Impact of Turbulence on the Control of a Hydrokinetic Turbine

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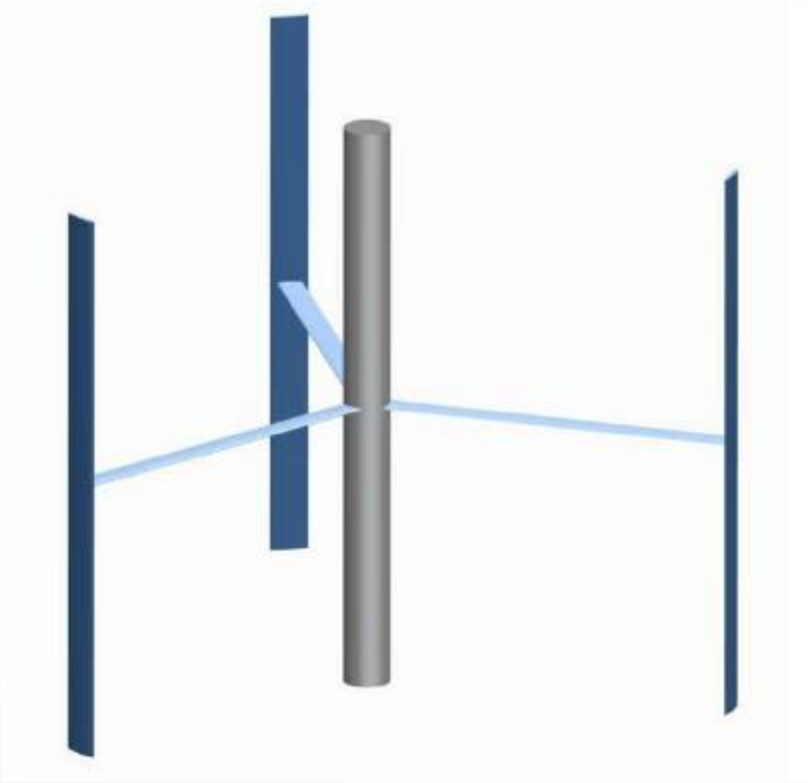
Motivation

- Work is being conducted on advanced controllers for hydrokinetic turbines
- Turbines will operate in high-energy, turbulent conditions
- Similarity to wind can be leveraged, but differences between atmospheric and marine environments impact turbine dynamics
- We can learn about how turbulence affects the dynamics and control of a turbine using simple linear analysis techniques

Analyzed Turbine – US DOE RM2



- **Openly accessible geometry**
- **Cross-flow turbine**
  - 3x Straight blades
  - Fixed-pitch
- ***R***: Turbine radius (3.2 m)
- ***A:*** Turbine area (31 m^2)
- ***J:*** Estimated inertia (8400 kg-m^2)
- ***B***: Estimated damping (37 Nm-rad/s)
- **Rated power:** 50 kW
- **Rated speed:** 2 m/s

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Barone, M. et al. (2011). Reference Model 2: "Rev 0" Rotor Design; Neely, J. et al. (2013). Electromechanical Emulation of Hydrokinetic Generators for Renewable Energy Research. In OCEANS'13 MTS/IEEE

