Micropower from Tidal Turbines

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Tidal Current Energy

Utility-scale (> 1 MW) turbines harnessing renewable, predictable kinetic energy from tidal currents


Siemens/MCT


Ocean Renewable Power Company


Andritz Hydro/Hammerfest

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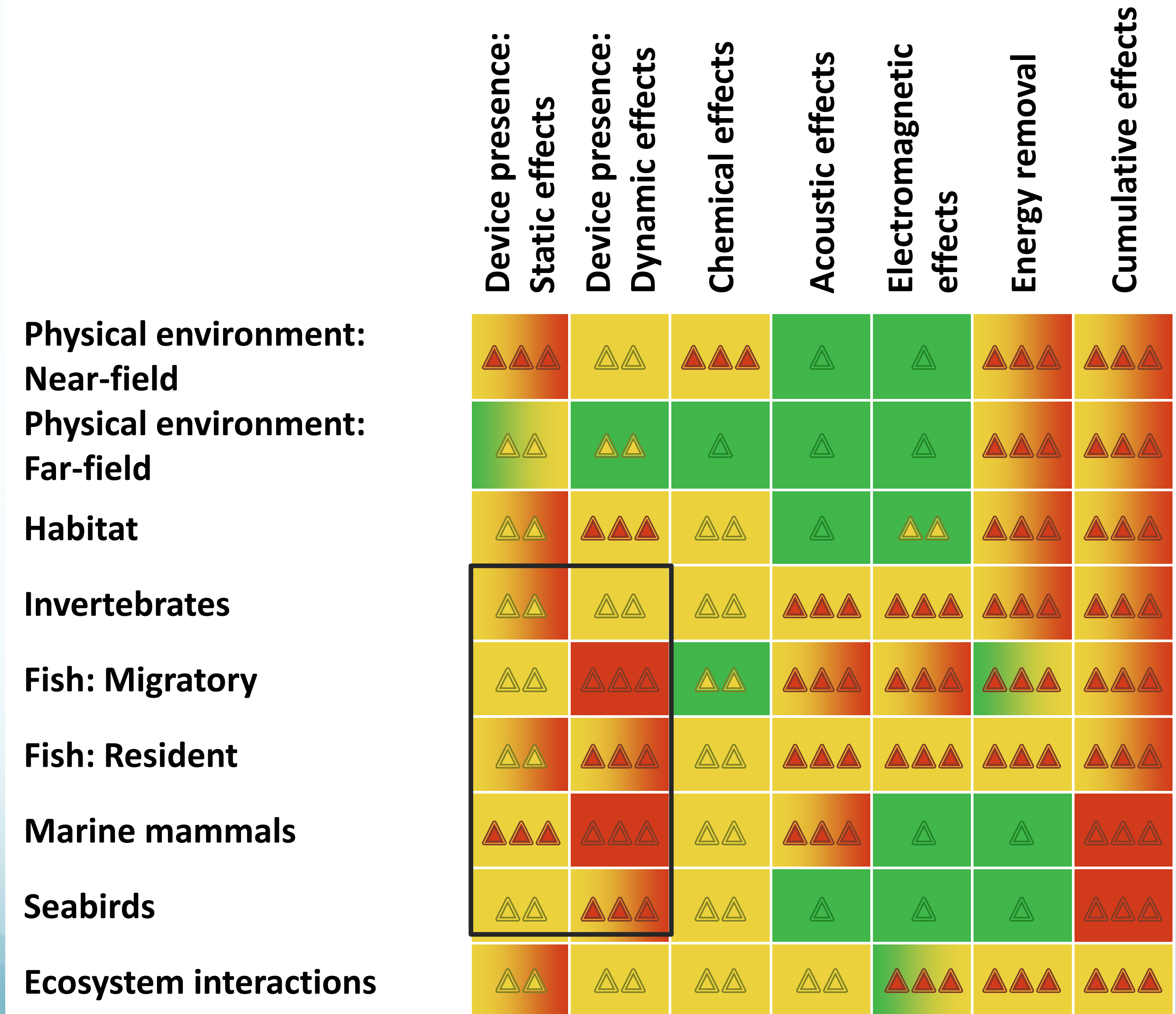
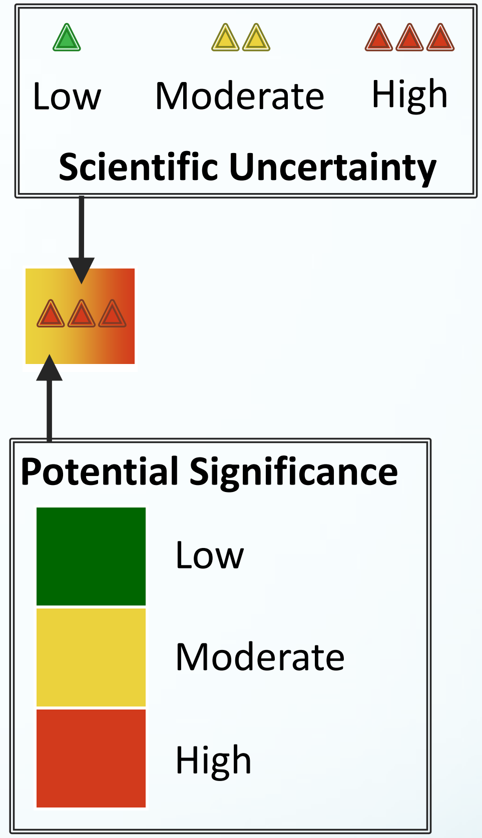
Potential Environmental Impacts





Polagye, B., B. Van Cleve, A. Copping, and K. Kirkendall (eds), (2011) Environmental effects of tidal energy development.

