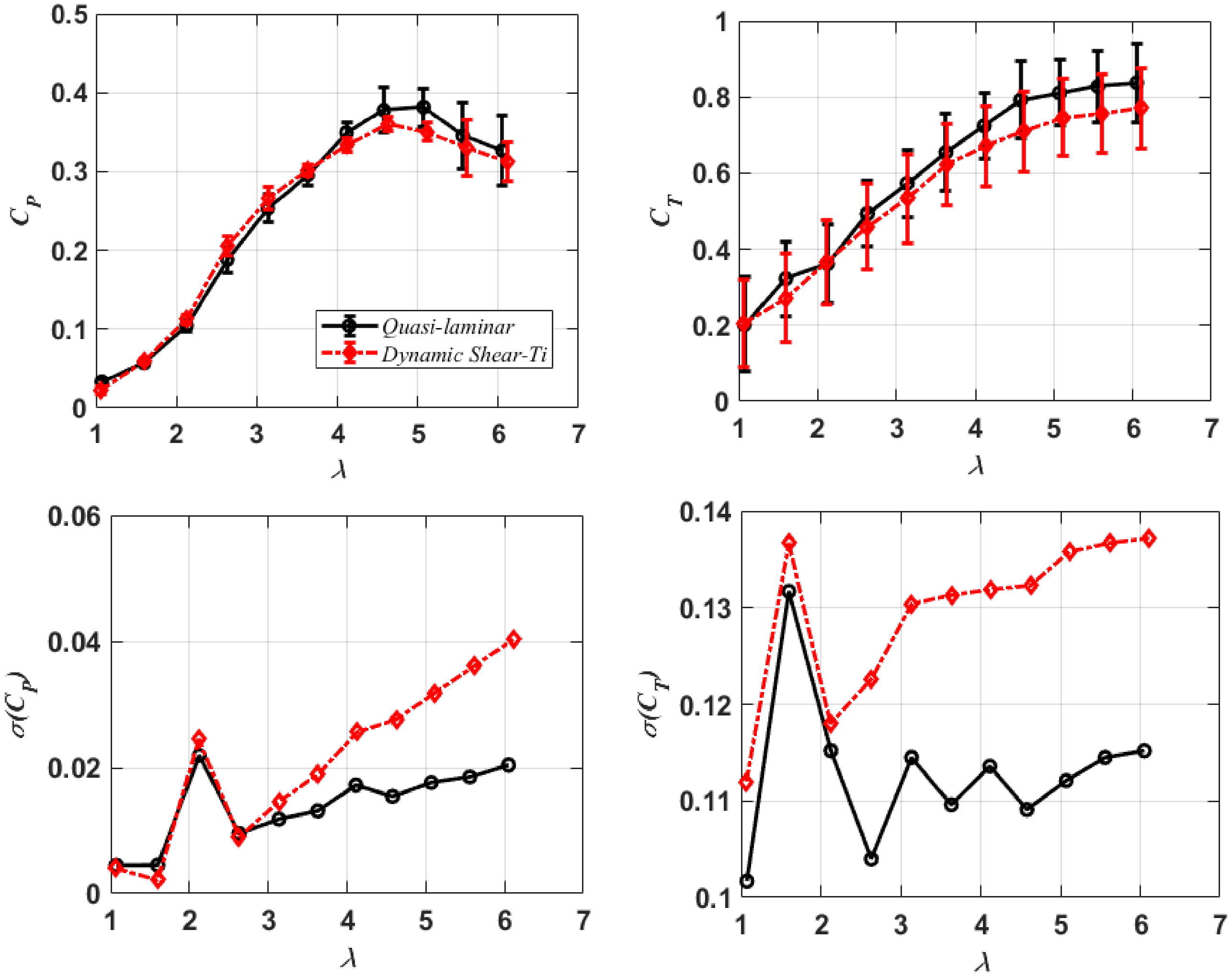
λ – Tip-speed ratio, C_P - Power Coefficient, C_T - Thrust Coefficient

ω- Angular Speed (rad/s)
U_{eq} - Equivalent Velocity (m/s)
A_T – Rotor Area (m^2)

Q – Torque (N-m)
ρ – Density (kg/m^3)
T – Thrust (N)

$$U_{eq} = \left(\frac{1}{A_T}\sum_{i=1}^{N=7} A_i U_i^3\right)^{1/3} \rightarrow$$





