Performance evaluation, emulation, and control of cross-flow hydrokinetic turbines

ROBERT J. CAVAGNARO

FINAL EXAMINATION

3/15/2016

UNIVERSITY of WASHINGTON

Overview

- Motivation
- Cross-flow turbine dynamics and prototype scaling
- System stall characterization
- Field scale system characterization
- Electromechanical emulation of cross-flow turbine
- Conclusions
- Future work

Committee Members:

Prof. Brian Polagye – UW Mechanical Engineering

Prof. Howard Chizeck – UW Electrical Engineering, GSR

Prof. Brian Fabien – UW Mechanical Engineering

Prof. Daniel Kirschen – UW Electrical Engineering

Motivation

Can understanding the dynamics of a cross-flow turbine system enable more effective performance evaluation and control?

Simpler prototype development & testing

Ability to utilize potentially safer control strategies

Lower LCOE

Cross-flow turbine dynamics

Critical definitions:

$\boldsymbol{\omega}$: Turbine rotation rate

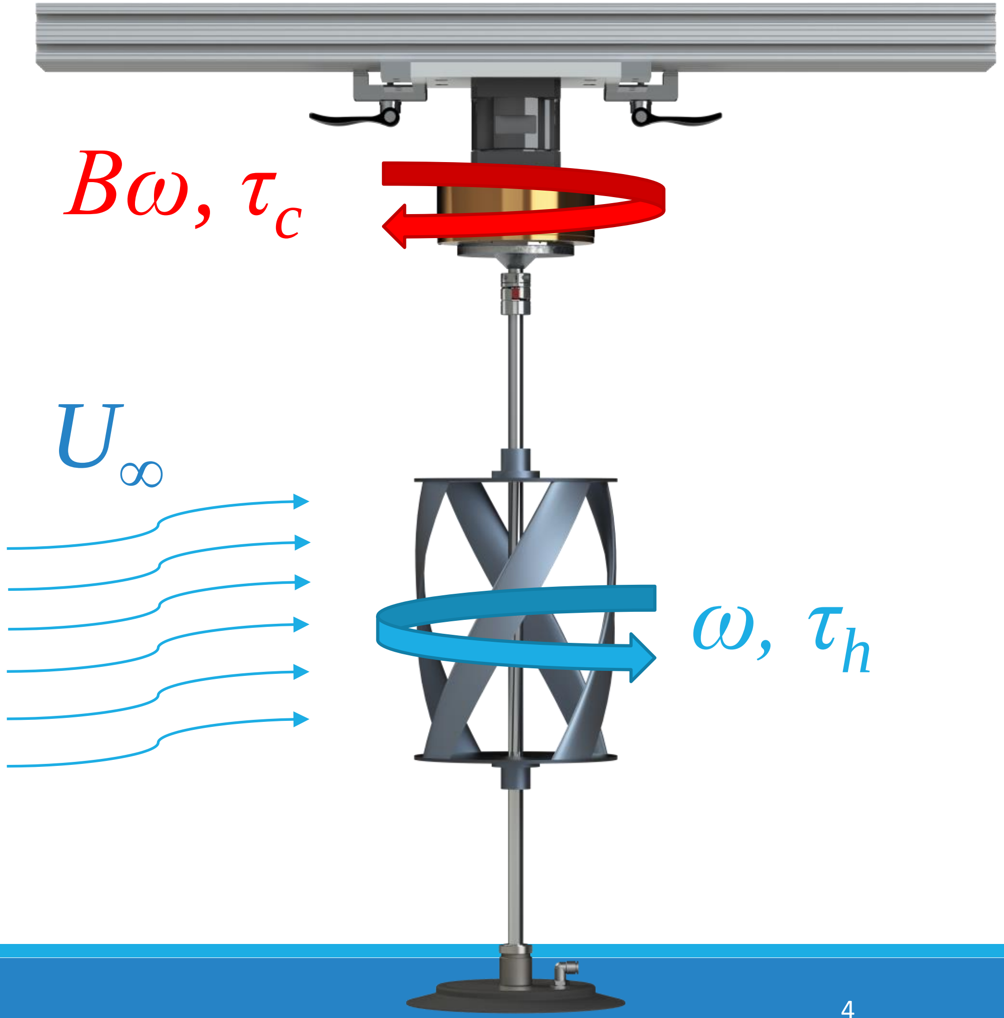
$\boldsymbol{\tau}$: Torque

$\boldsymbol{r}$: Turbine radius

$\boldsymbol{J}$: Rotational moment of inertia

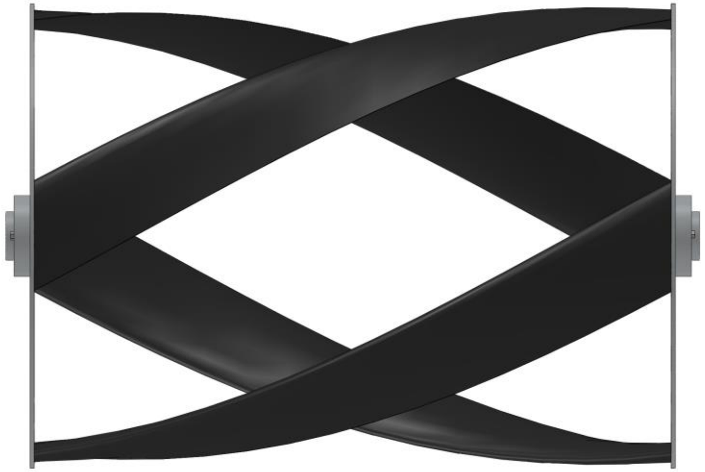
$\boldsymbol{B}$: Damping coefficient (friction)

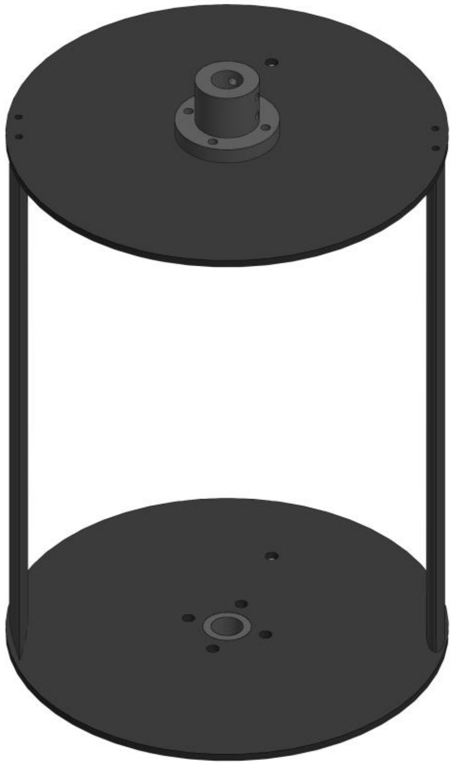
$\boldsymbol{U_\infty}$: Water speed



Cross-flow turbine dynamics

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





First-order ODE of angular acceleration

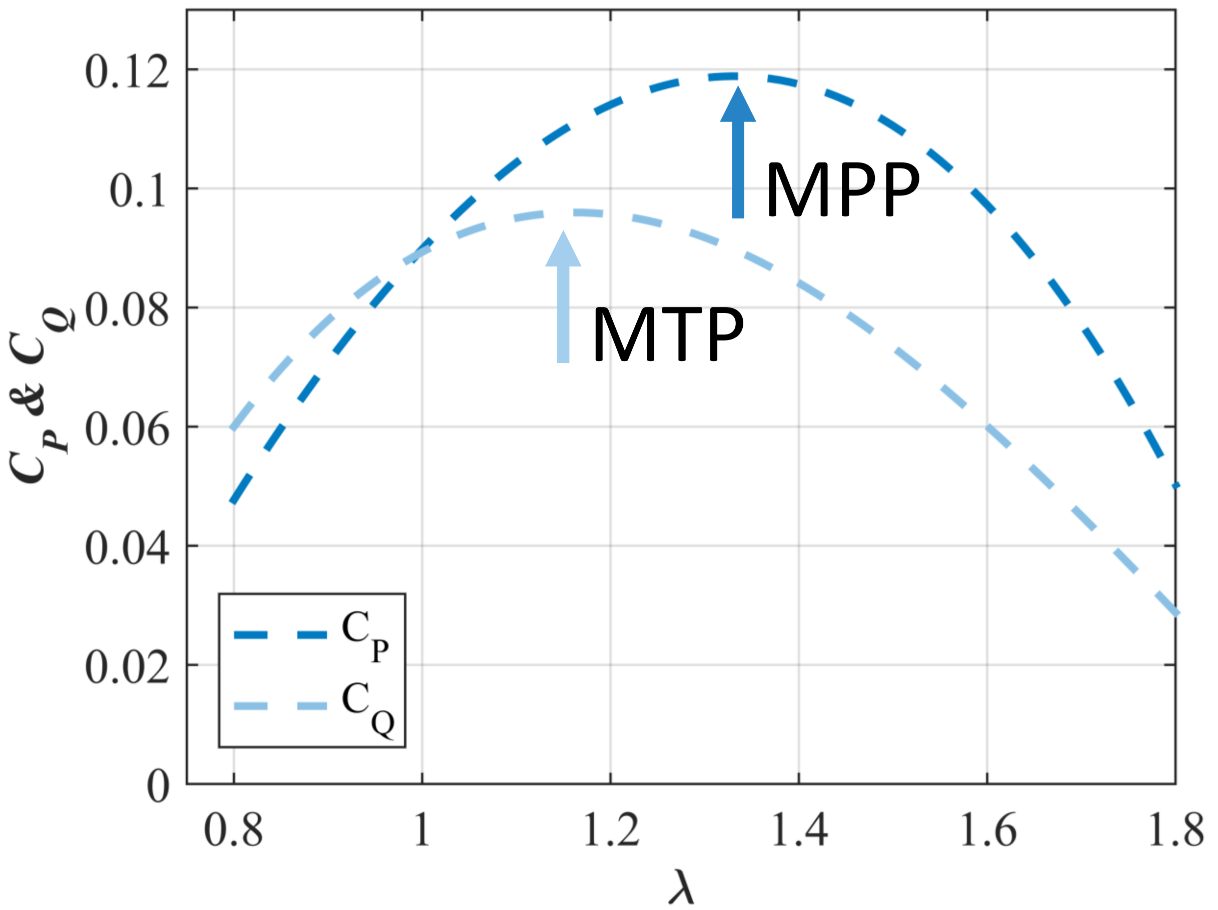
Does not include: added mass/inertia, PTO structural stiffness

Cross-flow turbine dynamics

$$\lambda = \frac{\omega r}{U_\infty}$$

$$C_P(\lambda) = \frac{\tau_h \omega}{\frac{1}{2}\rho A U_\infty^3}$$

$$C_Q(\lambda) = \frac{\tau_h}{\frac{1}{2}\rho A r U_\infty^2}$$



Cross-flow turbine dynamics

$$\dot{\omega} = \frac{\tau_h - B\omega - \tau_c}{J}$$ → τ_h depends on ω: system is nonlinear

$$C_Q(\lambda) = a\lambda^3 + b\lambda^2 + c\lambda + d$$ → Model torque curve

$$\phi = [\bar{U}_\infty, \bar{\omega}]$$ → Choose an operating point

$$\hat{\tau}_h = K_\omega \hat{\omega} + K_U \hat{U}_\infty$$ → Linearize torque

$$\hat{U}_\infty = U_\infty - \bar{U}_\infty$$ → Turbulent velocity appears

Cross-flow turbine dynamics

Replace τ_h with linearized version

$$\dot{\omega} = \frac{\tau_h - B\omega - \tau_c}{J} \longrightarrow \dot{\hat{\omega}} = \frac{(K_\omega - B)\hat{\omega}}{J} + \frac{K_U \hat{U}_\infty}{J} - \frac{\hat{\tau}_c}{J}$$

System dynamic response: sum of two transfer functions

$$\hat{\omega} = [G_1(s)\ G_2(s)][\hat{U}_\infty\ \hat{\tau}_c]^T$$

$$G_1(s) = \frac{K_U/J}{s + (\frac{B - K_\omega}{J})}$$ → Response to turbulence

$$G_2(s) = \frac{1/J}{s + (\frac{B - K_\omega}{J})}$$ → Response to control

Cross-flow turbine open-loop response

Mechanical time constant (ζ): influence of inertia relative to damping

Longer time constant: insensitive to smaller scales of turbulence or more frequent control action

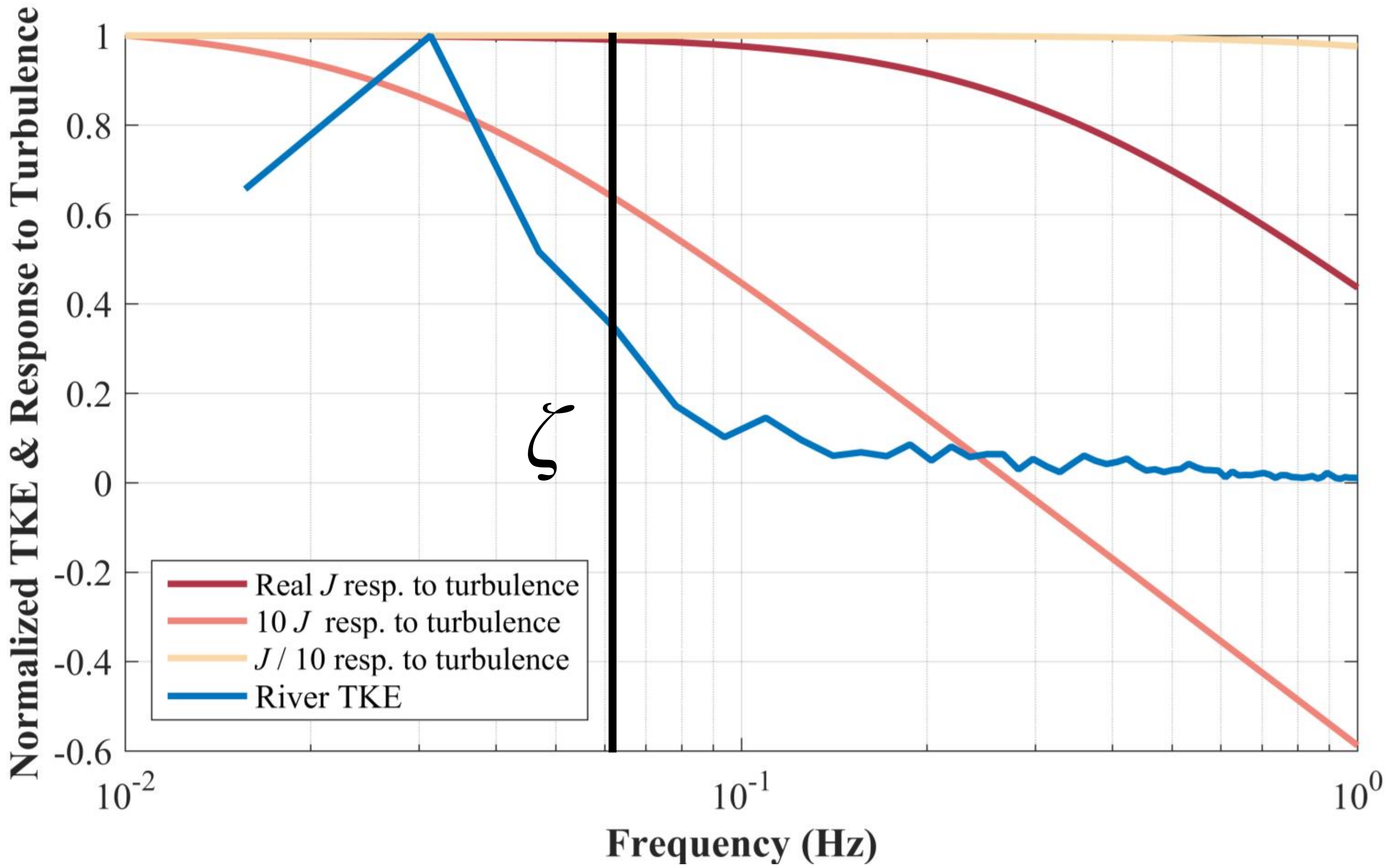
Shorter time constant: reactive to more frequencies, diminished response

Need to know something about turbulence spectrum to fully interpret

$$\zeta = \frac{J}{B}$$

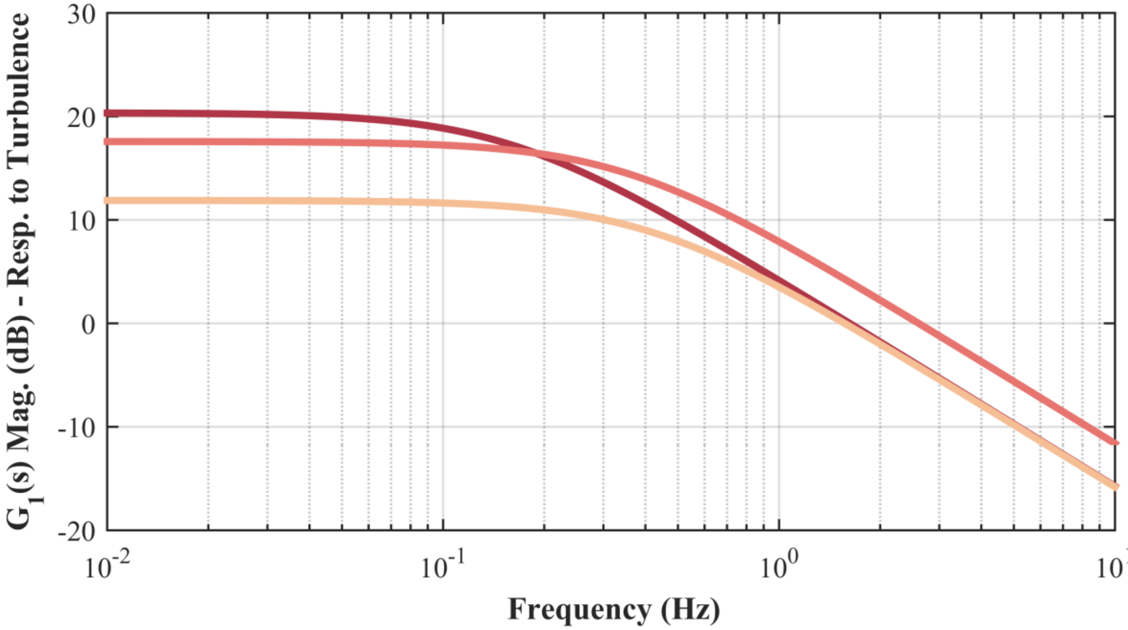
Cross-flow turbine open-loop response

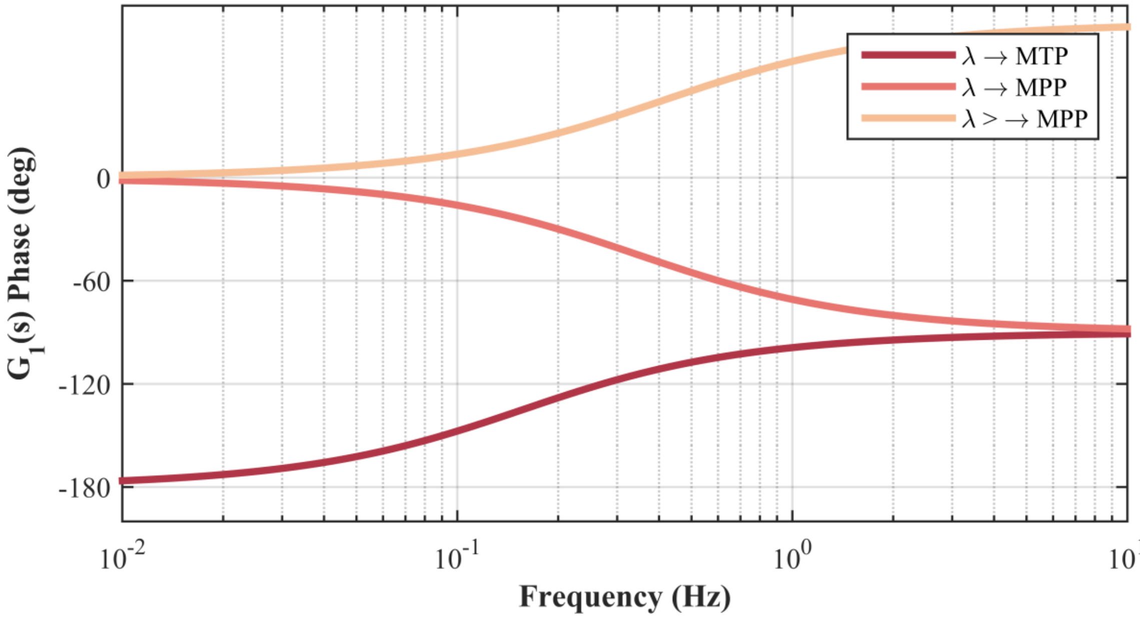
Magnitude response to turbulence: ORPC RivGen turbine