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Studying Changes to Distribution and Use

- **Pre-installation studies of tidal energy sites must typically rely on autonomous instrumentation**
- **Active acoustic sensors for observations of marine life have relatively high power draws (> 20 W)**

SoundMetrics DIDSON

BioSonics DTX

3-4 deep cycle lead acid batteries required to achieve 10% duty cycle for 1 month

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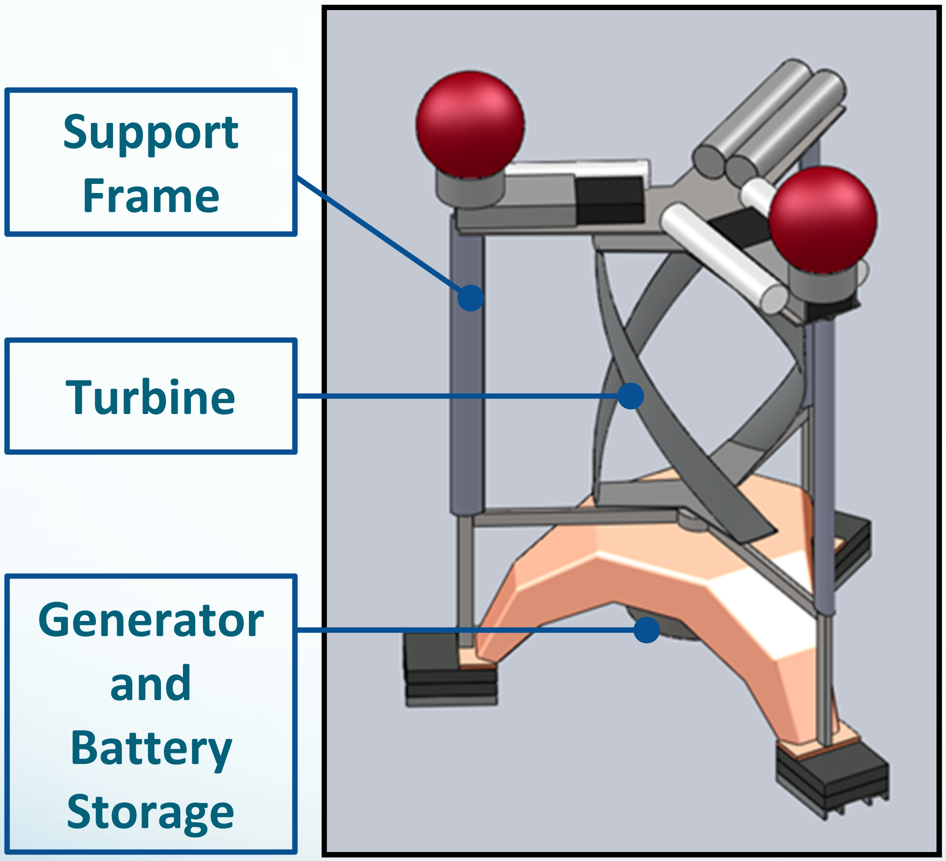
Tidal Micropower Concept



- Integrate energy harvesting capability into sensor package
- Modular alternative to cabled observatories
- Target 10-20 W/m^2 power output (including battery storage losses)