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Turbine Dynamics

$$J\dot{\omega}_t = \tau_h - B\omega_t - \tau_c$$

Turbine rotation rate

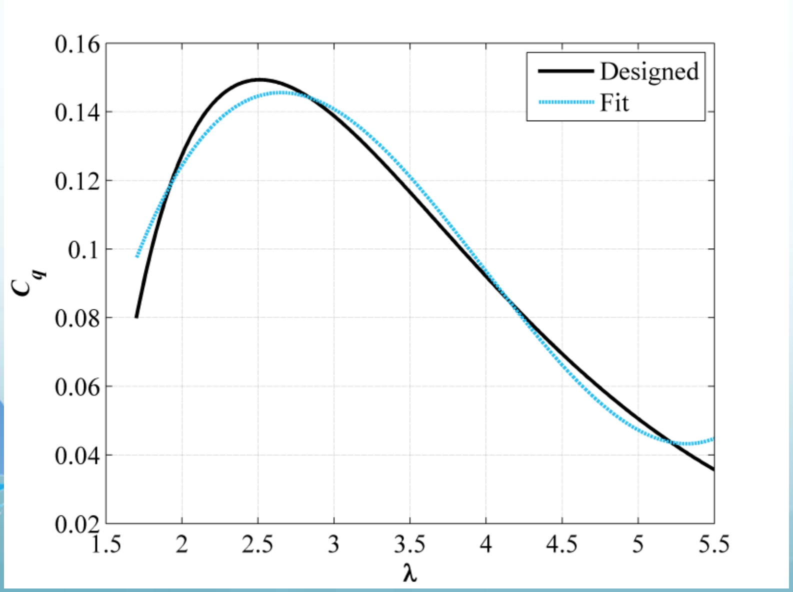
Damping coefficient

Control torque – control input

Moment of inertia

Hydrodynamic torque

$$\frac{1}{2}C_q(\lambda)\rho A_t R_t u^2$$



Source of nonlinear dynamics

$$C_q(\lambda) = a\lambda^3 + b\lambda^2 + c\lambda + d$$

$$\lambda = \frac{\overline{\omega}_t R_t}{\overline{u}}$$

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Linearization at Operating point

$$\theta = (\bar{u}, \bar{\omega}_t)$$

Operating point completely defined by mean water speed and rotation rate

$$\hat{u} = u - \bar{u}$$

Turbulent fluctuations are defined as instantaneous minus mean velocity

$$\tau_h = \frac{1}{2} C_q(\lambda) \rho A_t R_t u^2 \longrightarrow \hat{\tau}_h = K_\omega \hat{\omega}_t + K_u \hat{u}$$

A linear expression for τ_h can be formed using linearization constants defined at an operating point

$$K_\omega = \left. \frac{\partial \tau_h}{\partial \omega} \right|_\theta \qquad K_u = \left. \frac{\partial \tau_h}{\partial u} \right|_\theta$$

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Ginter, V. J., & Pieper, J. K. (2011). Robust Gain Scheduled Control of a Hydrokinetic Turbine. IEEE Transactions on Control Systems Technology, 19(4), 805–817.

Linearized Dynamic System

$$\dot{\omega}_t = \frac{\tau_h}{J} - \frac{B\omega_t}{J} - \frac{\tau_c}{J} \longrightarrow \dot{\widehat{\omega}}_t = \frac{(K_\omega - B)\widehat{\omega}_t}{J} + \frac{K_u \hat{u}}{J} - \frac{\hat{\tau}_c}{J}$$

Resulting linearized equation describes fluctuations in rotational acceleration in response to turbulence and fluctuations of control torque

The model can be written in state-space form…

$$\dot{\widehat{\omega}}_t = A(\theta)\widehat{\omega}_t + B_1(\theta)\hat{u} + B_2\hat{\tau}_c$$

$$\widehat{\omega}_t = C\widehat{\omega}_t + D\hat{\tau}_c$$

… and converted to a linear combination of transfer functions

$$\widehat{\omega}_t = [G_1(s) \quad G_2(s)] * [\hat{u} \quad \hat{\tau}_c]^T$$

In this form, turbulence is a disturbance and fluctuation of control torque is an input. Deviation of rotation rate from the operating point is the state and output.

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Bianchi, F. D., De Battista, H., & Mantz, R. (2007). Wind Turbine Control Systems: Principles, Modeling and Gain Scheduling Design. Springer-Verlag London Limited. (p. 83-91).