Cross-flow turbine dynamic stability

Evaluate response to turbulence across range of frequencies, different operating points

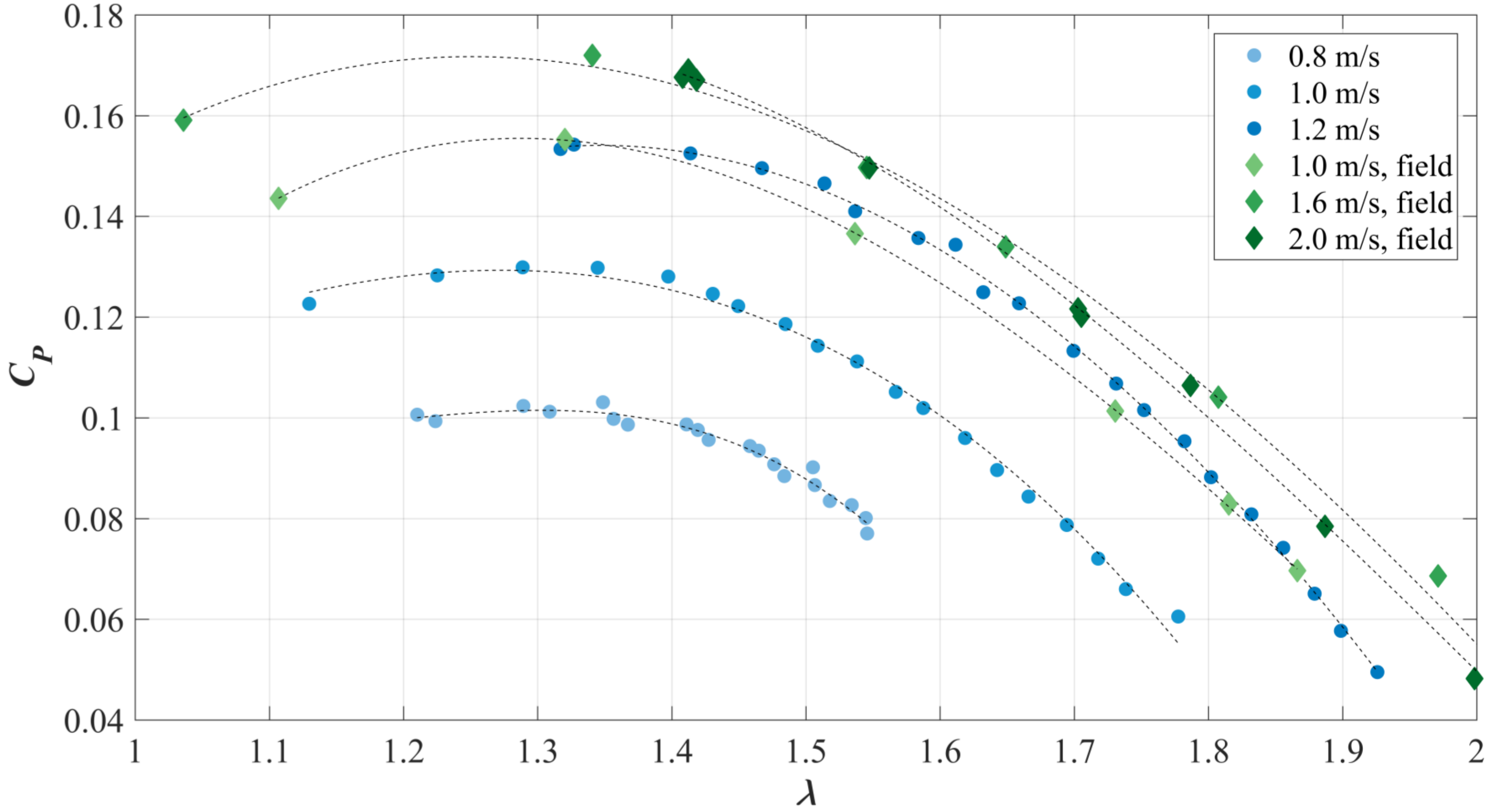




Operation at MTP results in real, positive pole

Cross-flow turbine prototype scaling

Can understanding system dynamics help explain differences between turbine scales?



Cross-flow turbine prototype scaling

Full-scale turbine dimensions and test parameters scaled to replicate physics

Scaling methods:

Geometric similarity: A prototype at 50% scale would have a moment of inertia roughly 3% of full-scale

Reynolds similarity: A prototype at 50% scale would produce twice as much power assuming same characteristic curve

Froude similarity: A prototype at 50% scale would produce 9% as much power assuming same characteristic curve

Time constant scaling

Same time constant without geometric similarity

Intended to achieve similar dynamics to turbulence and control action

Assumes characteristic curve and resource are the same between scales

$$\zeta = \frac{J}{B} \longrightarrow \begin{aligned} J_{scaled} &\propto \kappa \\ B_{scaled} &\propto \kappa \\ \tau_{scaled} &\propto \kappa \end{aligned} \longrightarrow \dot{\omega}_{scaled} = \dot{\omega}$$

A prototype at 50% scale would produce 50% as much power assuming same characteristic curve

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Safety first: Laboratory experiments at Bamfield Marine Sciences Center

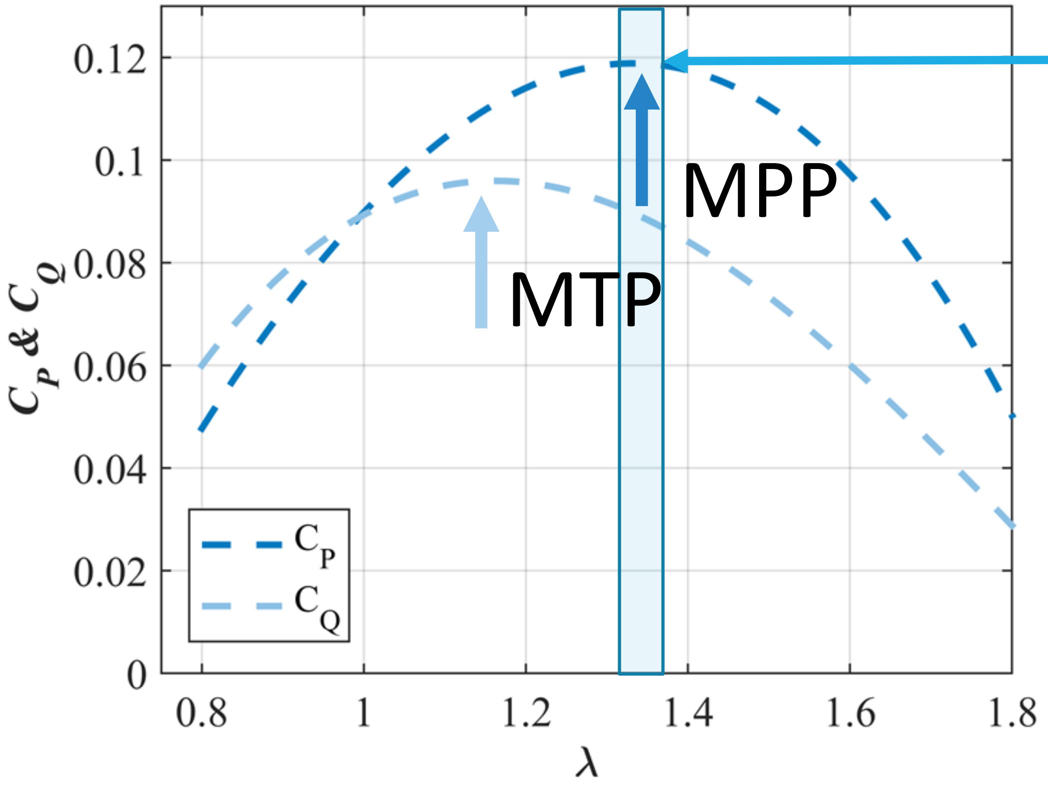
Motivation

Cavagnaro, R. and B. Polagye *Dynamics and System Stall Characteristics of a Cross-Flow Hydrokinetic Turbine*, (in preparation).

Can understanding system dynamics help us determine why a turbine will cease operation at low tip-speed ratio?

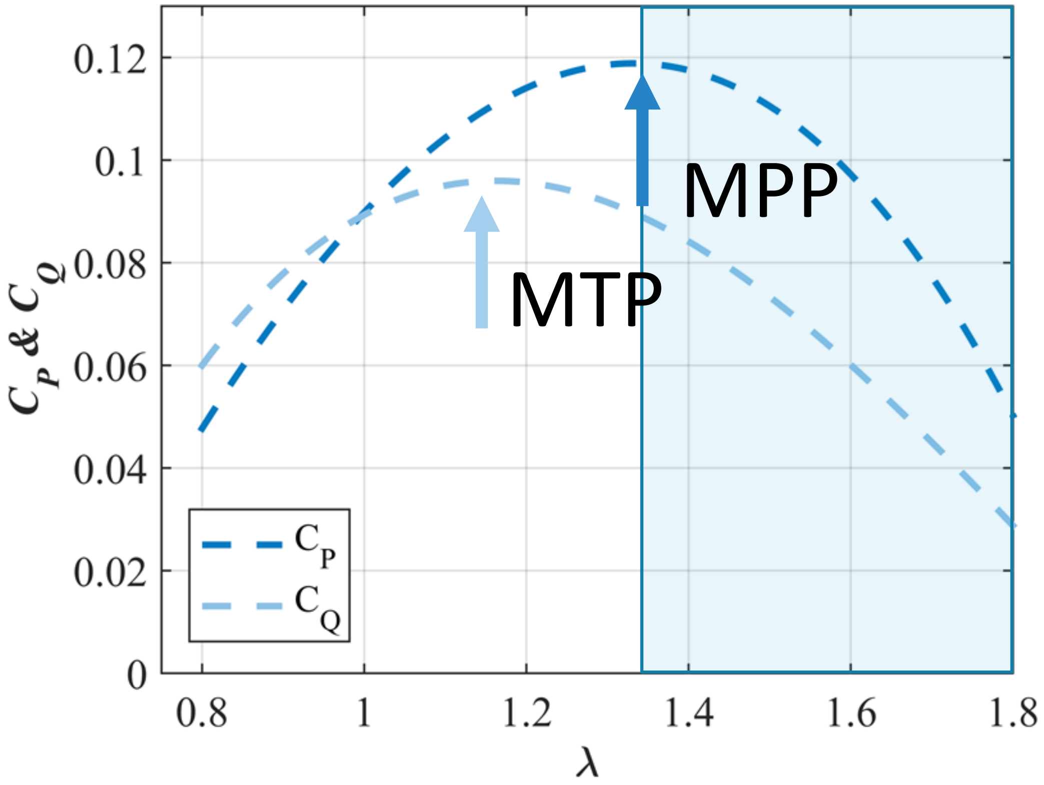
System stall characterization

Motivation



Maximum power point tracking

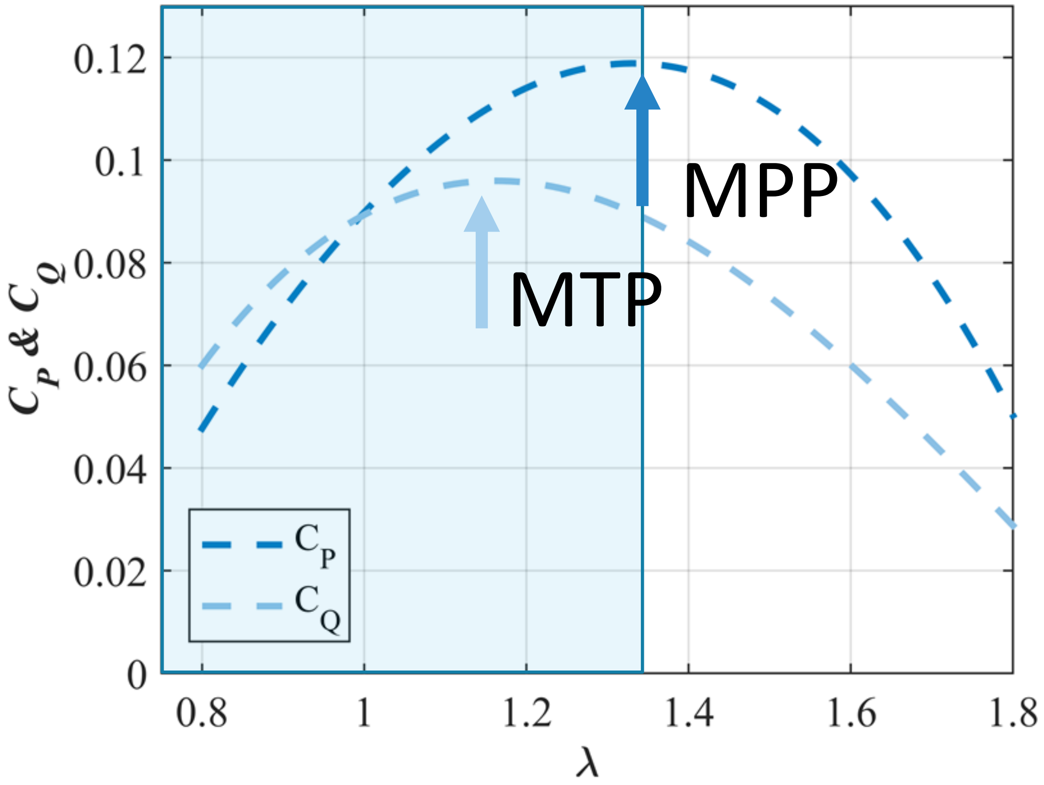
Motivation



'Overspeed' control

- \+ Shed power at faster speed
- \+ Stable
- \- Higher thrust loads
- \- Shuts down through MPP and MTP
- \- More cycles