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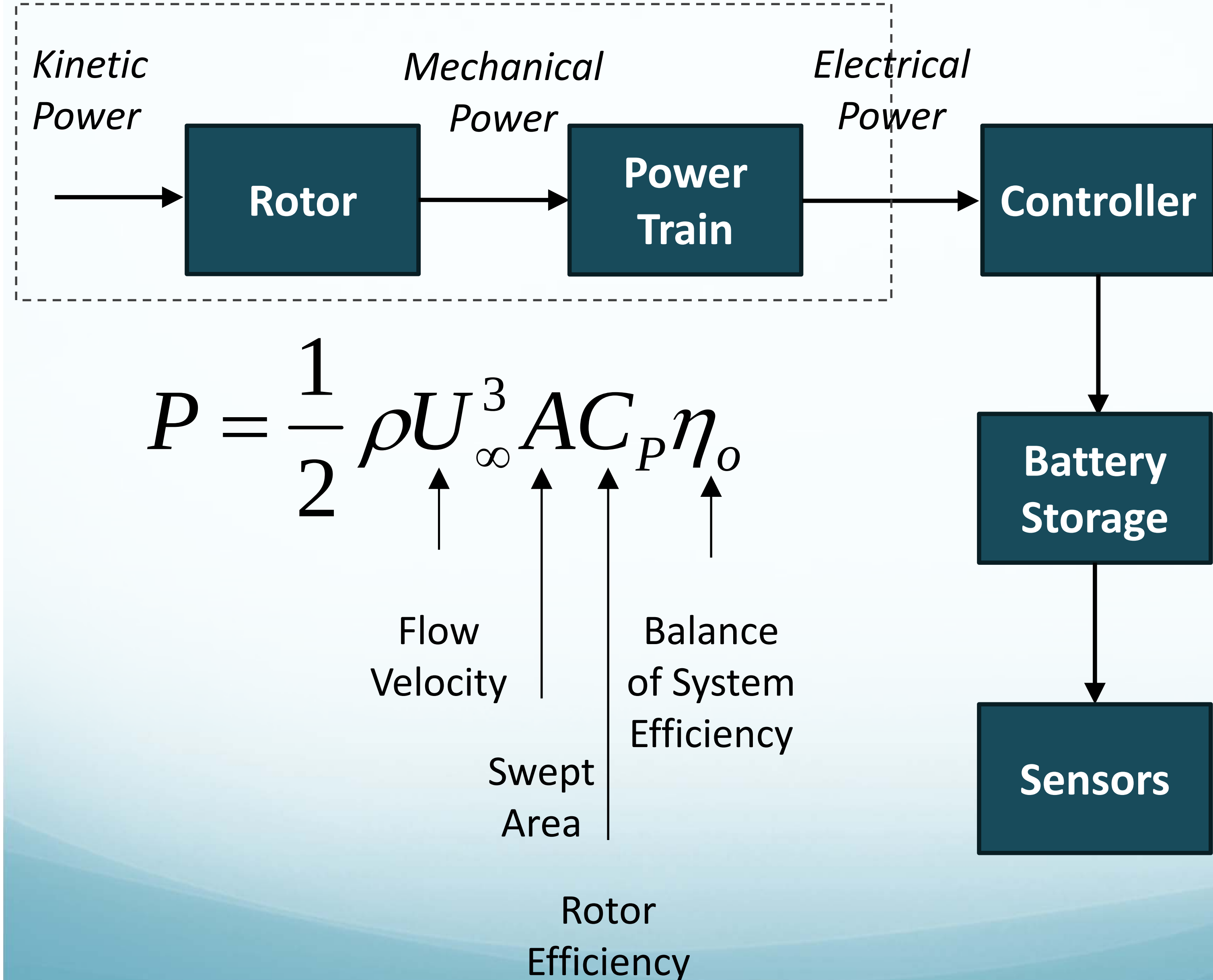
System Components



$$P = \frac{1}{2}\rho U_\infty^3 A C_P \eta_o$$

Micropower Rotor Requirements

- **Self-starting without external excitation**
- **Accommodate currents with time varying direction**
- **High efficiency conversion of kinetic power to electrical power**

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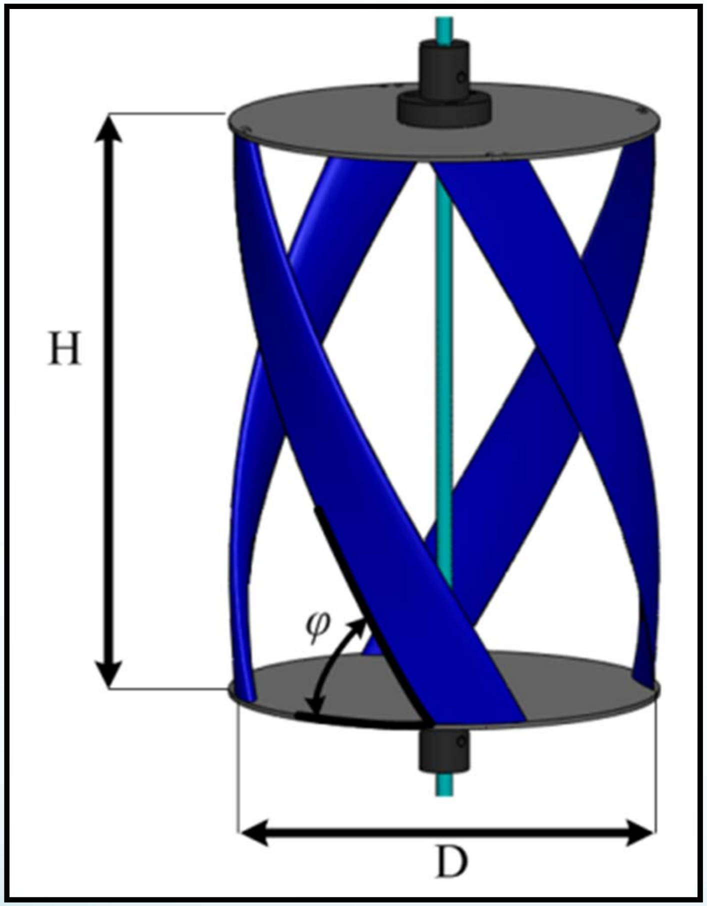
Rotor Selection



- **Cross-flow turbine**
  - High solidity
  - Helical blades
  - NACA 0018 profile
- ***N***: Number of blades (4)
- ***H/D****:* Aspect Ratio (1.4)
- ***φ****:* Blade helix angle (60°)
- **σ**: Turbine solidity (0.3) $\sigma = \frac{Nc}{\pi D}$
- **Limited existing parametric studies**

Shiono, M., Suzuki, K., and Kiho, S., 2002, "Output characteristics of Darrieus water turbine with helical blades for tidal current generations," *Proceedings of the Twelfth International Offshore and Polar Engineering Conference*, Kitakyushu, Japan, pp. 859-864.