Open-Loop Response using Transfer Functions

$$G_1(s) = \frac{K_u/J}{s + \left(\frac{B - K_\omega}{J}\right)}$$

← Response to turbulence

$$G_2(s) = \frac{1/J}{s + \left(\frac{B - K_\omega}{J}\right)}$$

← Response to control action

Both transfer functions have the same single pole

This type of system is analogous to a *low pass* filter

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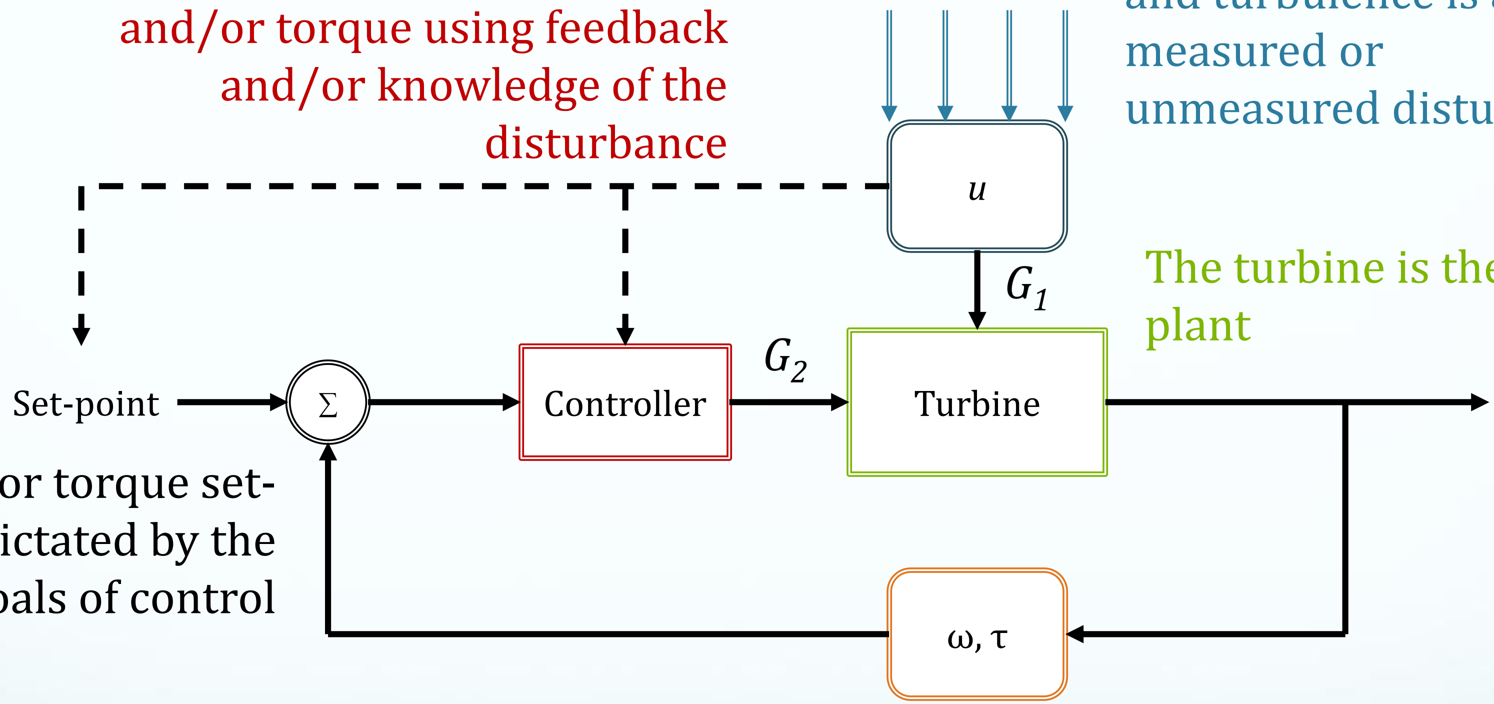
Fixed-Pitch Turbine Control

A controller can regulate speed and/or torque using feedback and/or knowledge of the disturbance