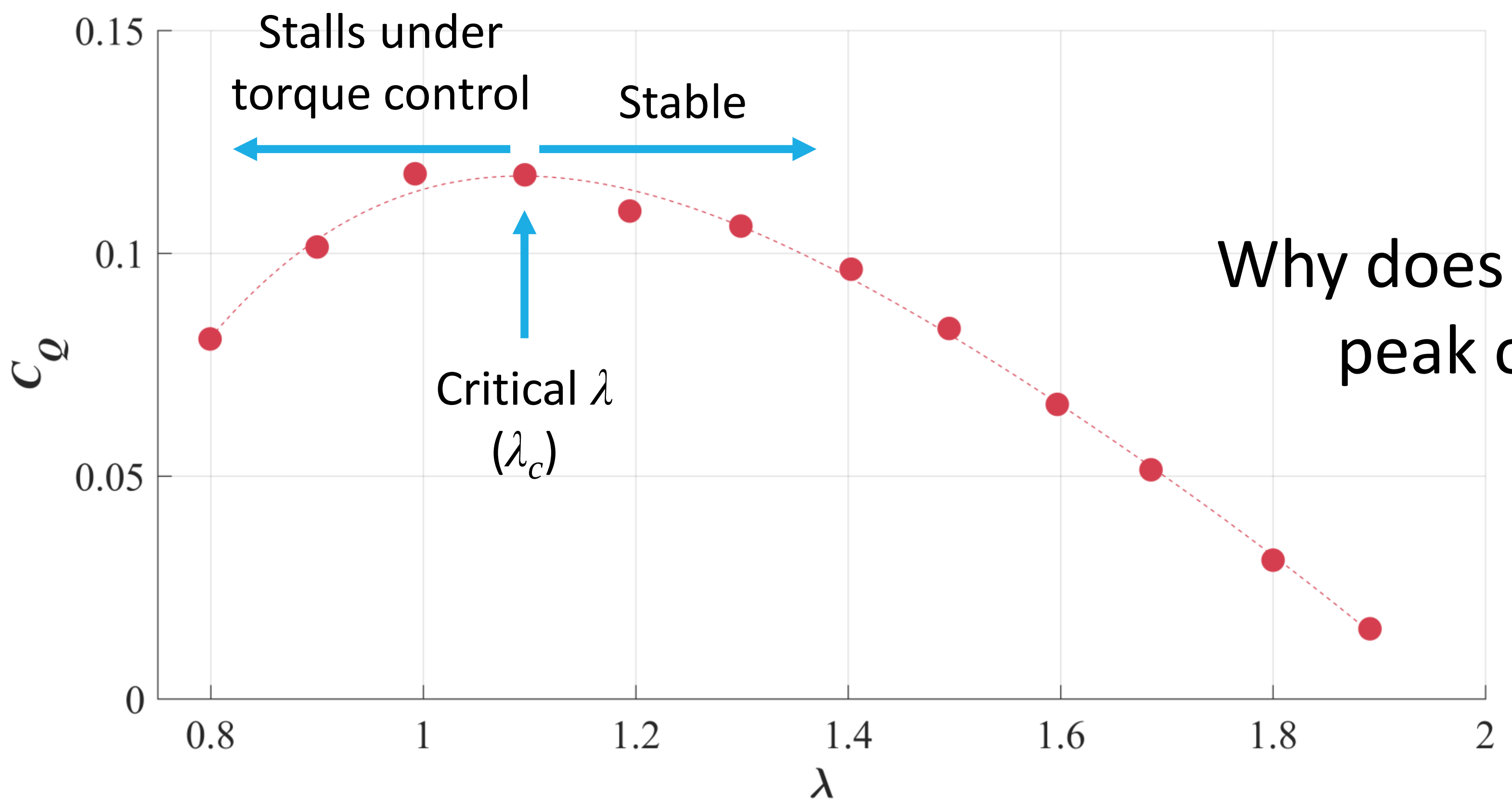
Motivation



'Underspeed' control

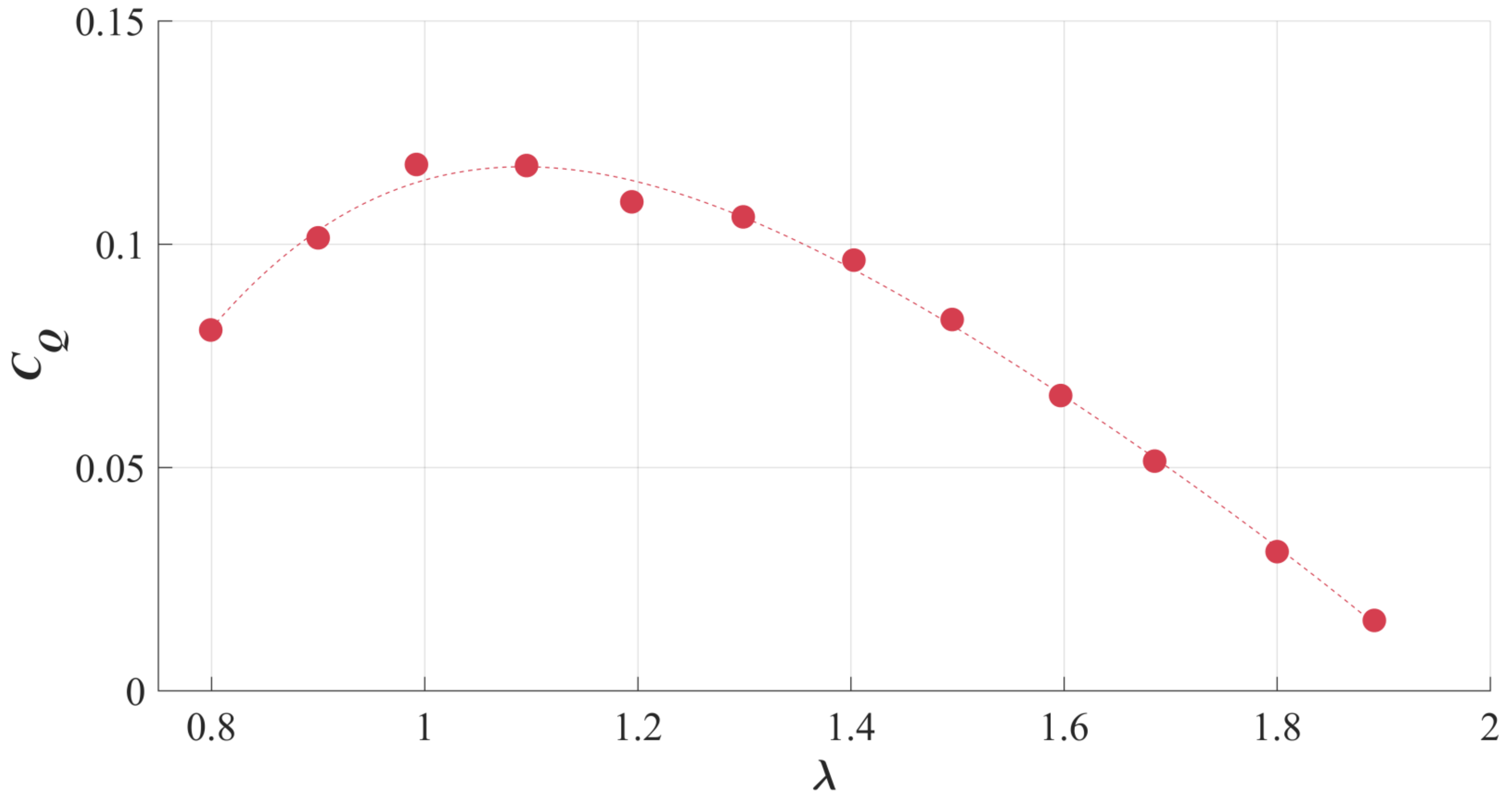
- \+ Shed power at slower speed
- \+ Fewer cycles
- +/- Shuts down through MTP
- \- Higher torque loads
- -- Potentially unstable

Cross-flow turbine stability



Why does a turbine stall near the peak of its torque curve?

Cross-flow turbine stability



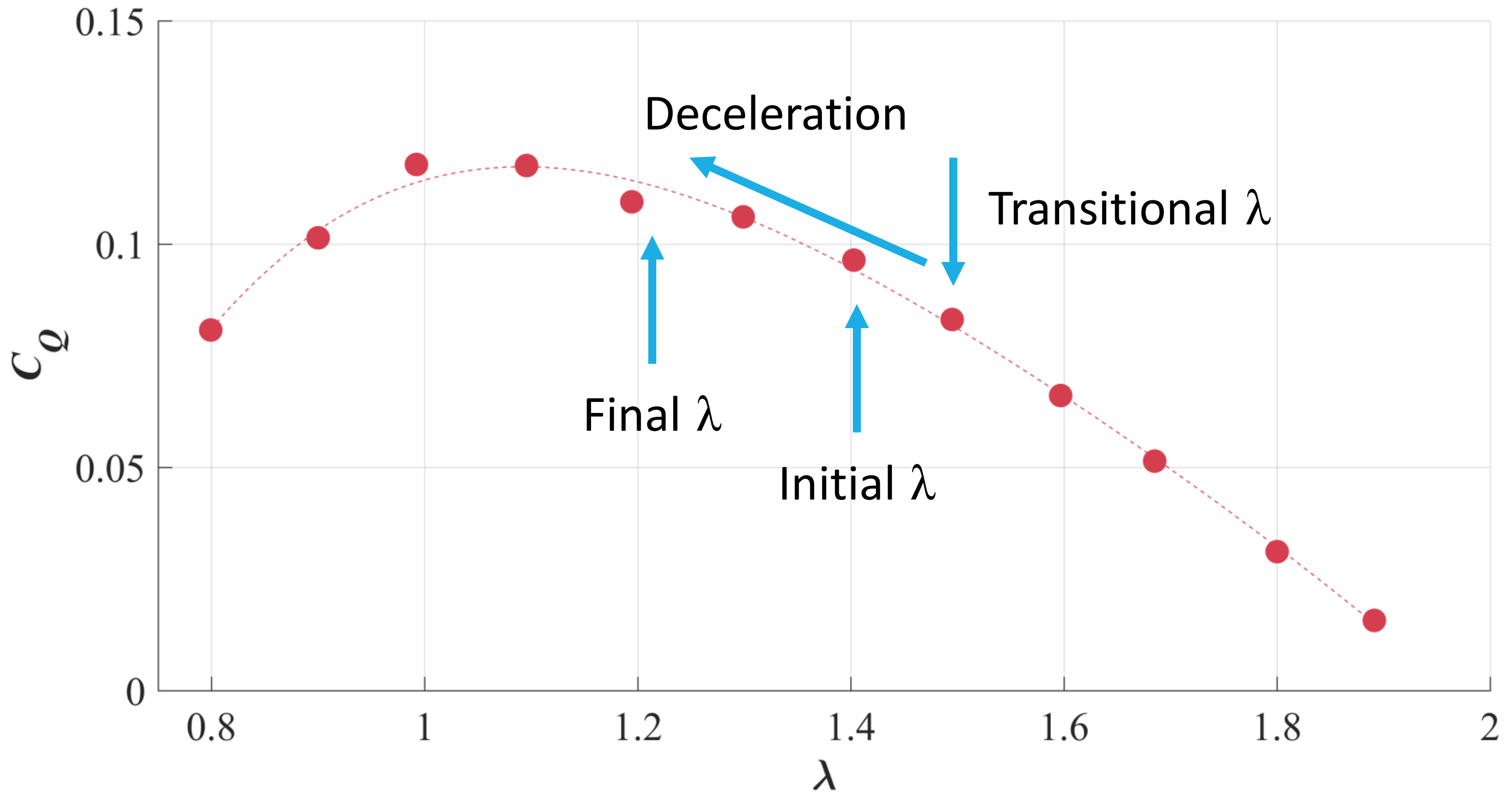
$$\tau_h(\lambda) = \frac{1}{2} C_Q(\lambda) \rho A r U_\infty^2$$

Stable rotation:

$$\tau_h = \tau_c + B\omega_t$$

Hold initial τ_c

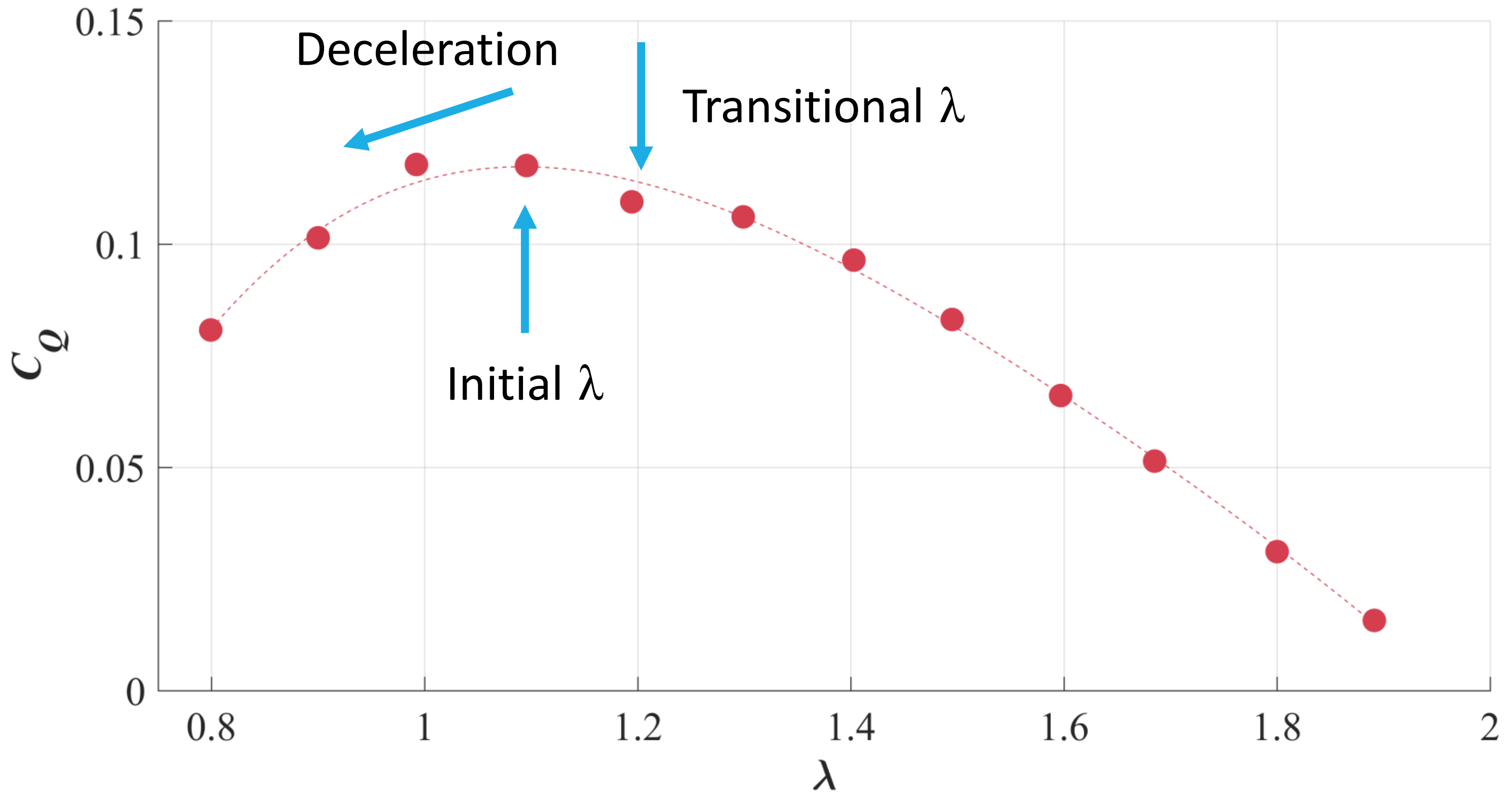
Cross-flow turbine stability



$$\tau_h(\lambda) = \frac{1}{2} C_Q(\lambda) \rho A r U_\infty^2$$

1. Decrease in U_∞, temporarily at higher λ
2. Turbine produces less torque, decelerates
3. Reaches new state where torques again balance

Cross-flow turbine stability



$$\tau_h(\lambda) = \frac{1}{2} C_Q(\lambda) \rho A r U_\infty^2$$

1. Decrease in U_∞, temporarily at higher λ
2. Turbine produces less torque, decelerates
3. As both C_Q and U_∞ are now lower, no stable final state: stalls

Characterizing a stall event

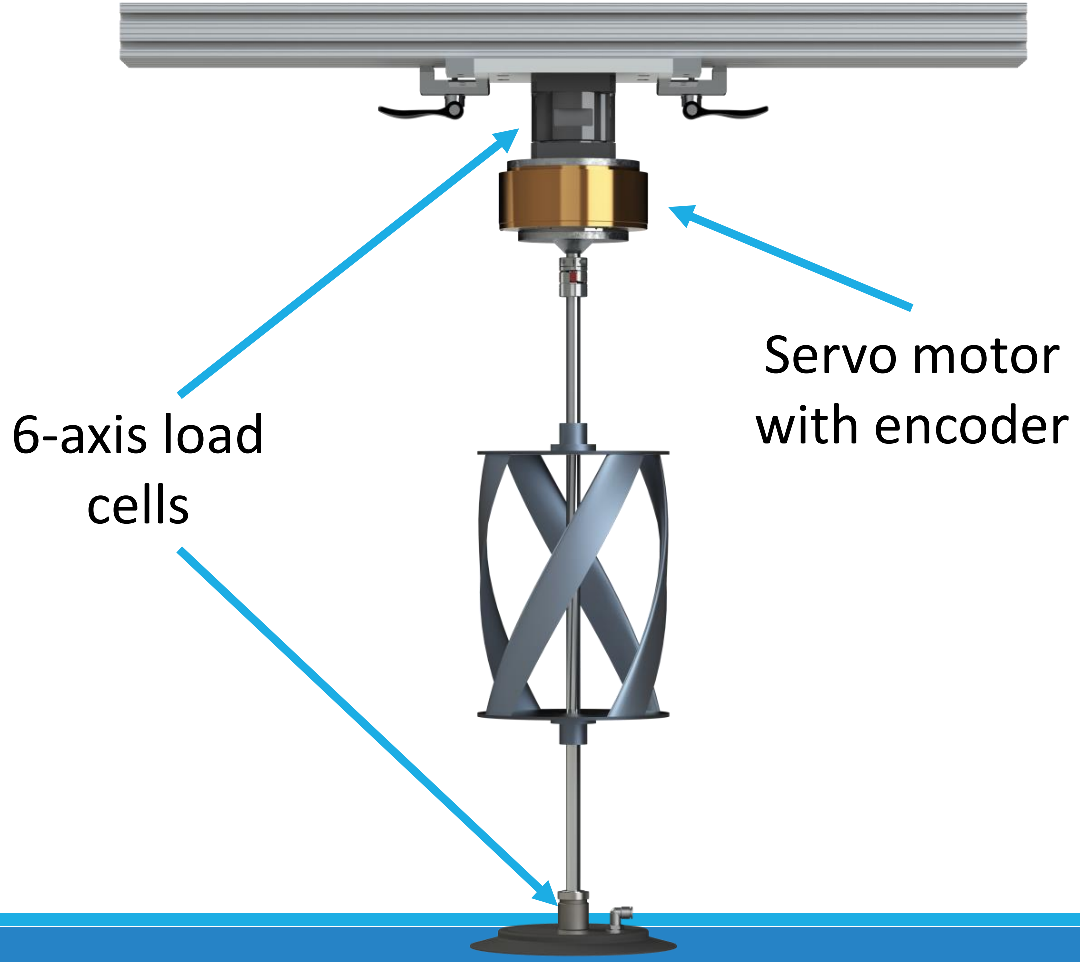
Allow turbine to freewheel in flume

Bring turbine to critical TSR under torque control

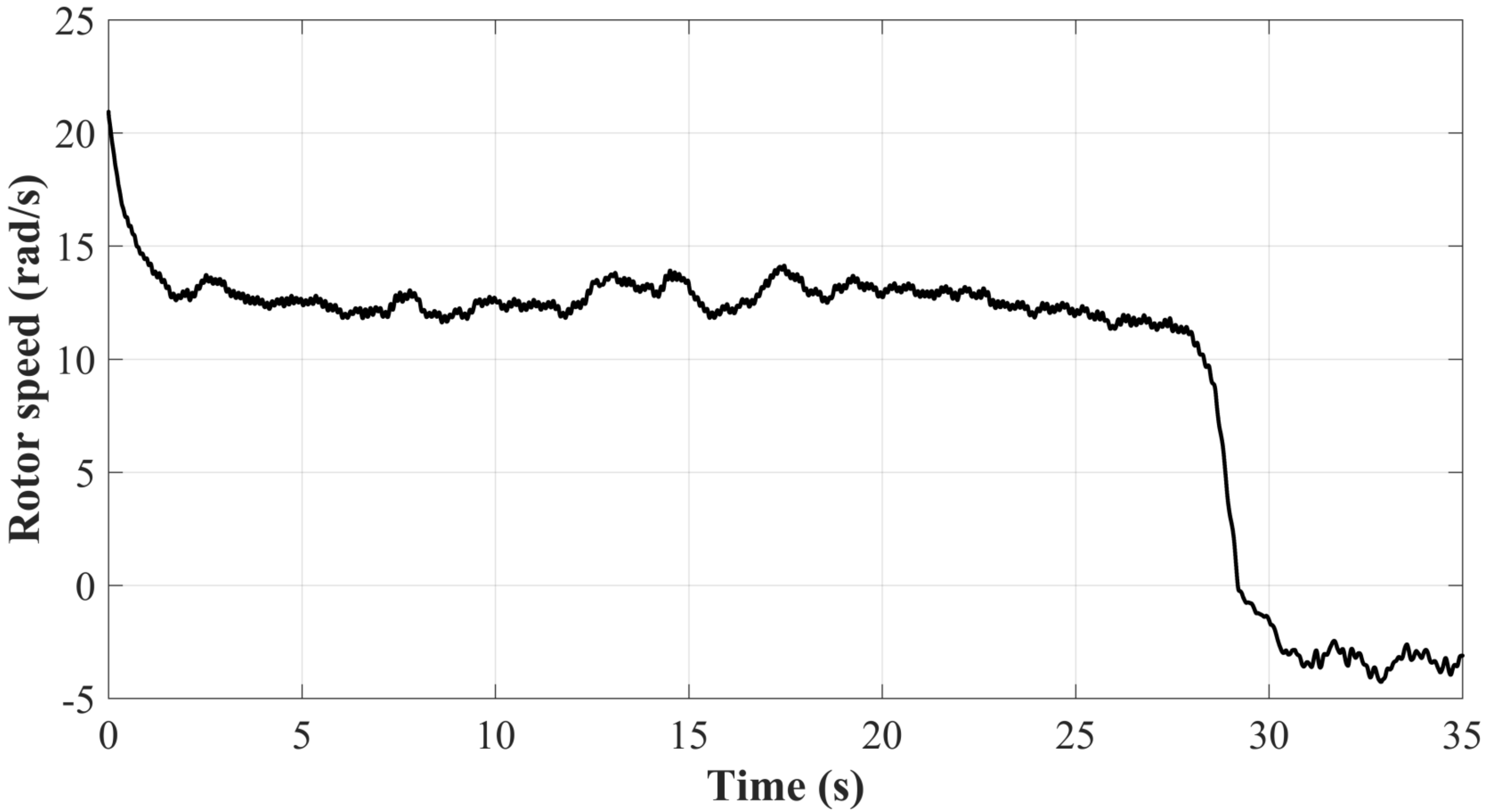
Allow turbine to rotate until it ceases (stall event)