Bachant, P., and Wosnik, M. 2011, "Experimental investigation of helical cross-flow axis hydrokinetic turbines, including effects of waves and turbulence," *Proceedings of the ASME-JSME-KSME 2011 Joint Fluids Engineering Conference*, Hamamatsu, Shizuoka, Japan.

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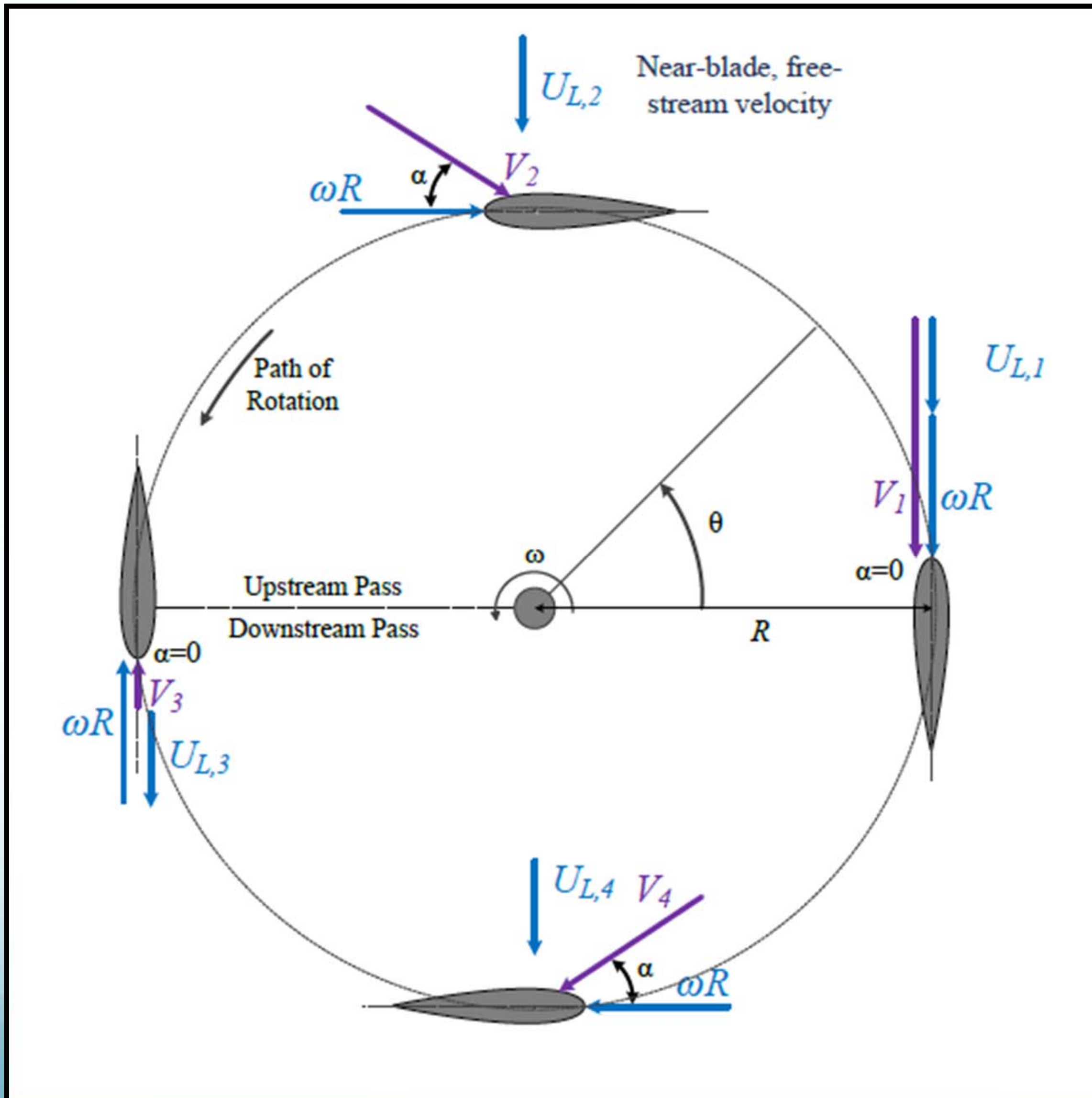
Principle of Operation