The inflow water speed and turbulence is a measured or unmeasured disturbance



The turbine is the system plant

Speed or torque set-point is dictated by the goals of control

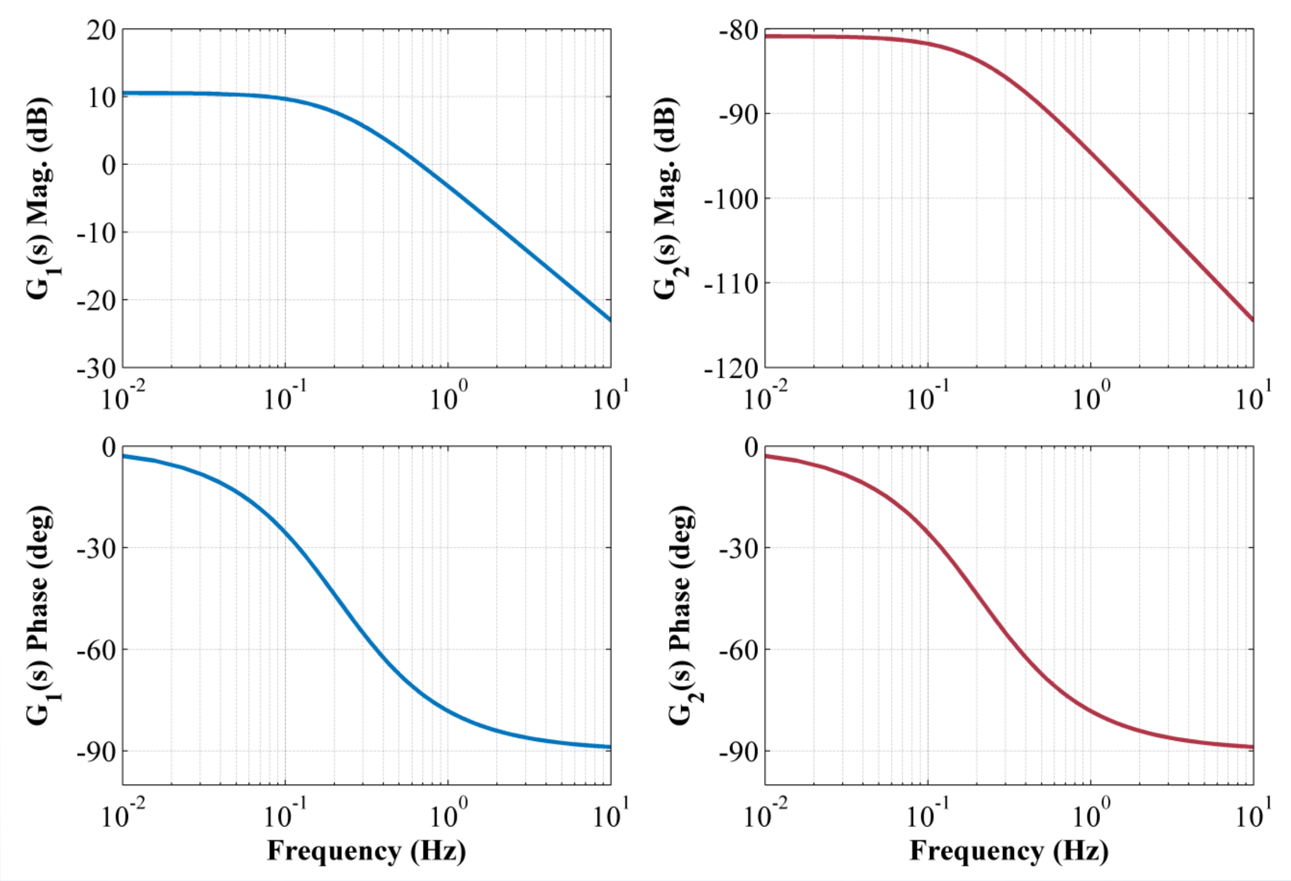
System sensors can provide feedback on turbine operating parameters

Magnitude and Phase Response

The turbine is most sensitive to *low frequency* turbulent fluctuations

Responsiveness decreases with increasing frequency

The same trend and roll-off of response is seen with fluctuation in control input