Repeat (288 times)

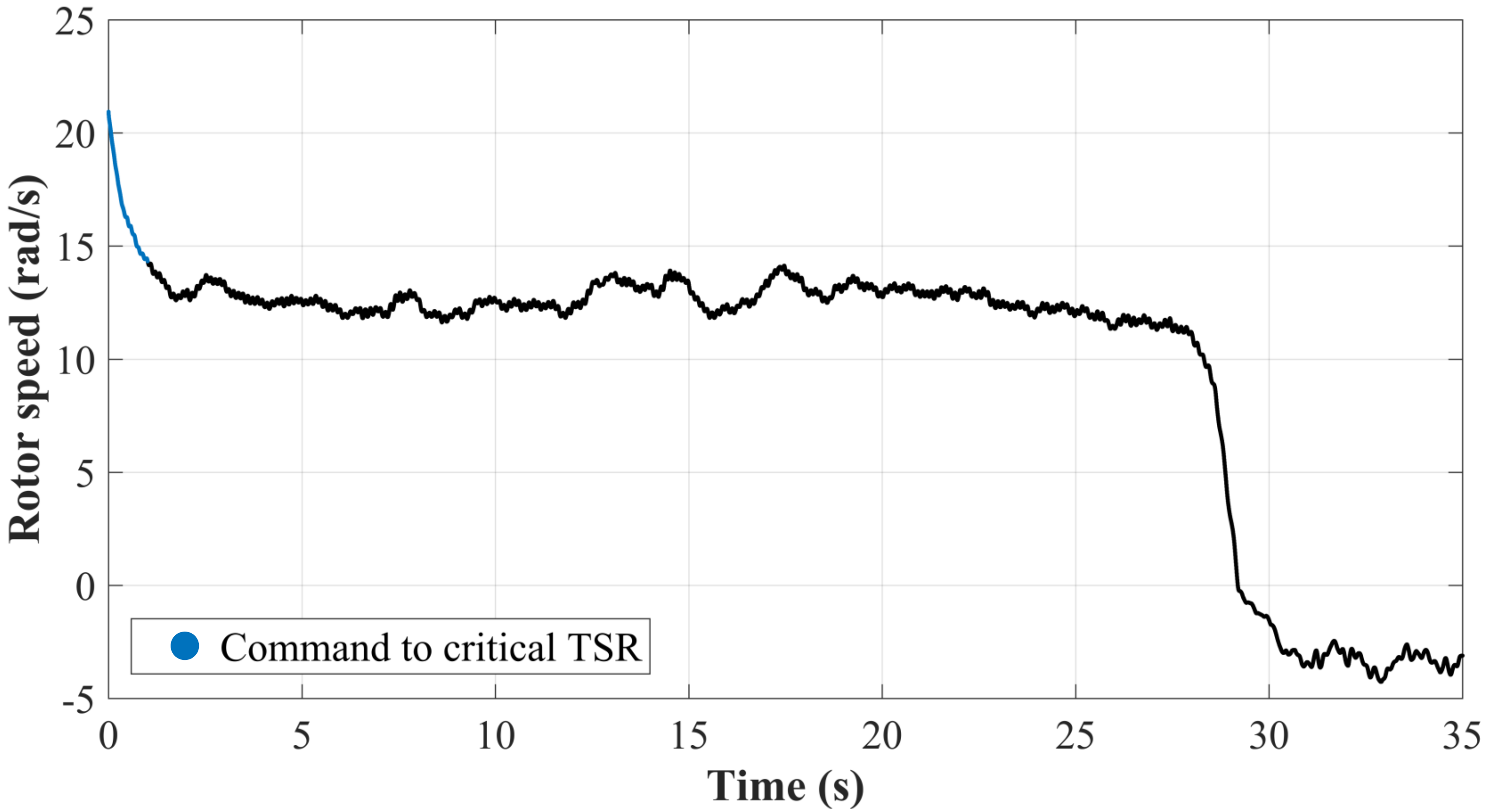
Analyze conditions using turbine sensor data, classification algorithm, and PIV