Radius

Rotational rate

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

Free-stream Velocity

$$U = \left(1 + \lambda^2 + 2\lambda\cos\theta\right)^{1/2}$$

Neglecting wake and induction

Local Velocity

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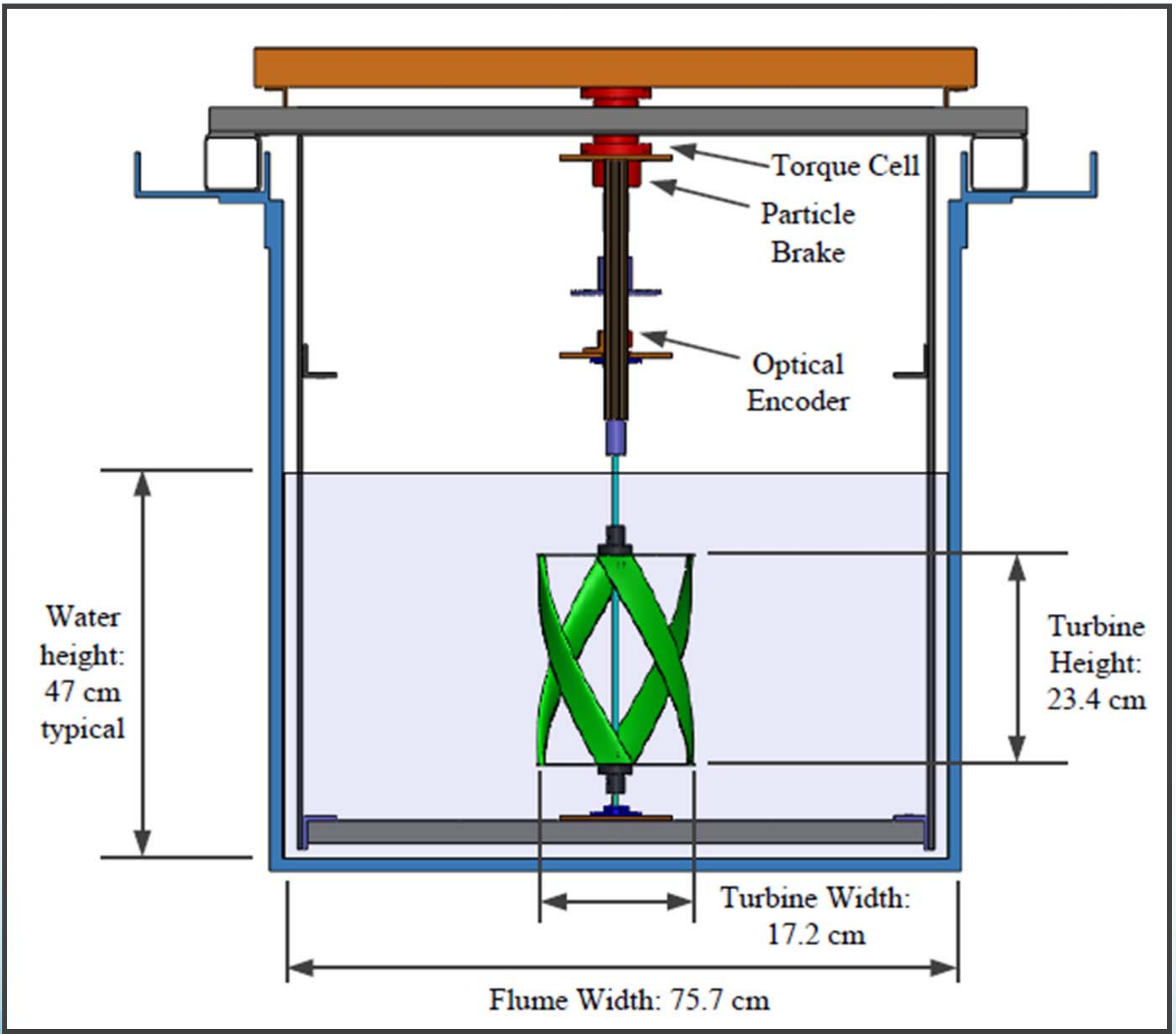
Laboratory Experiments



Chord Length *Re*

$$Re_c = \frac{Uc}{\upsilon} = 10^3 - 10^5$$

Blockage Ratio

$$\varepsilon = 18 - 21\%$$

Froude number

$$Fr = 0.2 - 0.4$$

Turbulence Intensity

$$I = \frac{\sigma_U}{\langle U \rangle} = 4\%$$

Niblick, A.L., 2012, "Experimental and analytical study of helical cross-flow turbines for a tidal micropower generation system," Masters thesis, University of Washington, Seattle, WA.