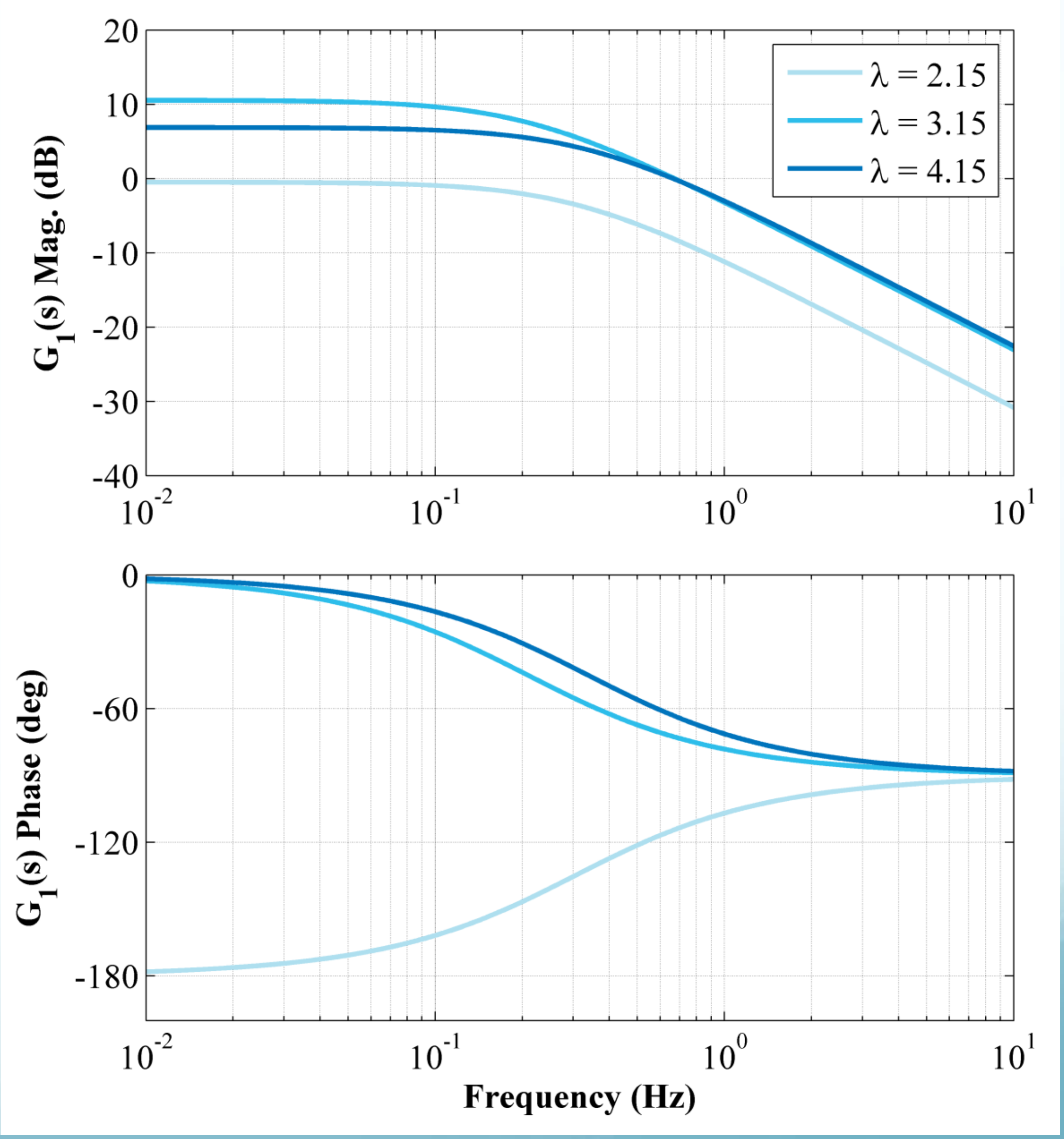


Magnitude and Phase Response

The turbine response changes depending on the operating point linearized near

For example, at, above, and below the point of peak efficiency are shown

At low λ, the system appears unstable due to *antiphase* response



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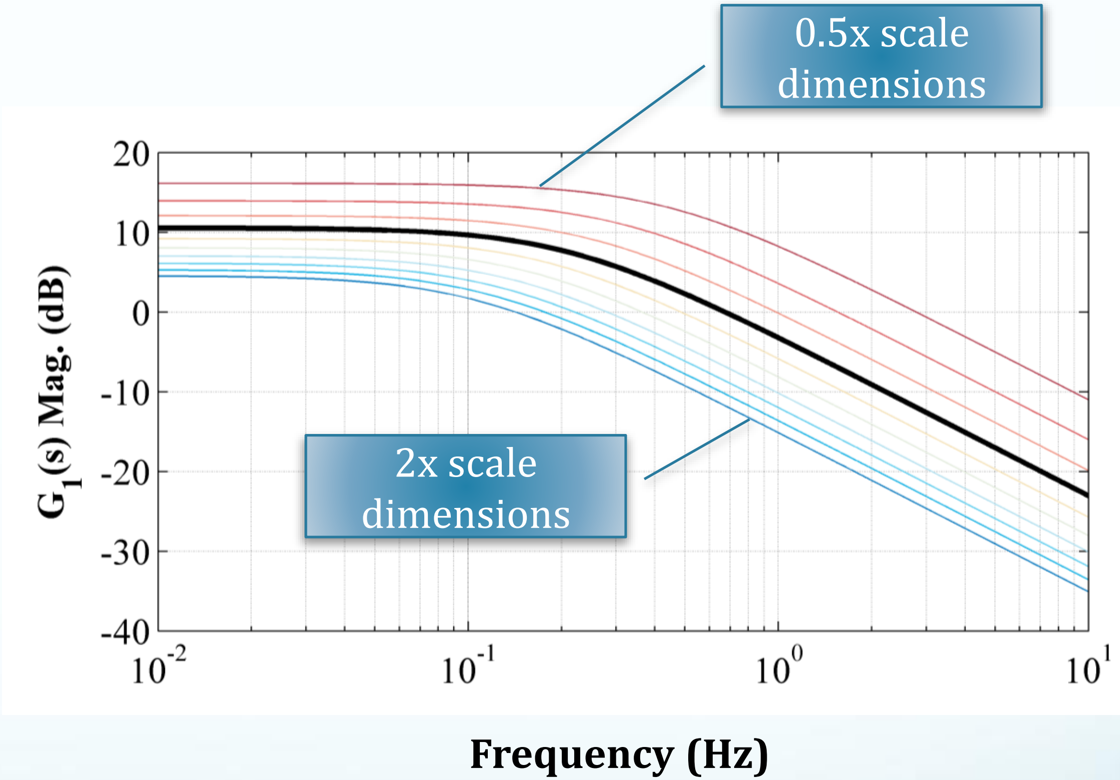
Other Drivers of Response

Increasing or decreasing the size of the turbine (geometry, mass, and moment of inertia) changes the response

Larger turbines have a diminished response and react over a shorter frequency band

These parameters can be adjusted in the design phase to achieve a desired open-loop response