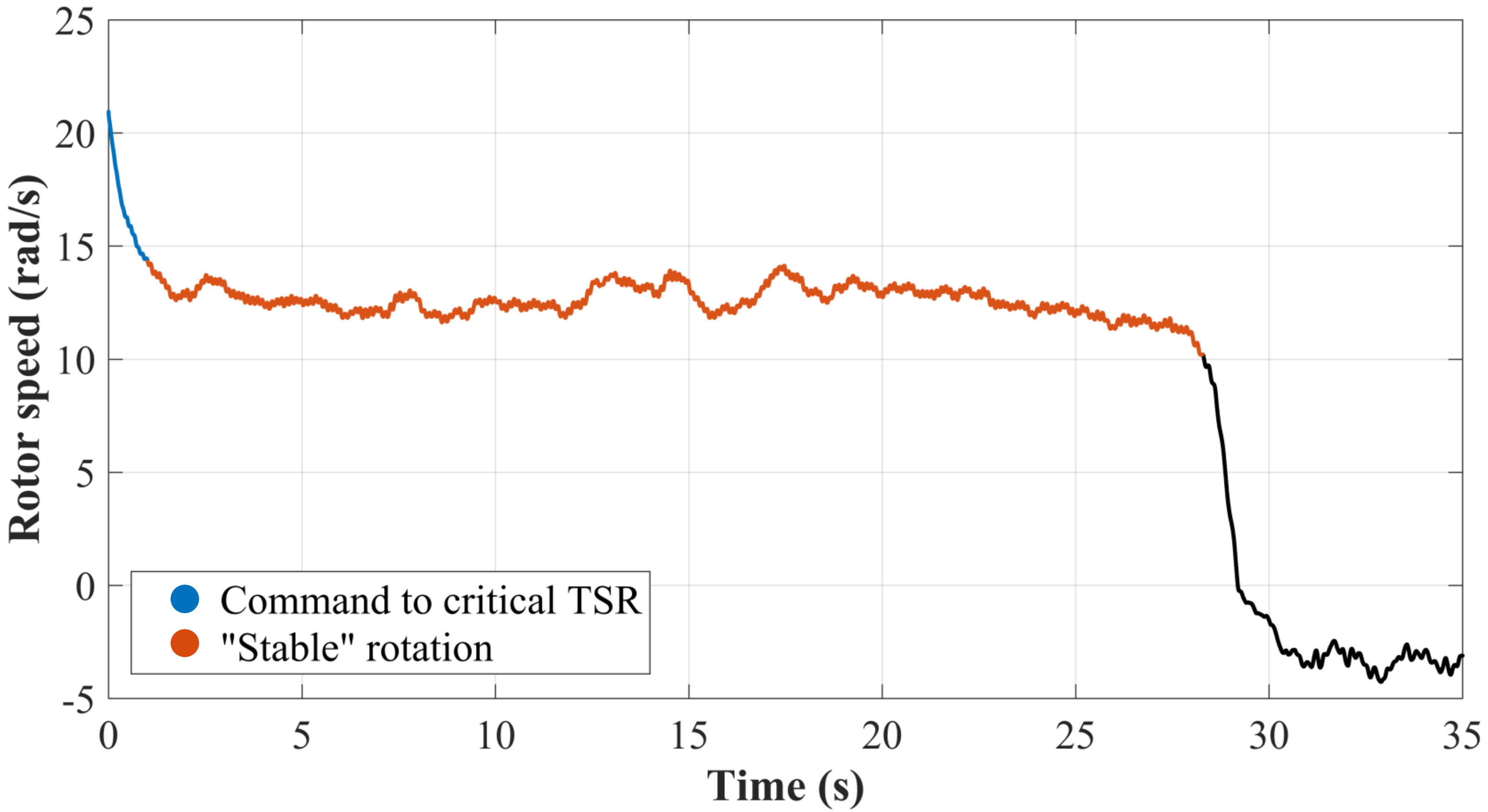
Characterizing a stall event



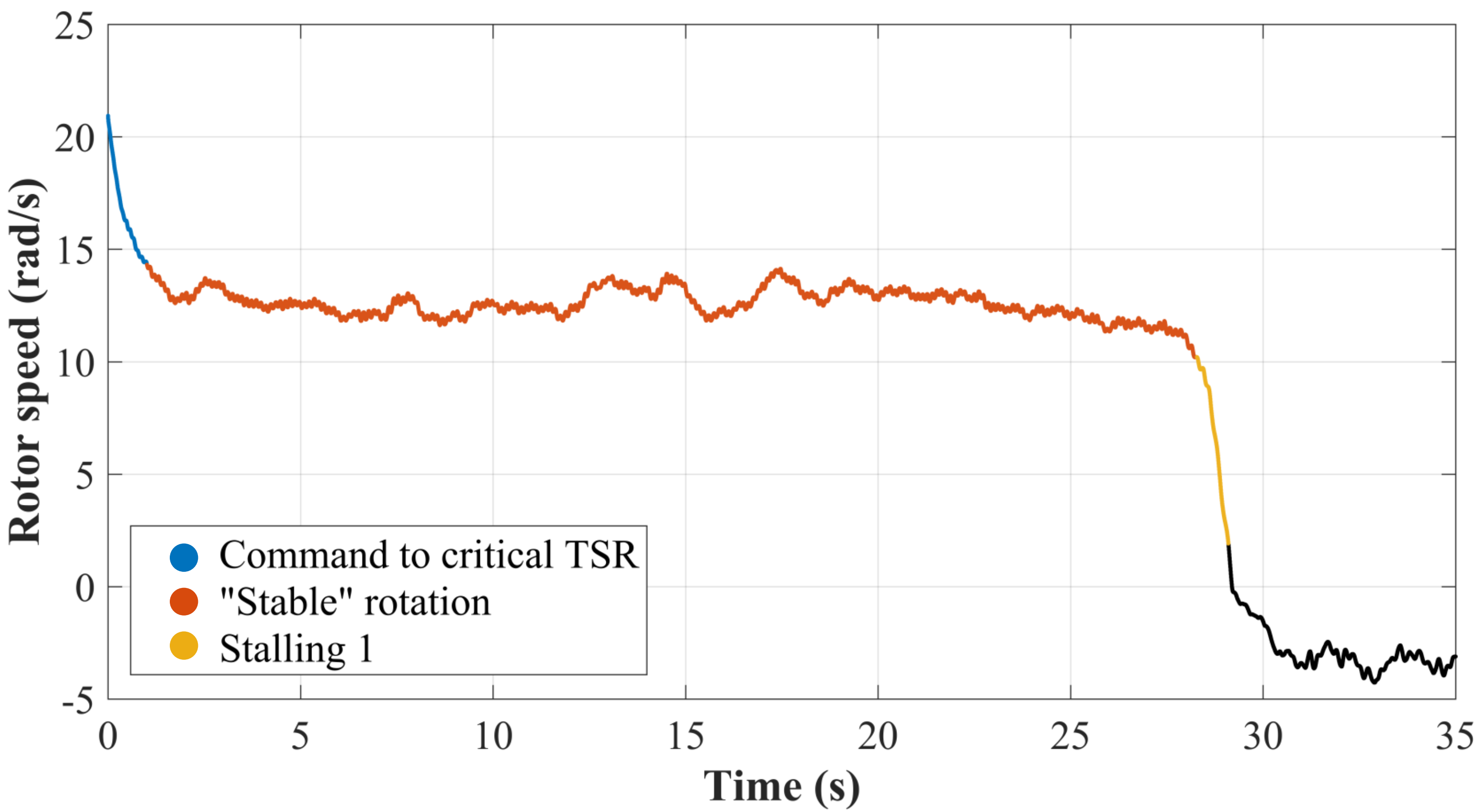
Characterizing a stall event



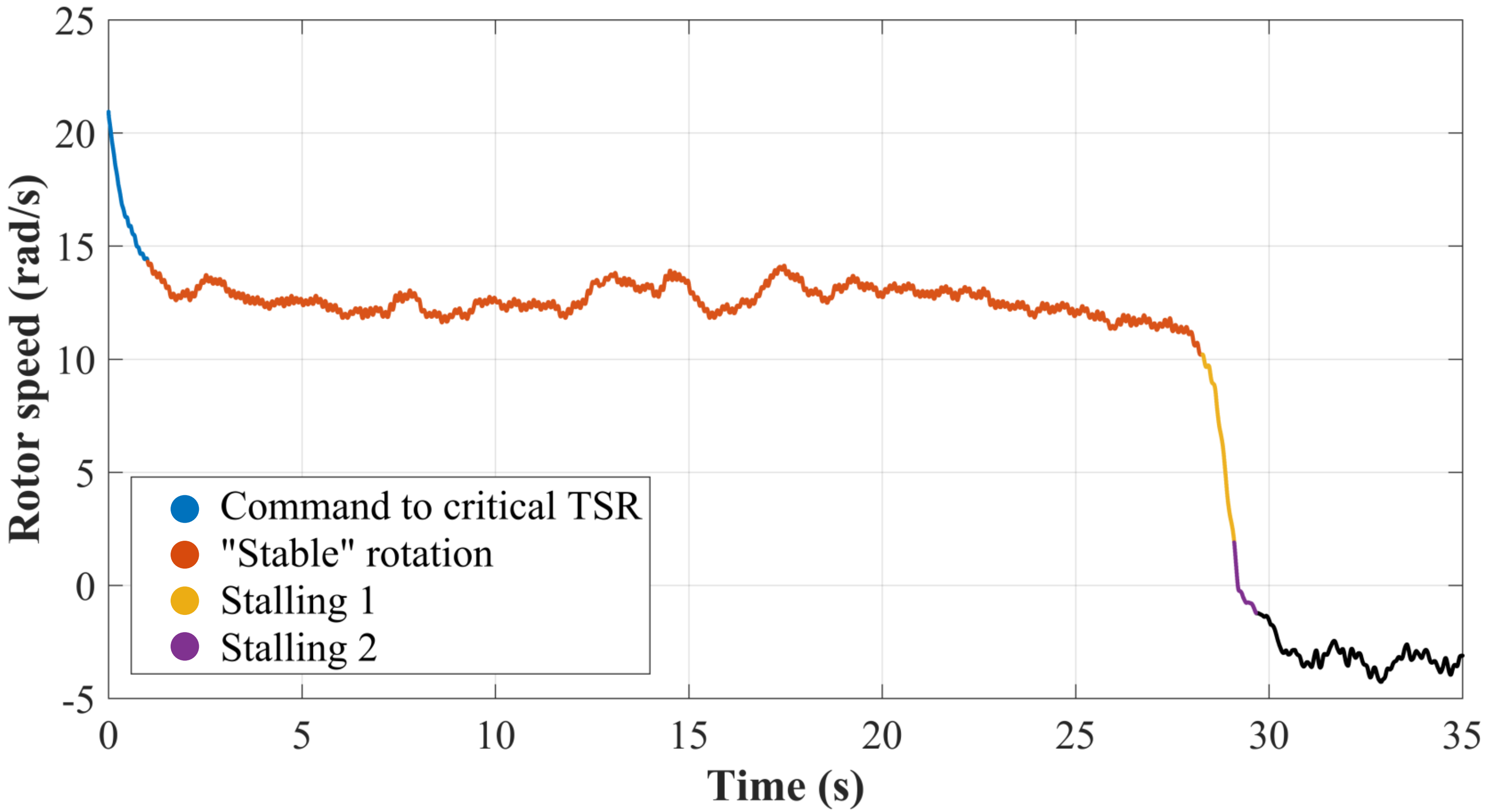
Characterizing a stall event



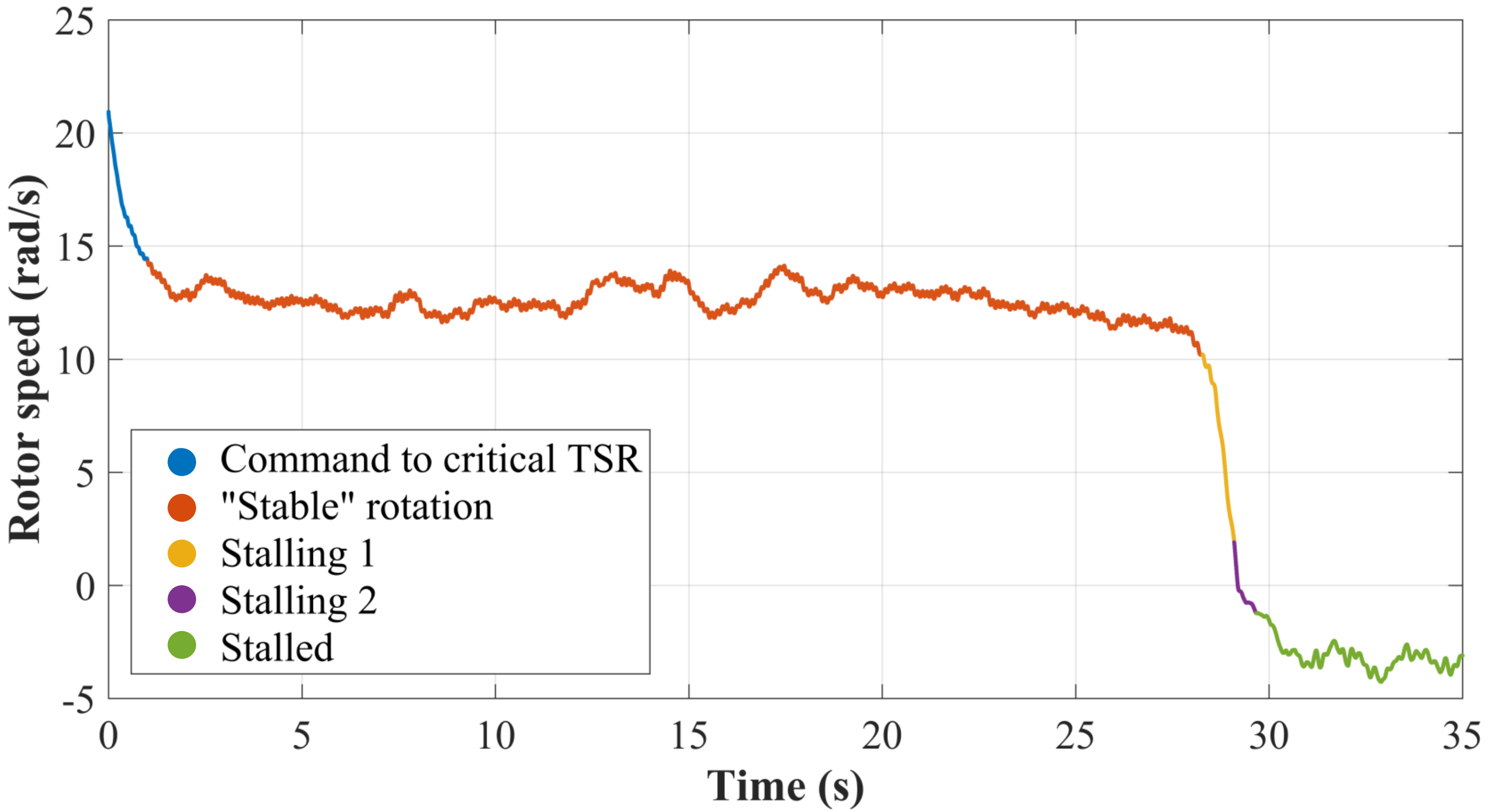
Characterizing a stall event



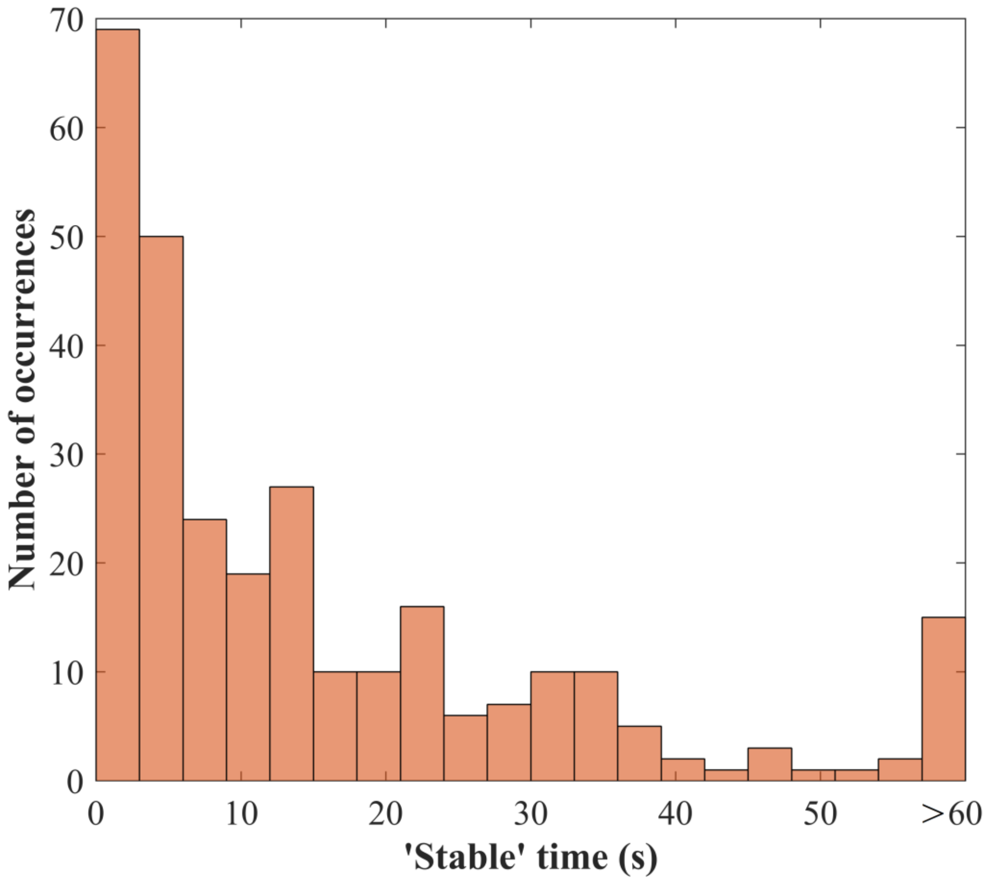
Characterizing a stall event

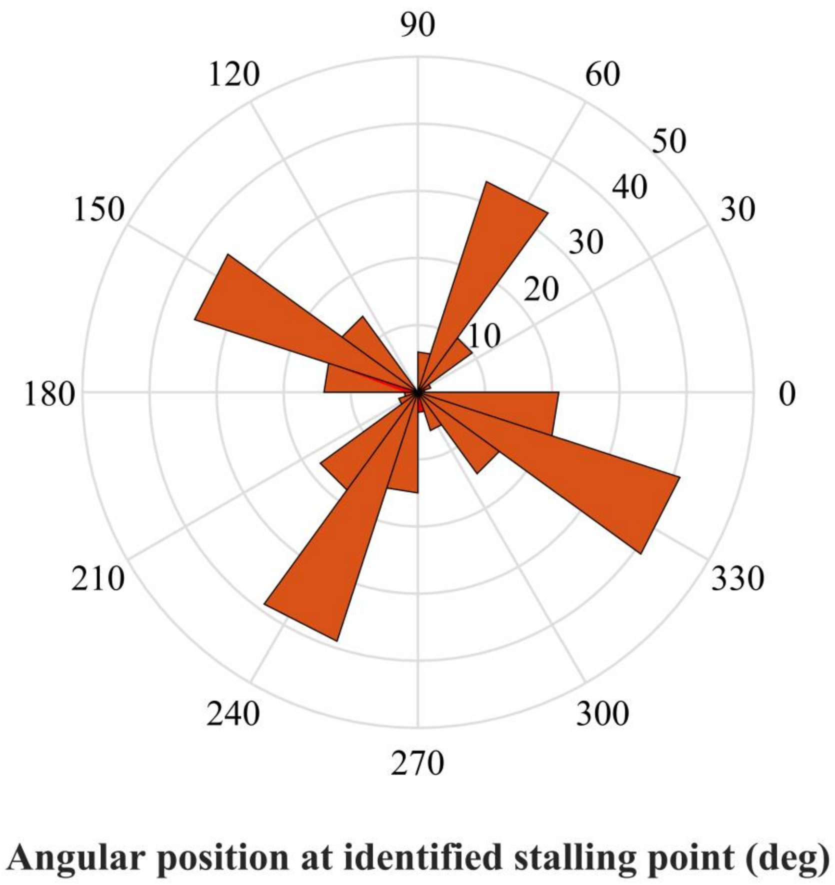


Characterizing a stall event



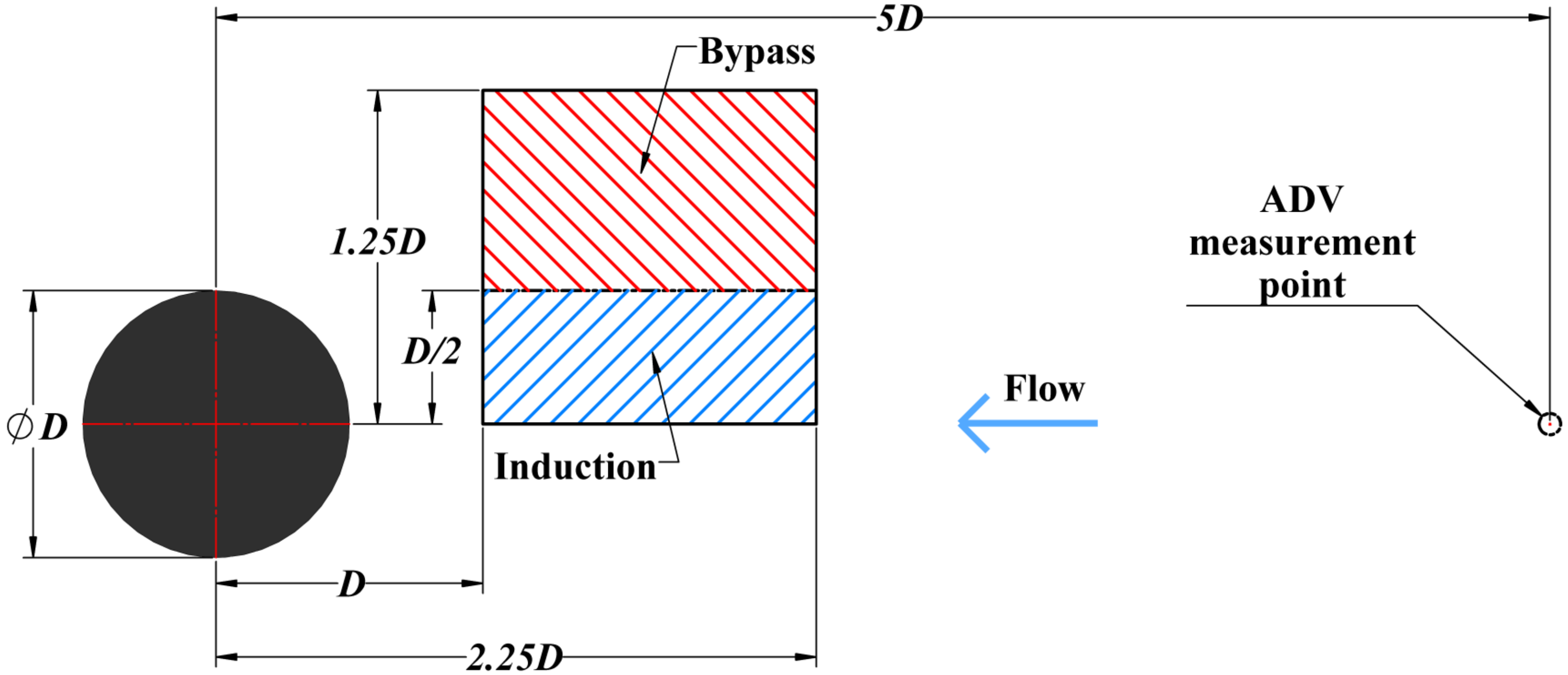
Stall statistics

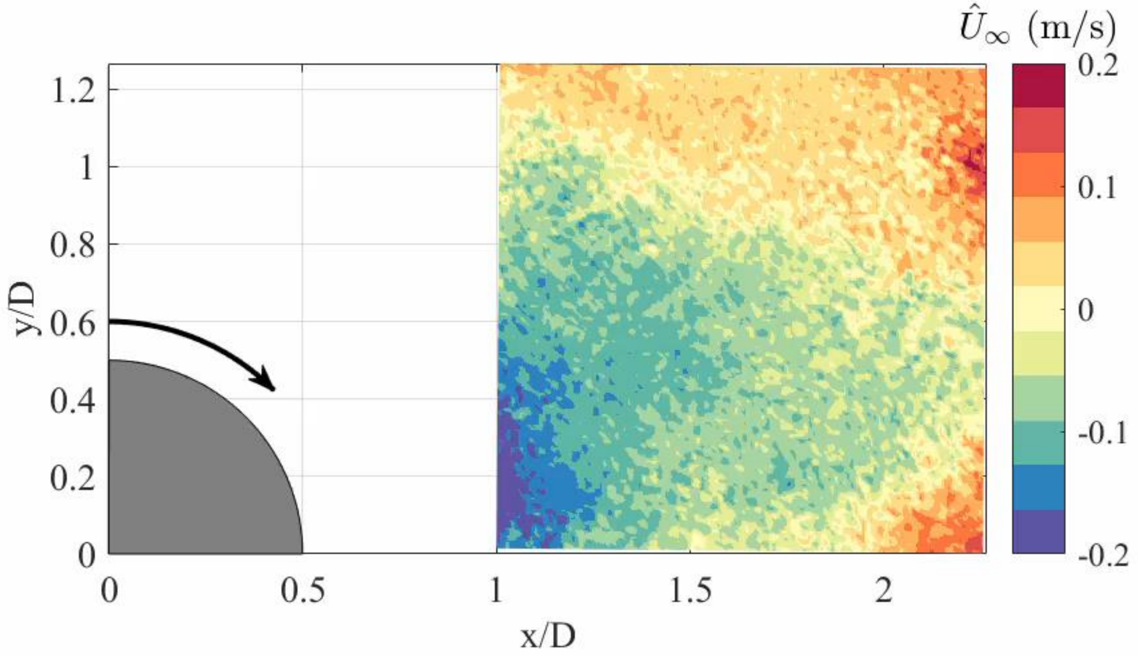




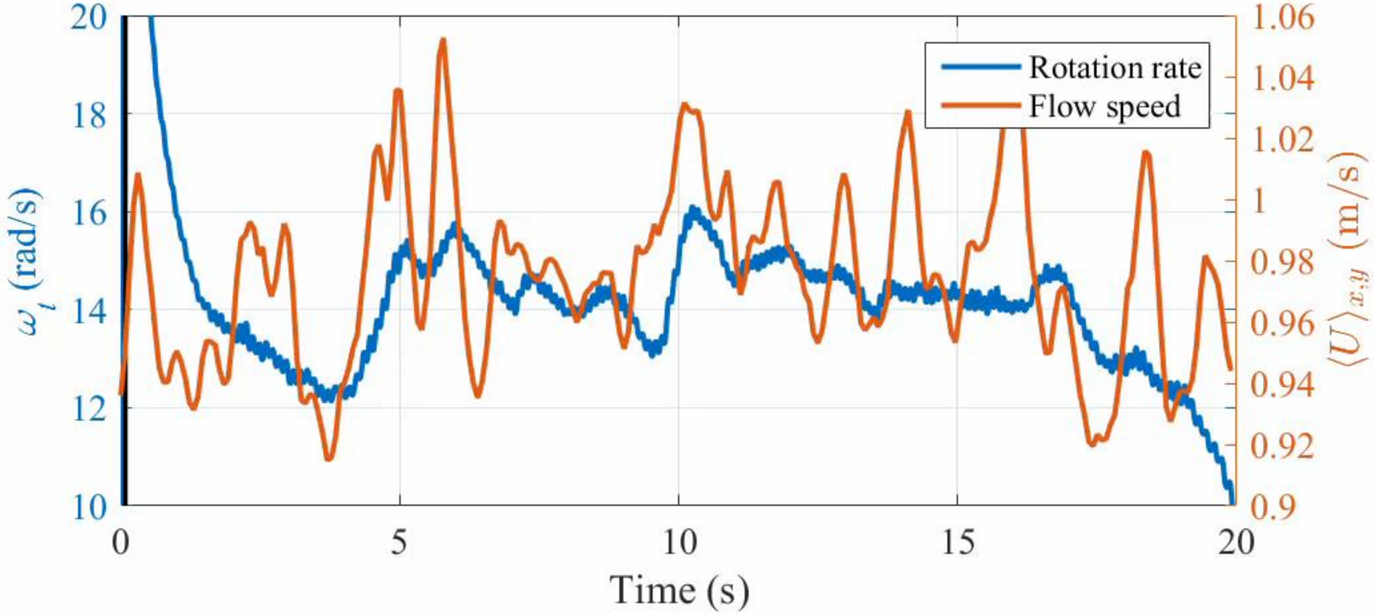
Flow measurement

Can measurements of flow be used to indicate when system stall will occur?



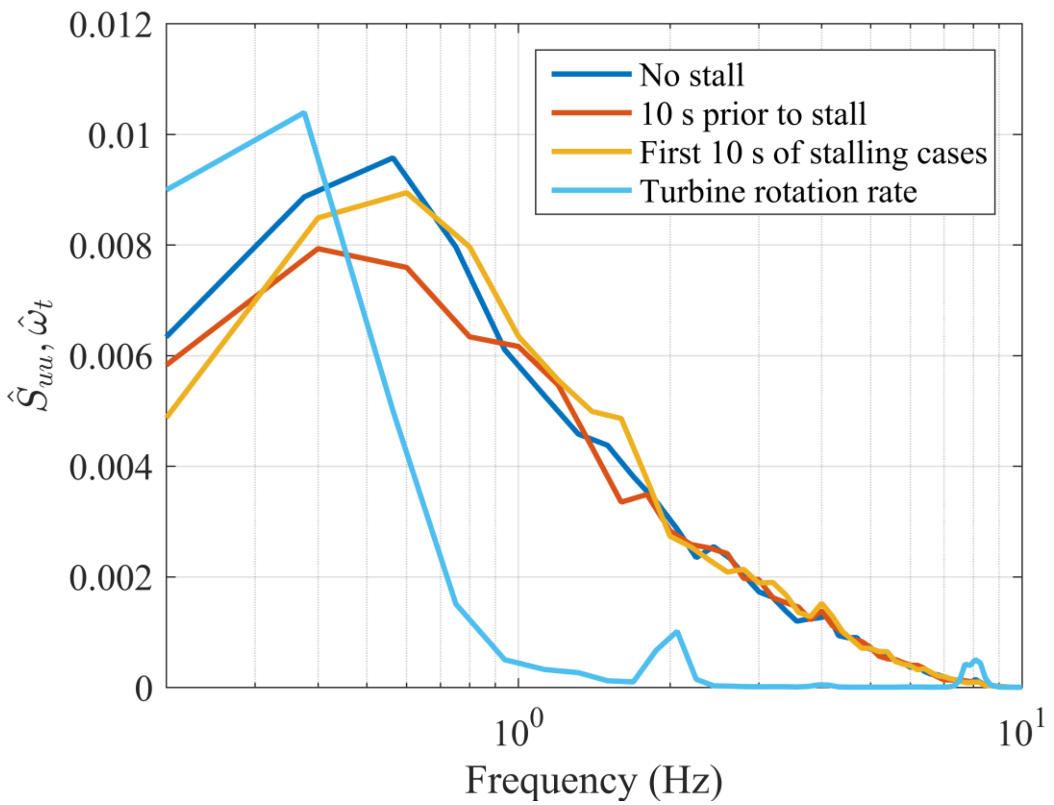


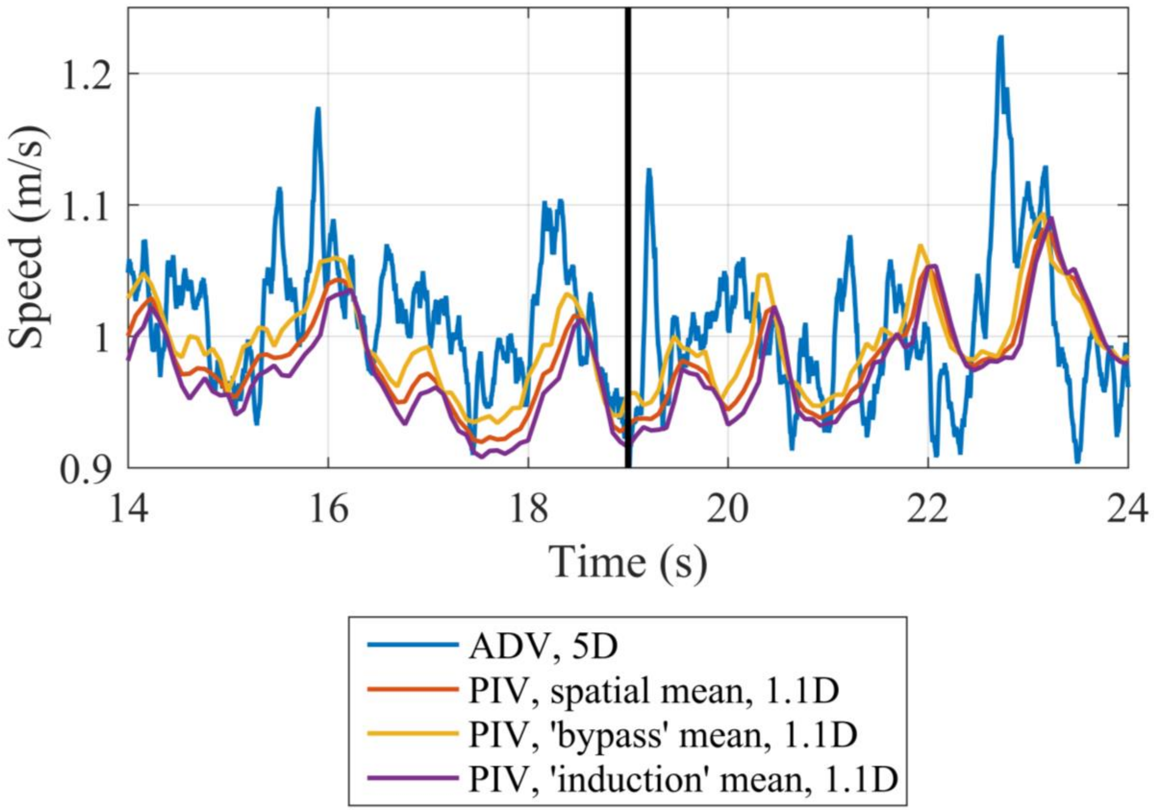
$\hat{U}_\infty$ (m/s)
0.2
0.1
0
-0.1
-0.2
y/D
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
x/D