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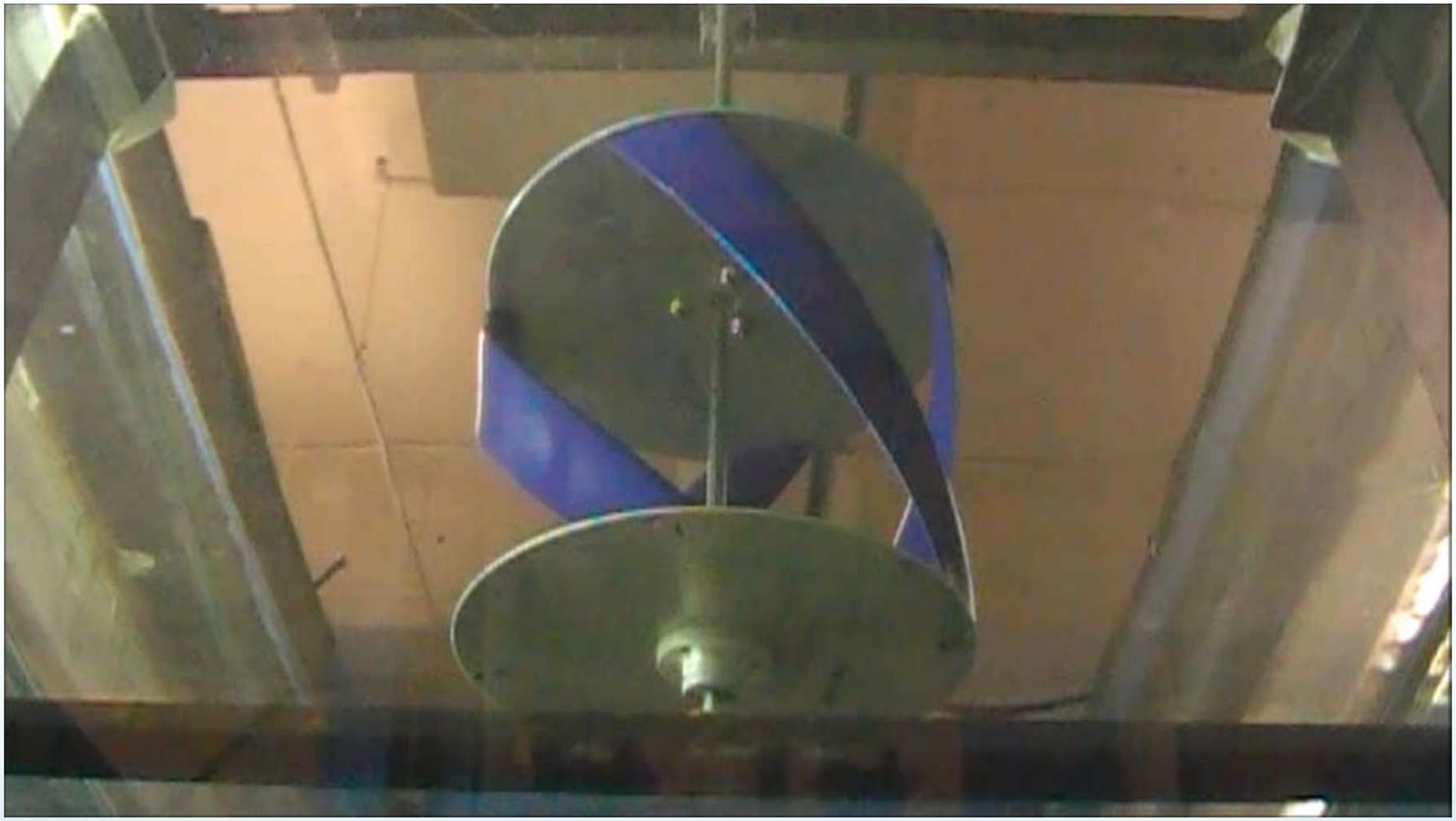
Turbine Operation



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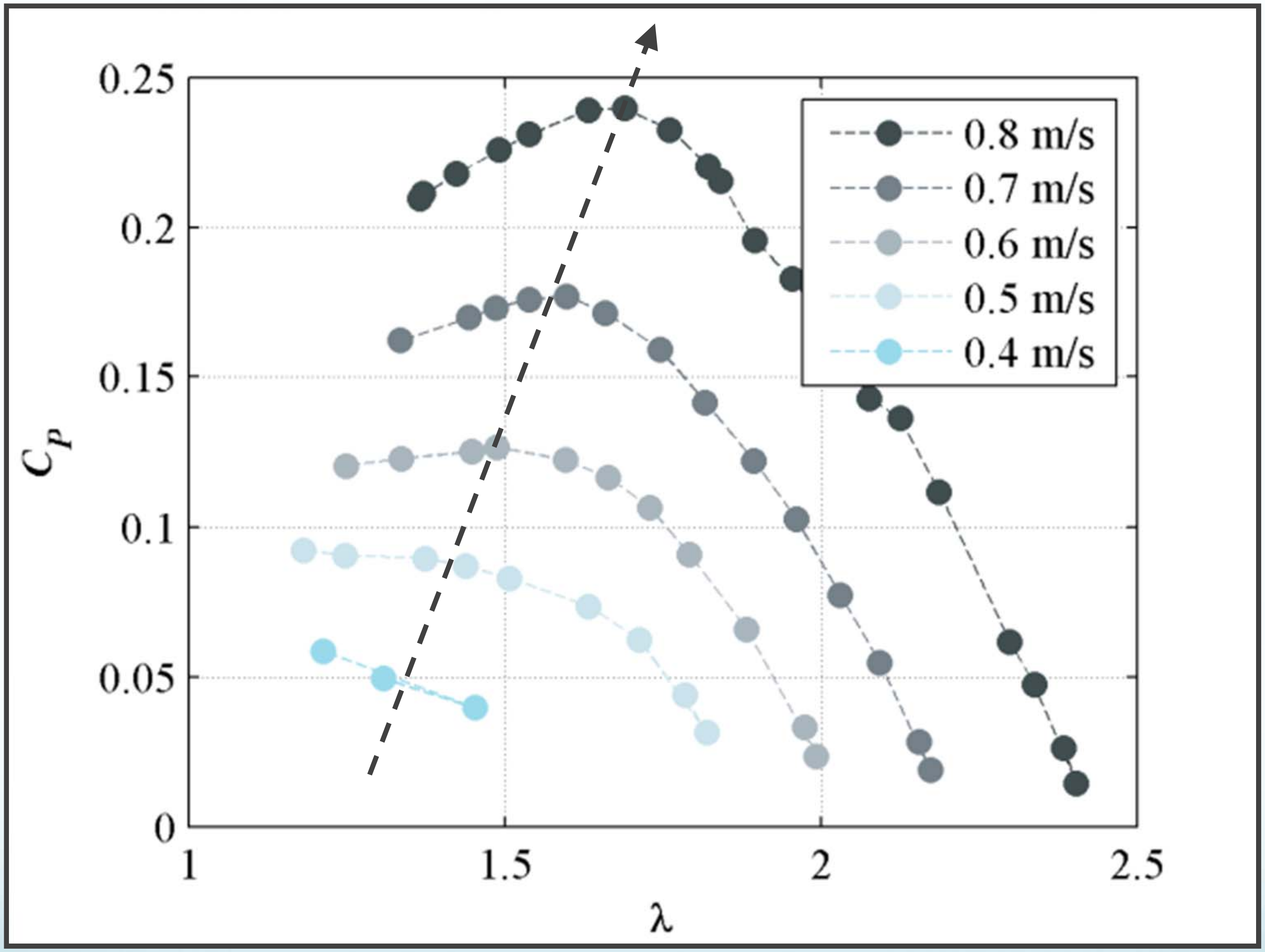
C_p-λ Velocity Dependence