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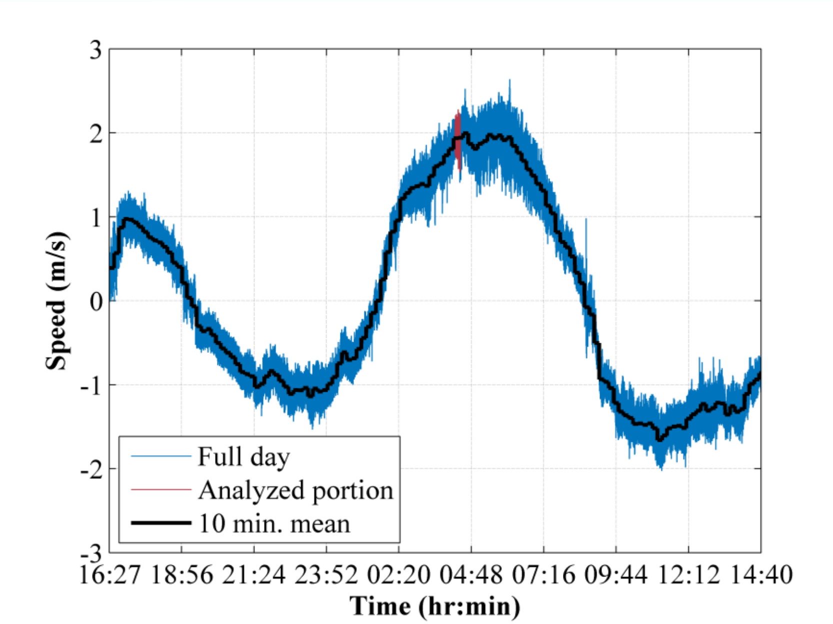
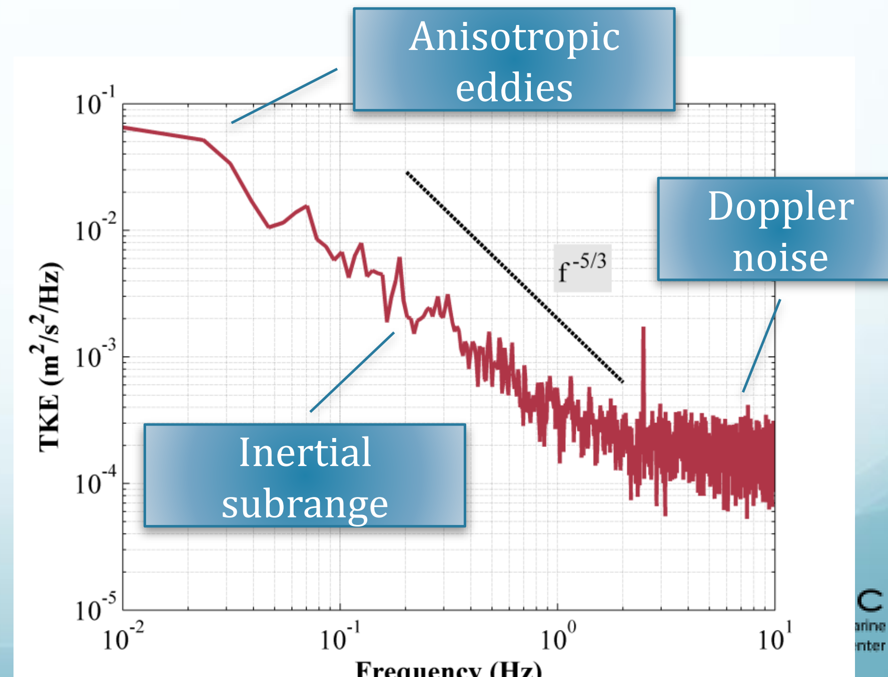
Turbulence of a Tidal Channel



Velocity time-series data is obtained from studies of Admiralty Inlet, Puget Sound, WA