Rotation rate
Flow speed
ω_t (rad/s)
$\langle U \rangle_{x,y}$ (m/s)
20
18
16
14
12
10
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0
5
10
15
20
Time (s)

Upstream ADV





Overview

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- Cross-flow turbine dynamics and prototype scaling
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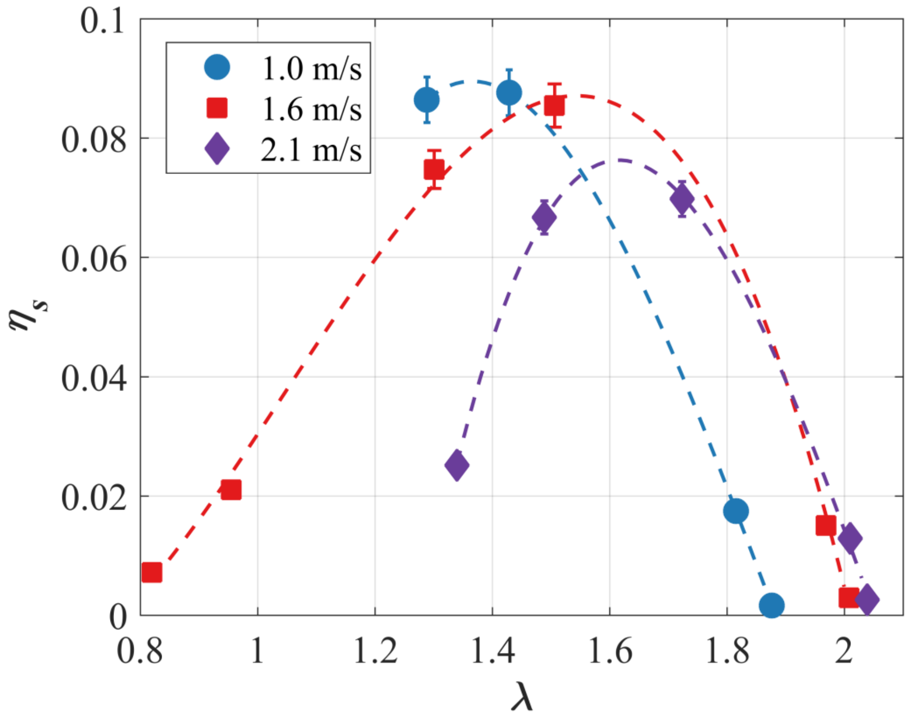
Preparing for field testing in Lake Washington (2012)

Motivation

Cavagnaro, R. and Polagye, B. (2016) Field performance assessment of a hydrokinetic turbine, International Journal of Marine Energy, doi:/10.1016/j.ijome.2016.01.009.

FIELD-SCALE FULL SYSTEM EFFICIENCY

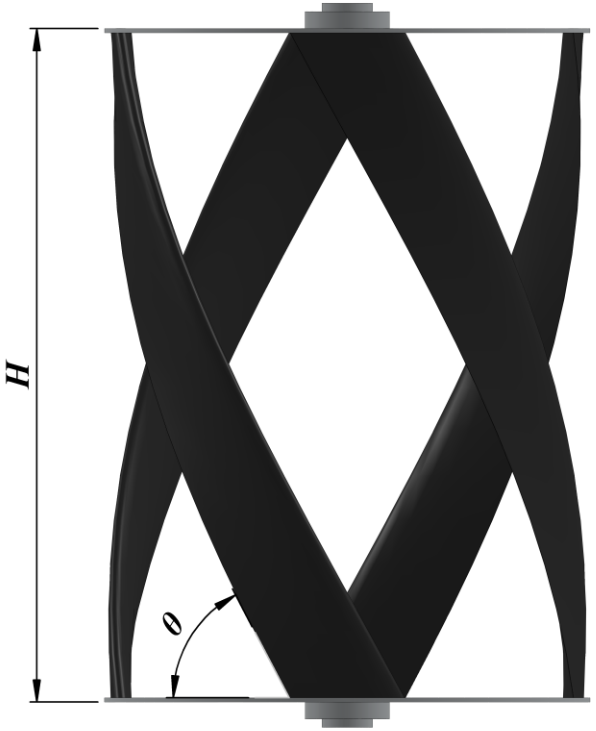


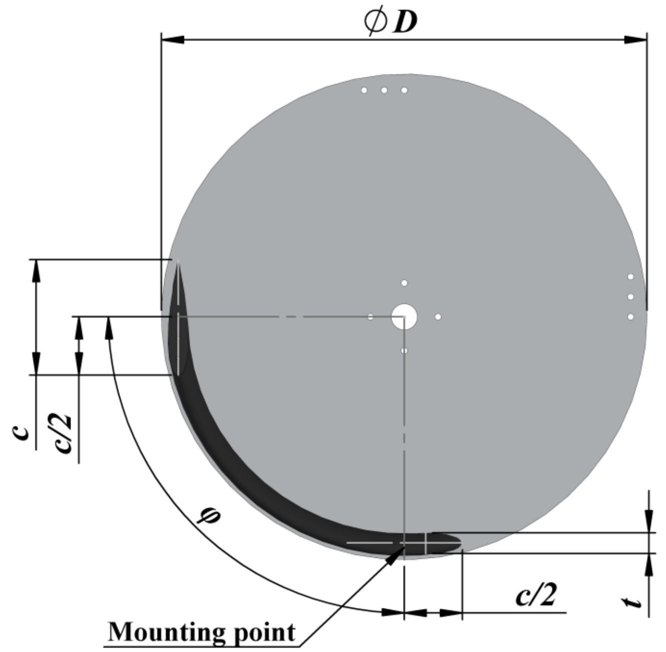
Can characterizing system dynamics help us interpret system (electrical) efficiency dependence on inflow speed?

Full-system characterization

Field-scale turbine and test rig

Parameter	Value
Blade profile	NACA 0018
Turbine diameter (D)	72.4 cm
Turbine height (H)	101.3 cm
Turbine aspect ratio (H/D)	1.40
Helical pitch angle (θ)	60°
Helical sweep angle (ϕ)	90°
Blade chord length (c)	17.3 cm
Blade thickness (t)	3.1 cm
Solidity ratio (σ)	0.30





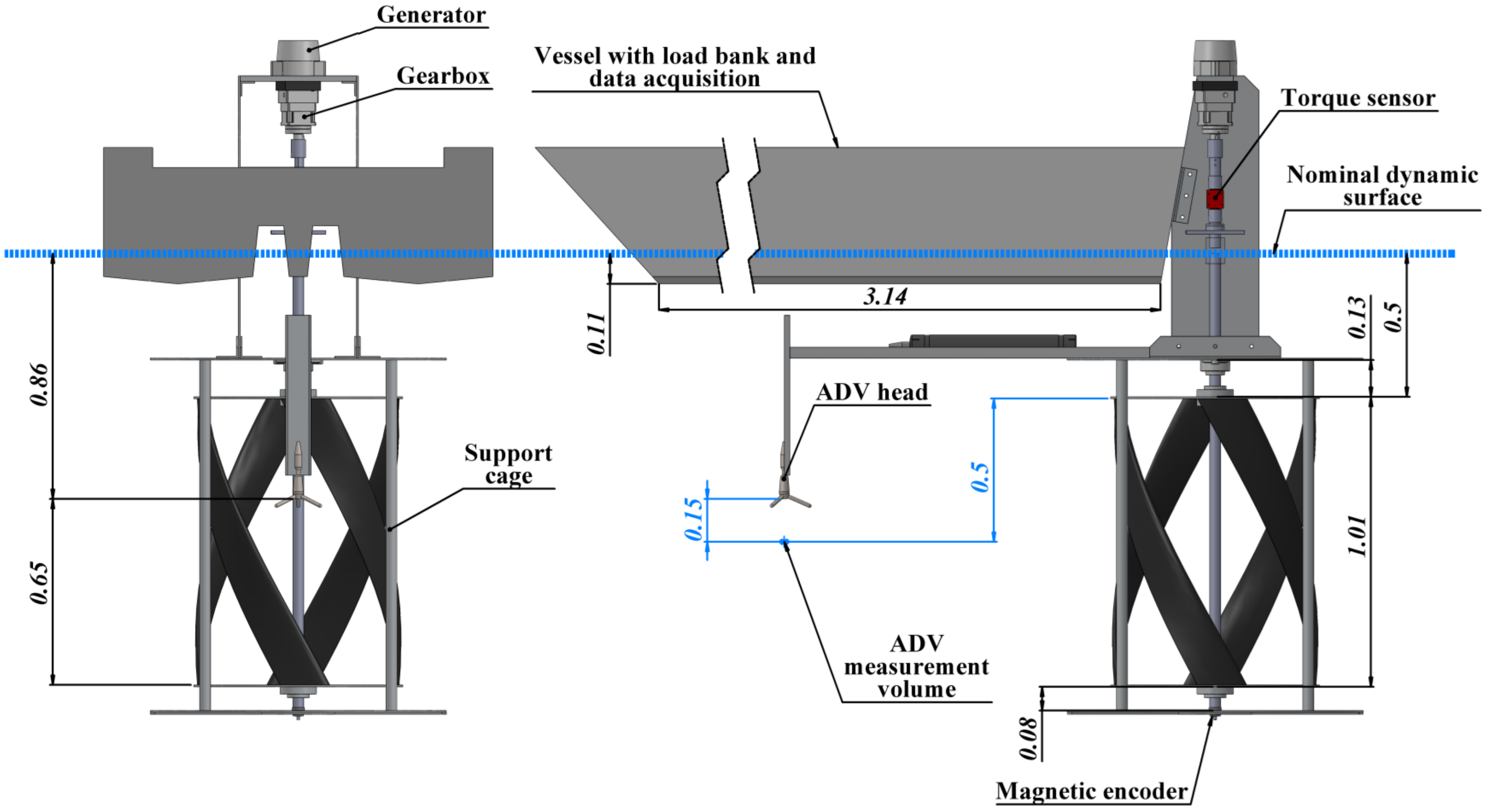
Field-scale turbine and test rig

Turbine towed through quiescent lake

Upstream ADV measures inflow velocity

Sensors for measuring torque and rotation rate

Power through gearbox & generator to resistive load bank

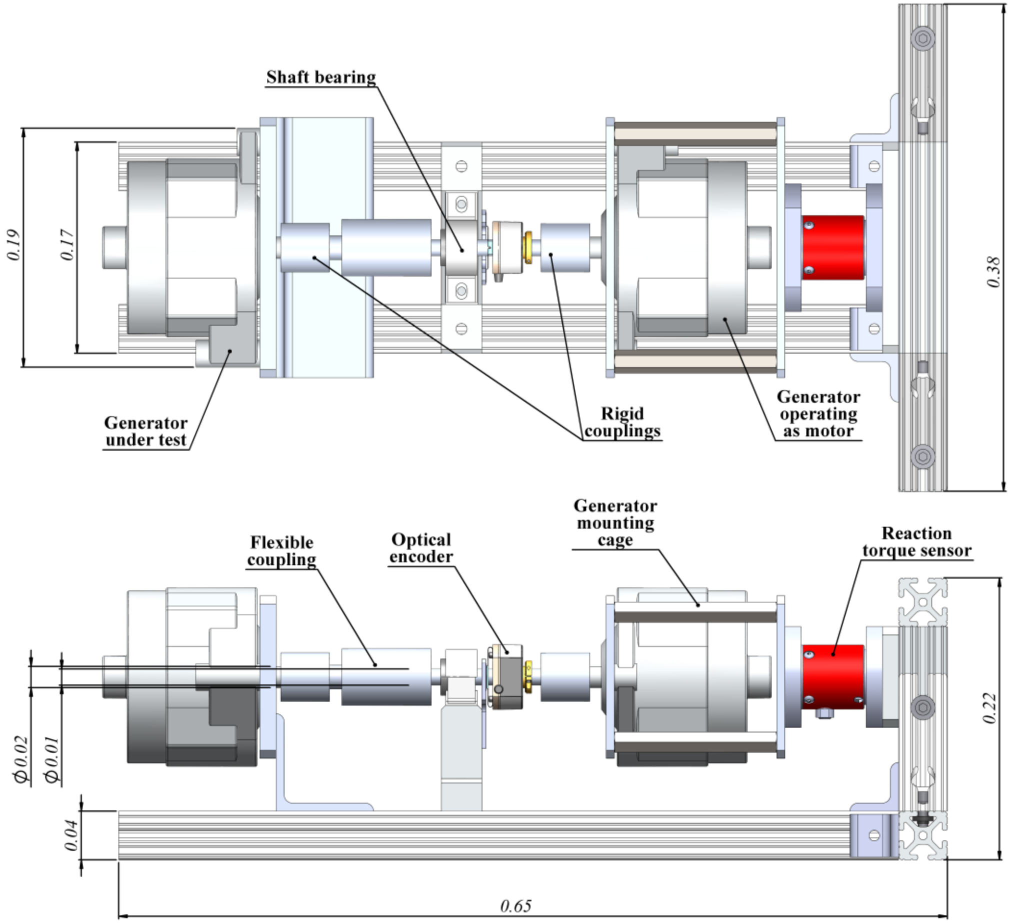


Power take-off dynamometry

Dynamometer measures efficiency of generator and allows determination of gearbox efficiency

Utilizes same load bank and rotation rates as field test

Measures torque, rotation rate, & electrical power



Efficiency formulations

Skipping some derivation…

Total system efficiency; Generator speed; Resistance setting

$$\eta_s(R, \omega_g) \longrightarrow C_P(R, \omega_g) = \frac{VI}{1/2\rho A U_\infty^3} \frac{\tilde{\tau}_g \tilde{\omega}_g}{\tilde{V}\tilde{I}} \frac{\tilde{V}\tilde{I}}{VI} = \frac{\tilde{\tau}_g \tilde{\omega}_g}{1/2\rho A U_\infty^3}$$

System efficiency

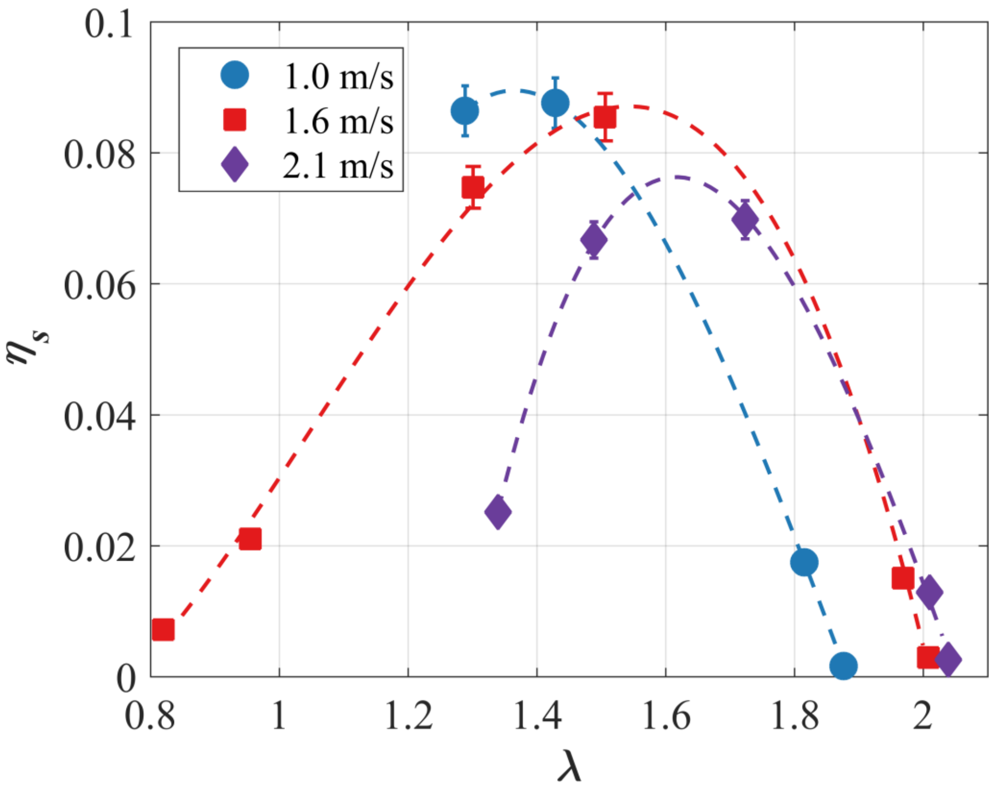
1 / Gearbox & balance of system efficiency

1/ Gen efficiency

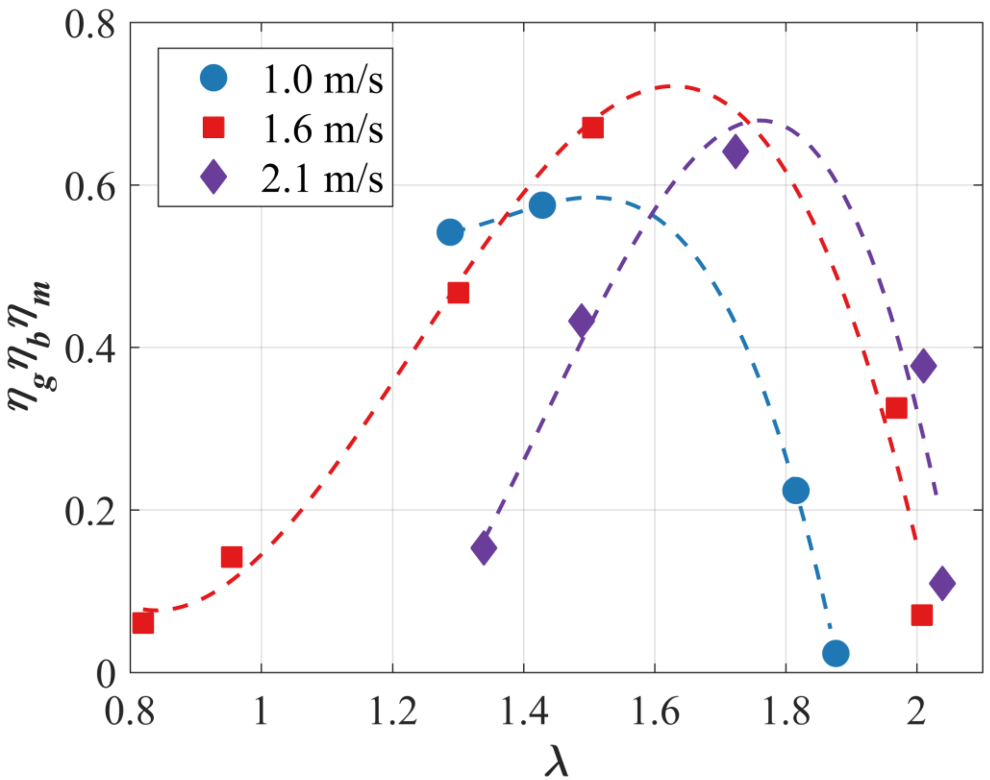
Rotor mean efficiency with two dyno measurements and two field measurements