Whelan, J. I., J. M. R. Graham, and J. Peiro (2009) A free-surface and blockage correction for tidal turbines. *Journal of Fluid Mechanics* 624, 1: 281-291.

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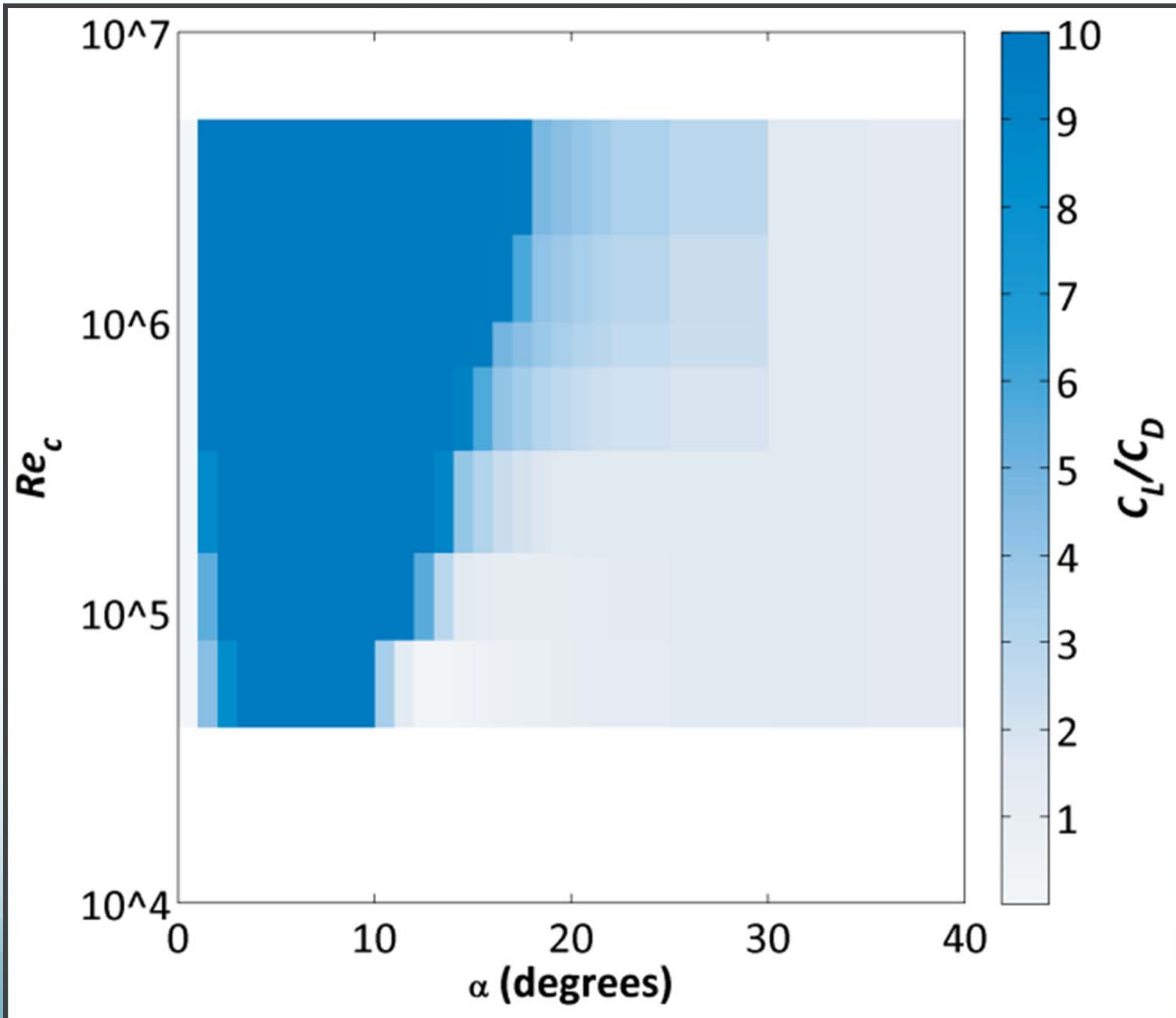
Possible Effect of Reynolds Number