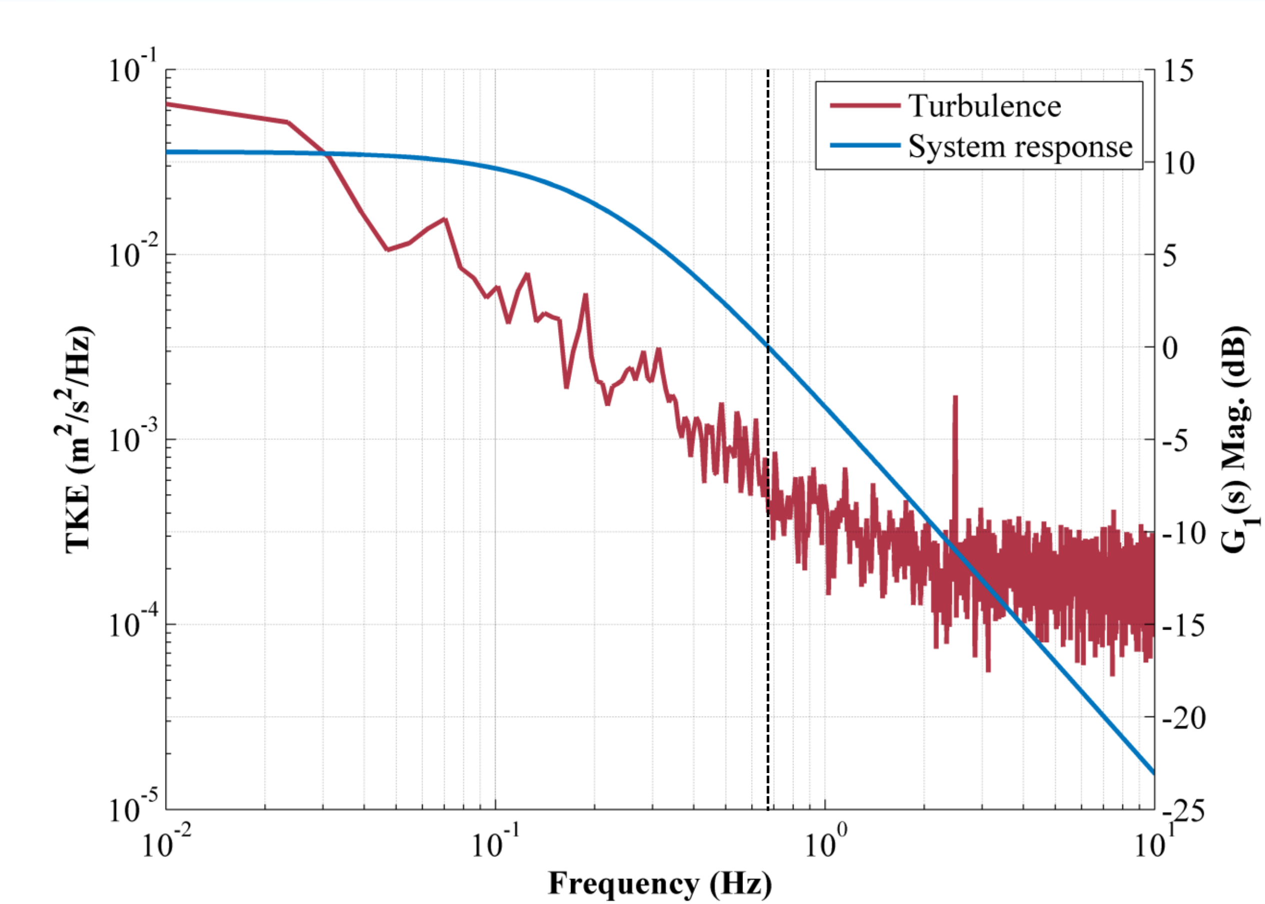
A segment with stationary mean near the turbine's rated speed is analyzed



Viewed in the frequency domain, turbulent kinetic energy (TKE) represents strength of turbulence

Thomson, J., Kilcher, L., Richmond, M., Talbert, J., DeKlerk, A., Polagye, B., Cienfuegos, R. (2013). Tidal turbulence spectra from a compliant mooring. In Proceedings of the 1st Marine Energy Technology Symposium; Map data from Google.

Turbulence and Turbine Response



The turbine is most sensitive to the most energetic turbulent frequencies

Response decays at close to the same rate as TKE (when viewed in these scales)

TKE reduced by >2 orders of magnitude at 0-crossing frequency

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Implications for Control

- **Mean velocity changes over the course of hours, cycling through all the turbine's operating regimes (cut in, below rated, and above rated speed)**
  - **A controller should adjust for these states**
- **A controller that tracks high frequency turbulence may not be necessary**
  - **The turbine does not react strongly and there is little energy at frequencies > 1 Hz**
- **Measuring turbulent fluctuations on the order of seconds to minutes may be beneficial for control and stability**
  - **Turbulence at this scale strongly influences dynamics**

Conclusions

- **A first-order, linear turbine model for a simple geometry is analyzed**
  - **Enables well-established linear systems techniques to be used**
- **Sensitivity to turbine parameters is established**
- **Frequency band of strongest turbulence is shown to match frequency band of strongest turbine response**
- **Recommendations for control based on these results are established**

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Acknowledgements

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