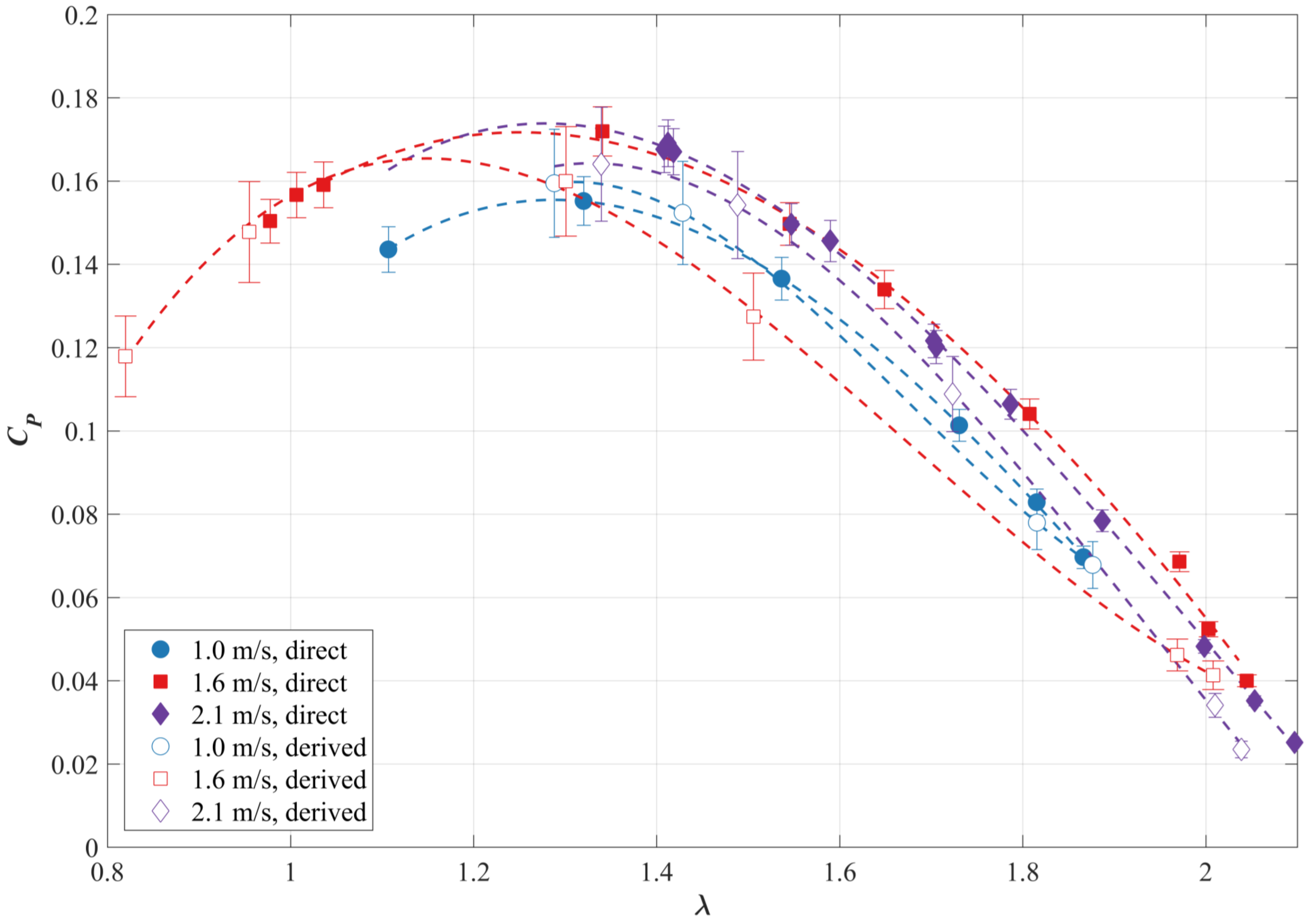
Results

System efficiency



PTO efficiency



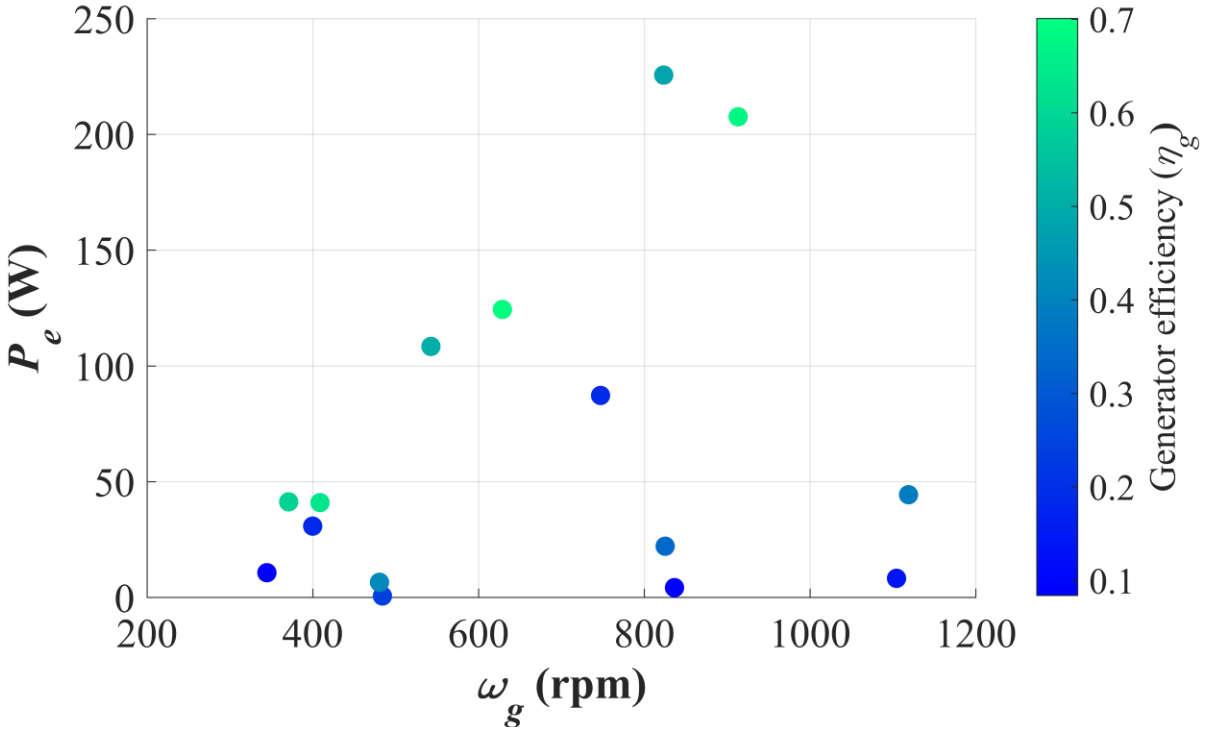


System efficiency corrected for PTO efficiency yields rotor efficiency

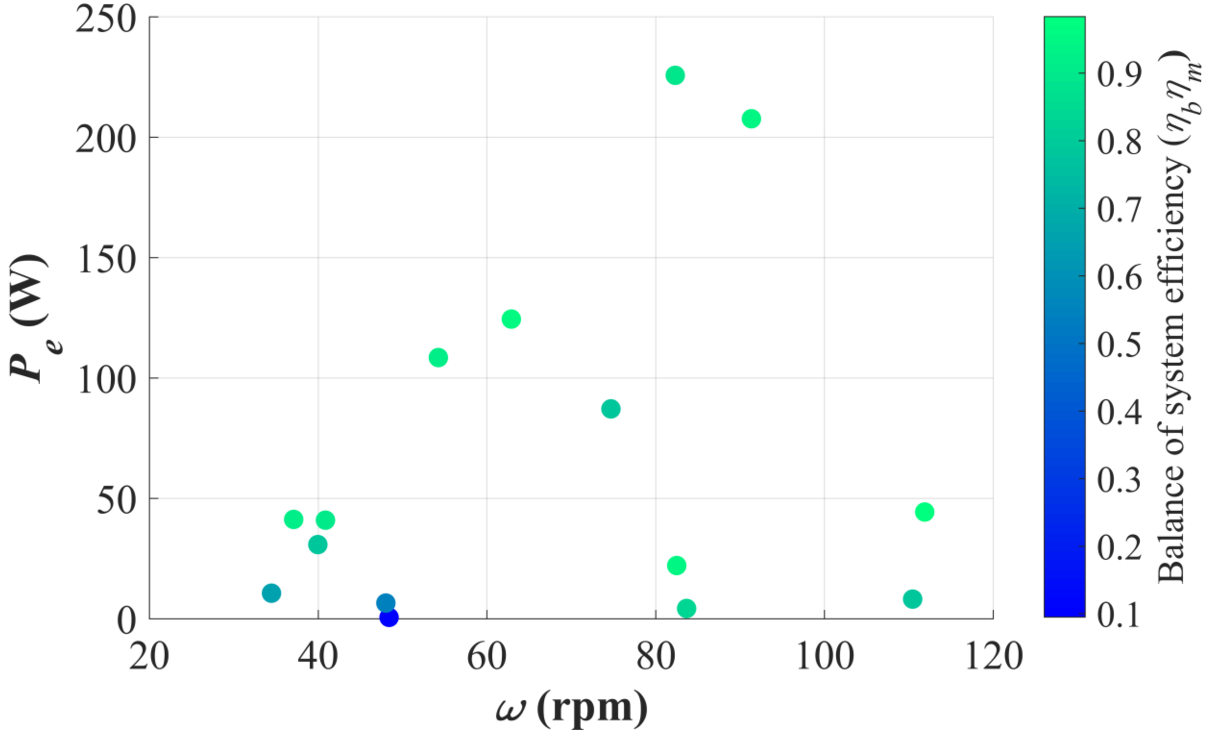
Uncertainty greater for derived points

Results

Generator efficiency

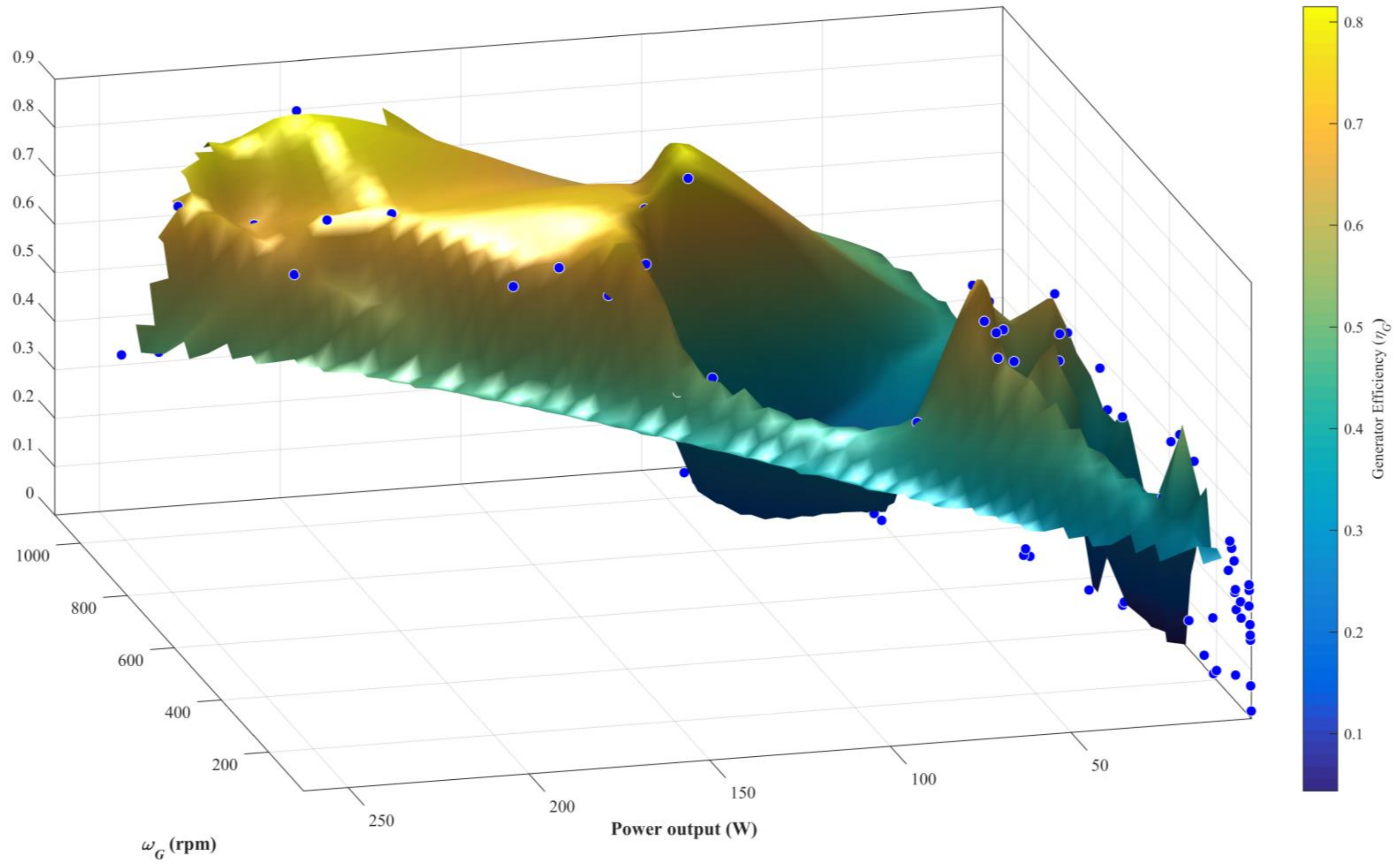


Balance of system efficiency



Results

Generator efficiency surface



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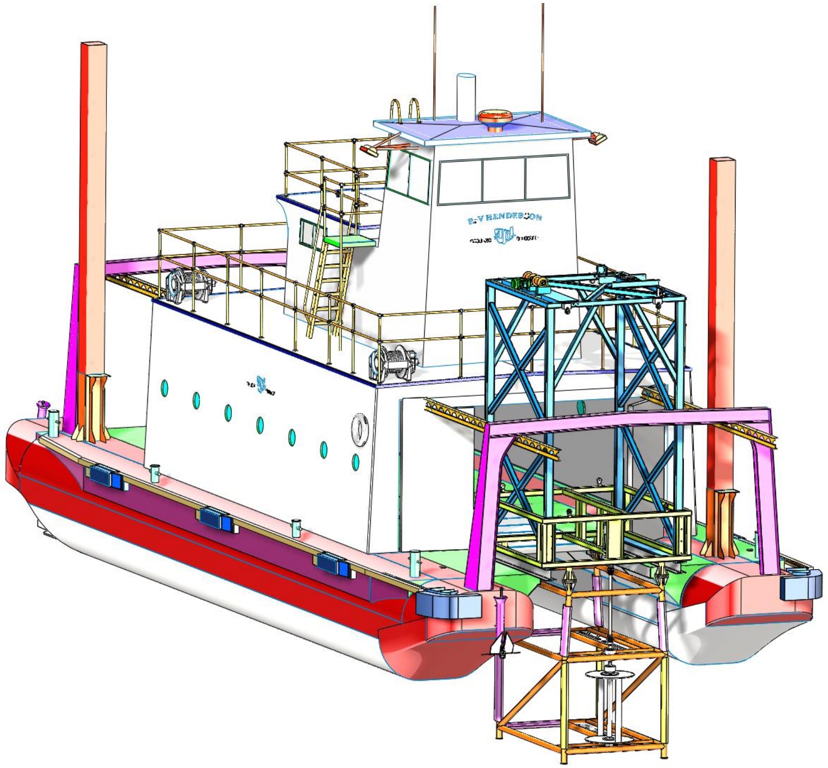
Electromechanical emulator control center

Motivation

Cavagnaro, R. J., Neely, J. C., Fay, F.-X., Mendia, J. L., Rea, J. A. (2016) Evaluation of electromechanical systems dynamically emulating a candidate hydrokinetic Turbine, IEEE Transactions on Sustainable Energy, vol.7, no.1, pp.390-399

Cavagnaro, R. J., Polagye, B., Thomson, J., Fabien, B., Forbush, D., Kilcher, L., Donegan, J., McEntee, J. *Emulation of a hydrokinetic turbine to assess control and grid integration*, Proceedings of the 11th European Wave and Tidal Energy Conference, (EWTEC 2015), Nantes, France. Sept. 6-11, 2015

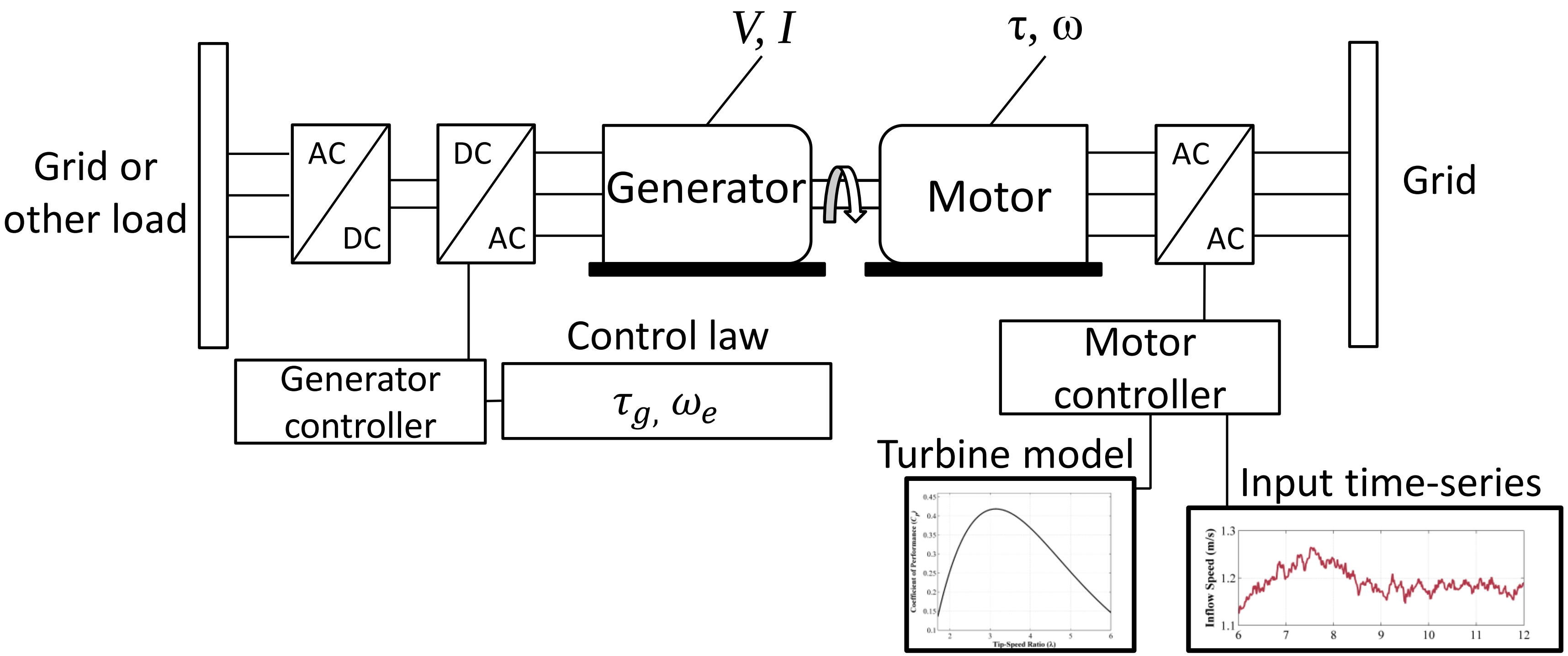
FIELD TEST VESSEL FOR NAVFAC MHK DEVELOPMENT



Can we use our knowledge of turbine and system dynamics to test control strategies and grid integration in the lab?