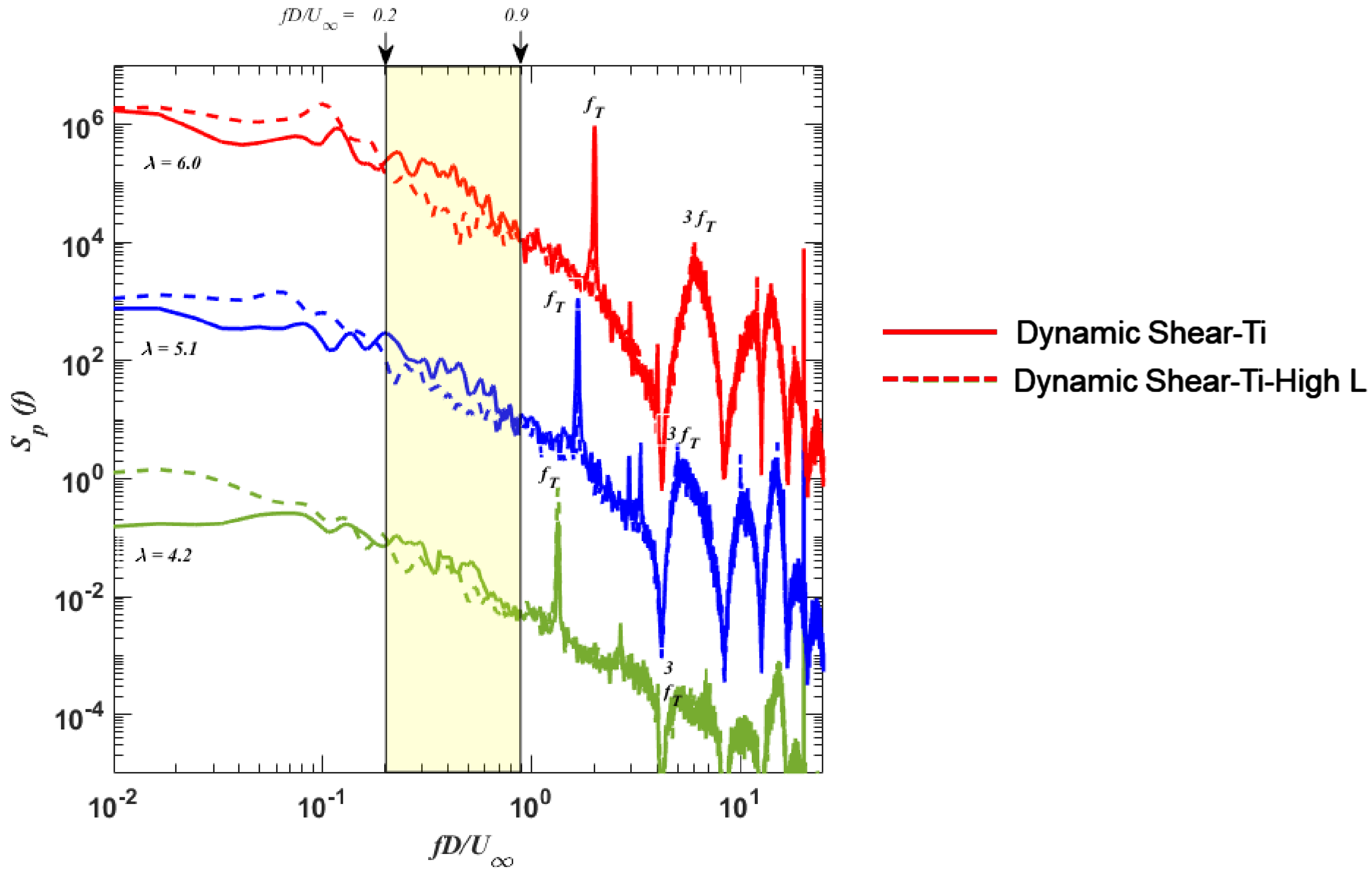
A. Vinod, A. Banerjee, Performance and near-wake characterization of a tidal current turbine in elevated levels of free stream turbulence, Applied Energy, Volume 254,2019,113639,ISSN 0306-2619