Turbine dynamic emulation

Electromechanical emulation



Electromechanical emulation

Round-robin testing on three machines

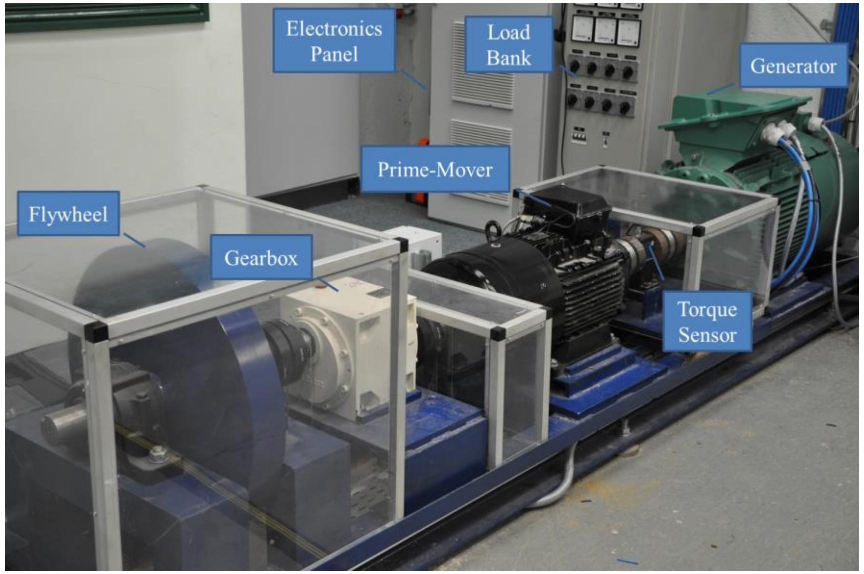
Evaluated reference model 50 kW device scaled to maintain time constant

Benchmark test is response to step rise in inflow speed

Velocity from tidal channel used to drive emulation

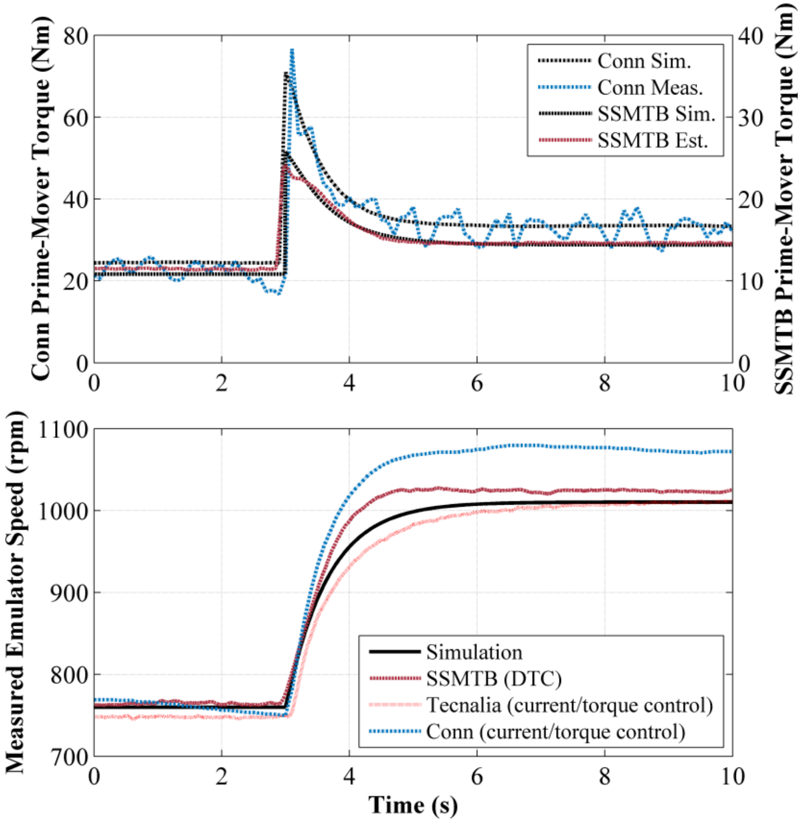
Grid-connected and controlled with optimal $K\omega^2$ scheme, compared to simulation

DOE RM2 turbine

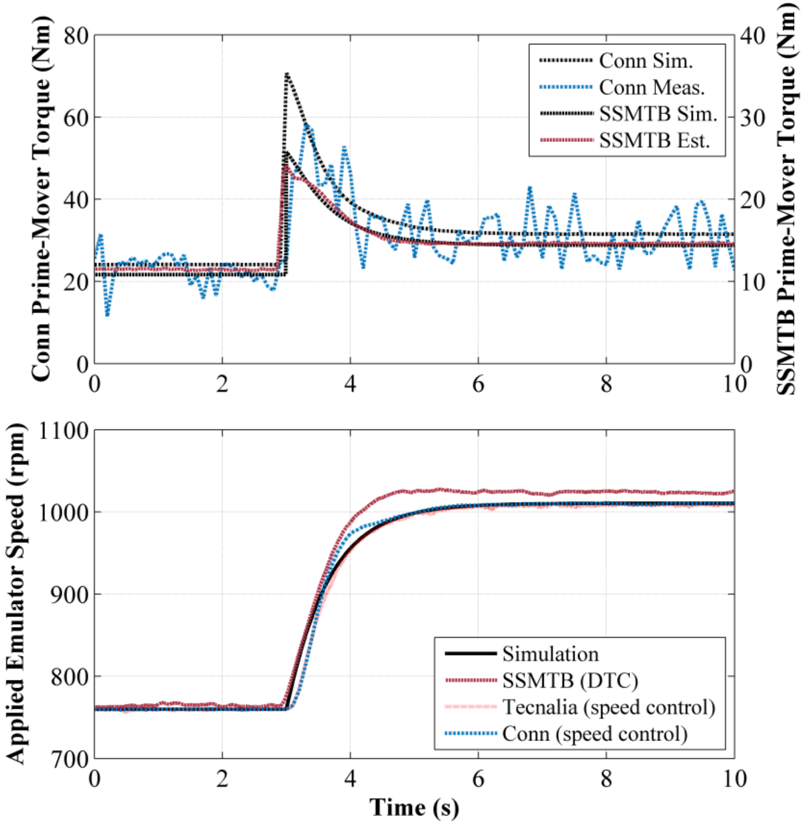


Conn emulator, Cork, Ireland

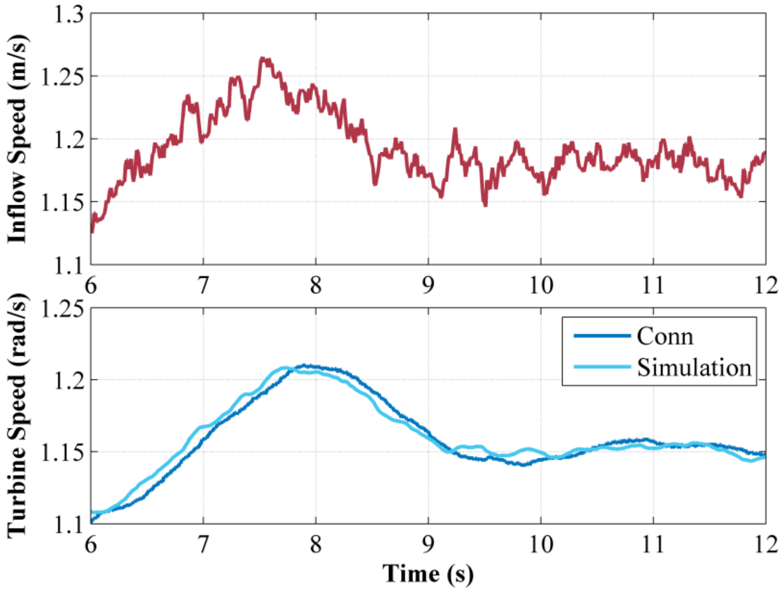
Results: comparison of performance



Step direct torque/current tests



Step direct torque/speed tests



Dynamic MPPT test

Emulation of RivGen Turbine

Results compared to ORPC RivGen turbine

Turbine scaled to maintain time constant

Realistic time-series from river measurements driving emulation

Efficiency under speed and TSR controllers compared with optimal $K\omega^2$ scheme and simulation

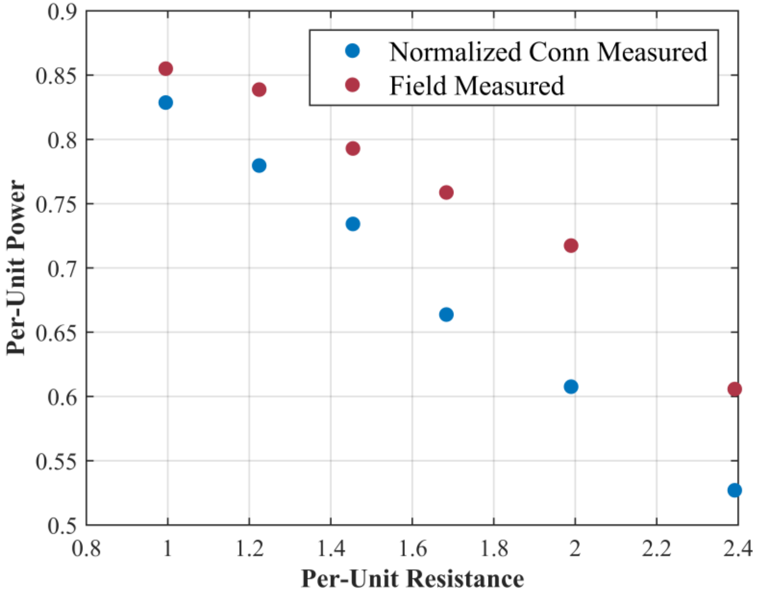
ORPC RivGen cross-flow turbine

Results: emulation of RivGen

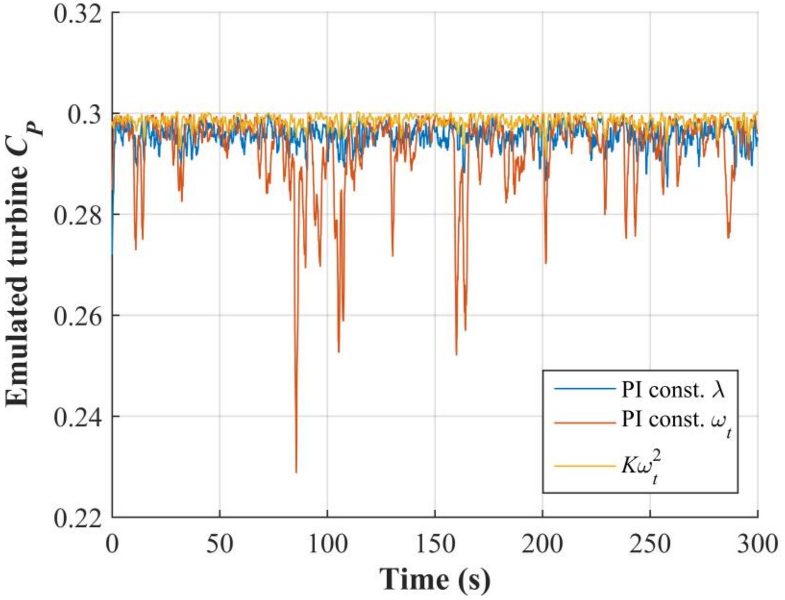
$$\tau_g = \frac{\gamma}{N_V \eta_g} \frac{\omega K_v^2}{R}$$

$$\tau_g = K\omega^2 = \frac{\gamma}{N_v}\left(\frac{1}{2}\rho A r^3 \frac{C_{Pmax}}{\lambda^{*3}}\right)\omega^2$$

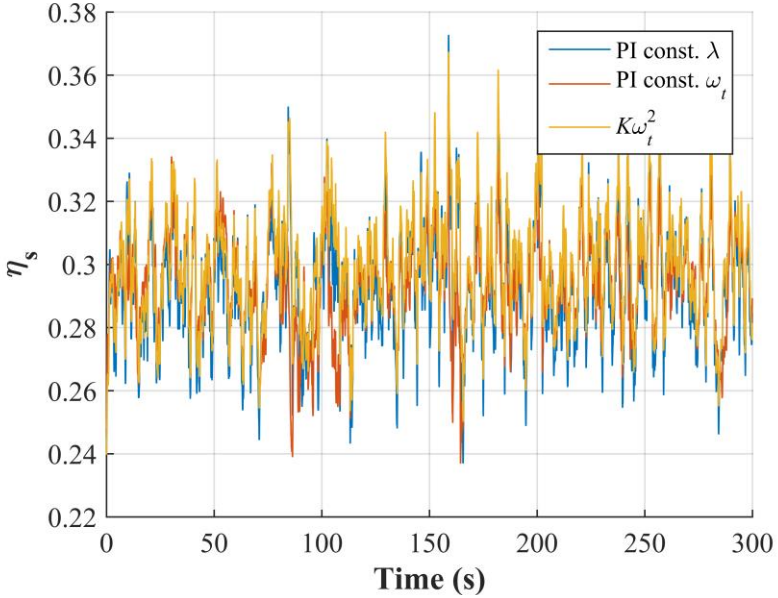
$$\tau_g = K_P(\omega - \omega^*) + K_I \int_0^t (\omega - \omega^*) d\tau$$



Real/emulated power output



Emulated rotor efficiency



Emulated system efficiency

Overview

- Motivation
- Cross-flow turbine dynamics and prototype scaling
- System stall characterization
- Field scale system characterization
- Electromechanical emulation of cross-flow turbine
- Conclusions
- Future work

Missing: Field test tow skiff

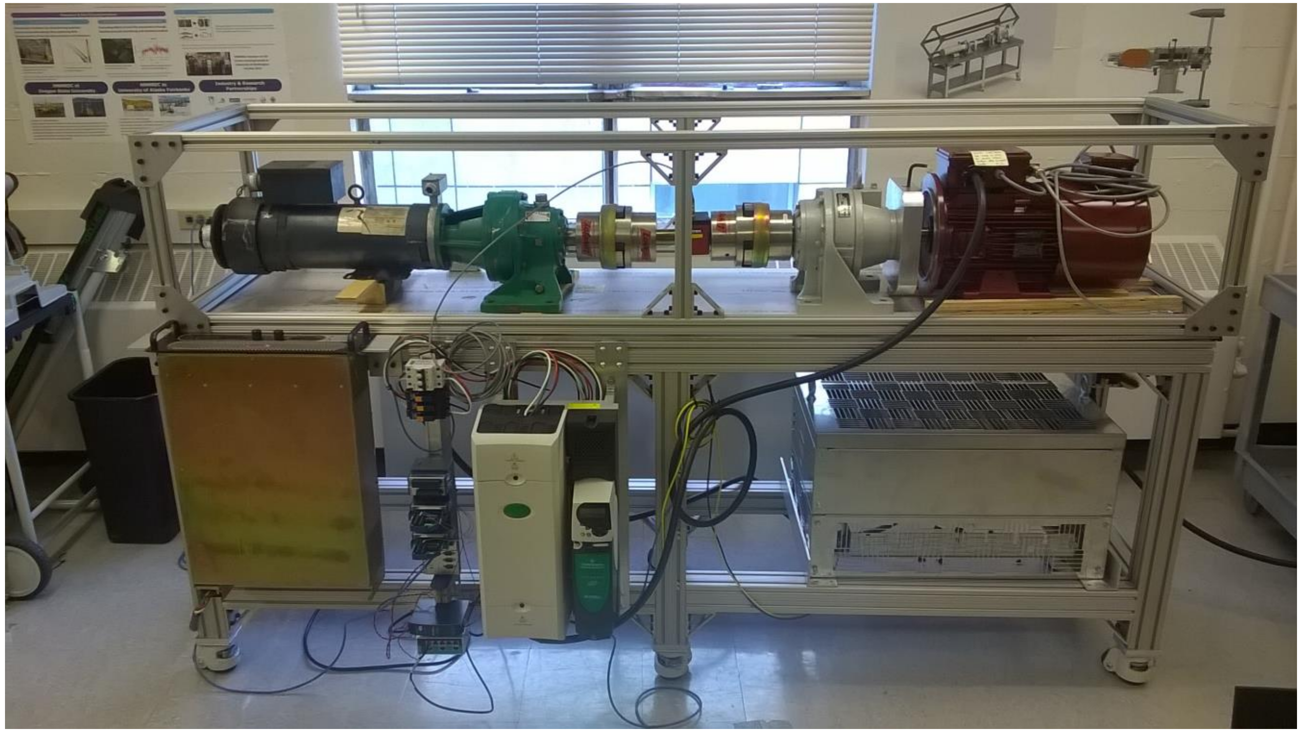
Conclusions

- System time constant qualitatively describes bandwidth and magnitude of response
- A turbine system stalls probabilistically
- Characterization of system components reduces required field measurements
- Emulators can successfully replicate the dynamics of a hydrokinetic turbine

Future work

MHK test platform

- Lab EEM
- Field PTO (turbine & WEC)
- Controller development



Benchtop PTO for landside development

Acknowledgements

Thanks are due to my committee, many fantastic colleagues, and advisement team at UW MREL/NNMREC and MaREI-Beaufort, UCC, funding from Dr. Roy Martin, the US DOE EERE Postdoctoral Research program, ORPC, and NAVFAC.

Questions?