Effect of Integral Length Scale on Turbine Power Spectra

$$P'(t) = Q'(t)\omega$$

$$S_P(f) = \int_{-\infty}^{\infty} \overline{p'(t)p'(t+\tau)}\, e^{-i2\pi f\tau} d\tau$$

where S_P is the PSD



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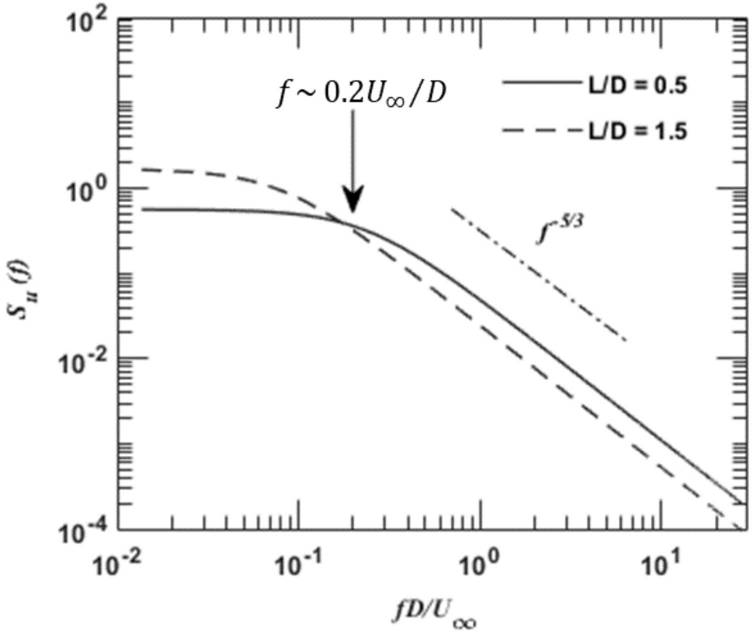
Spectral Analysis: Explanation using Semi-analytical Model

Von Karman Turbulence Spectrum:

$$S_u(f) = \frac{4\overline{u'^2}\, L/U}{[1 + 70.8(f\, L/U)^2]^{\frac{5}{6}}}$$



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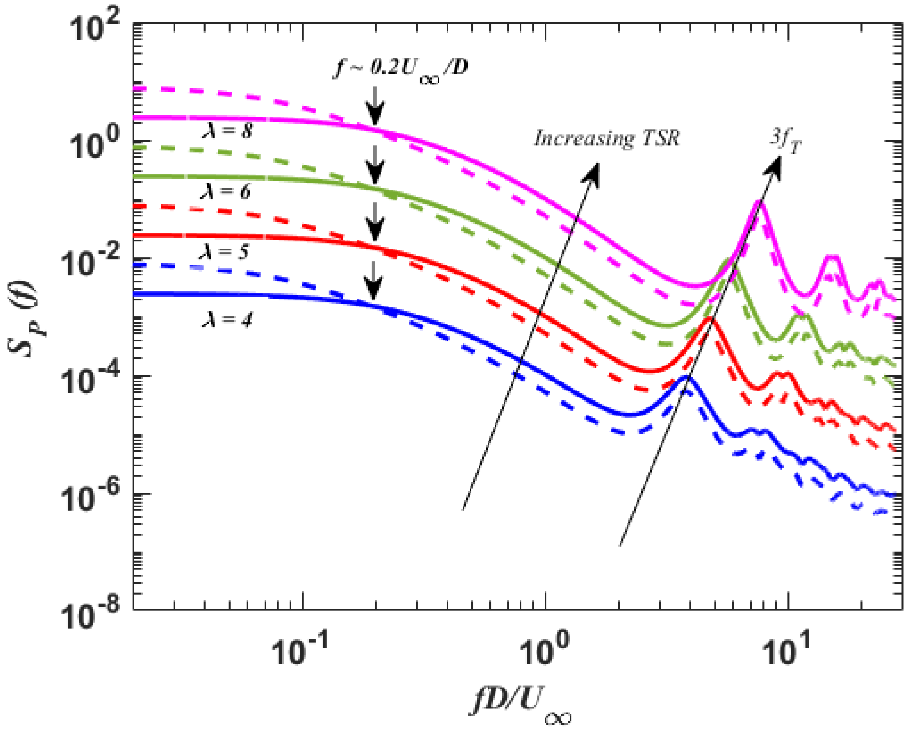

Conclusions

- The turbine performance drops in presence of shear and elevated-turbulence
- As integral length scale is increased, the turbine power spectra shifts to lower frequencies
- The spectral amplitude drops in the mid-frequency region (0.2-0.9U_∞ /D) for larger length scale at all tip-speed ratios when compare to smaller length scale
- Analytical explanation is provided for the experimentally obtained results

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