Approximate Local Velocity

$$Re_c = \frac{Uc}{\upsilon} = 10^3 - 10^5$$

Sheldahl, R. E. and Klimas, P. C., 1981, "Aerodynamic characteristics of seven airfoil sections through 180 degrees angle of attack for use in aerodynamic analysis of vertical axis wind turbines," SAND80-2114, March 1981, Sandia National Laboratories, Albuquerque, New Mexico.

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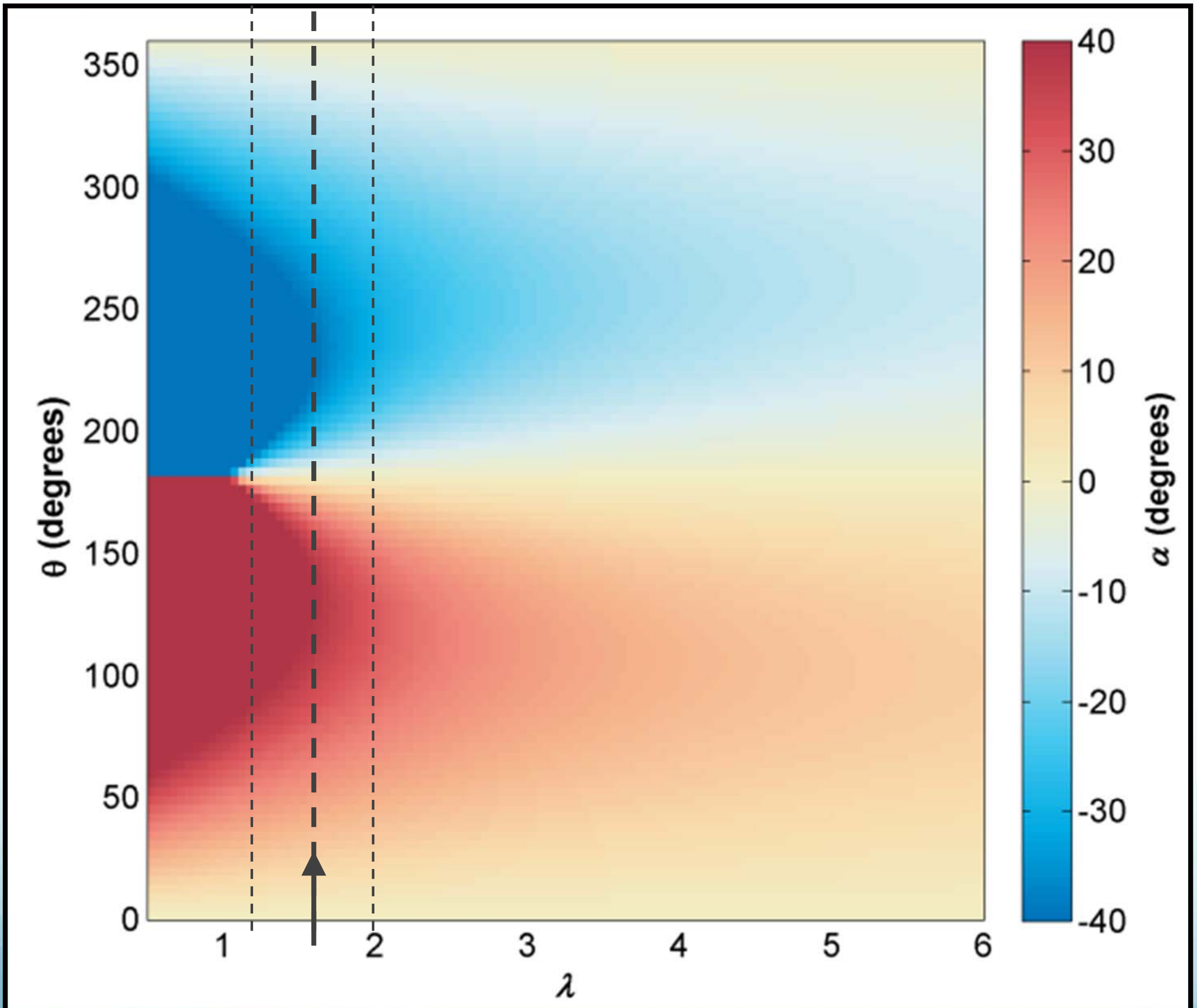
Angle of Attack Variation



Angular Position

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\lambda + \cos\theta}\right)$$

Tip Speed Ratio

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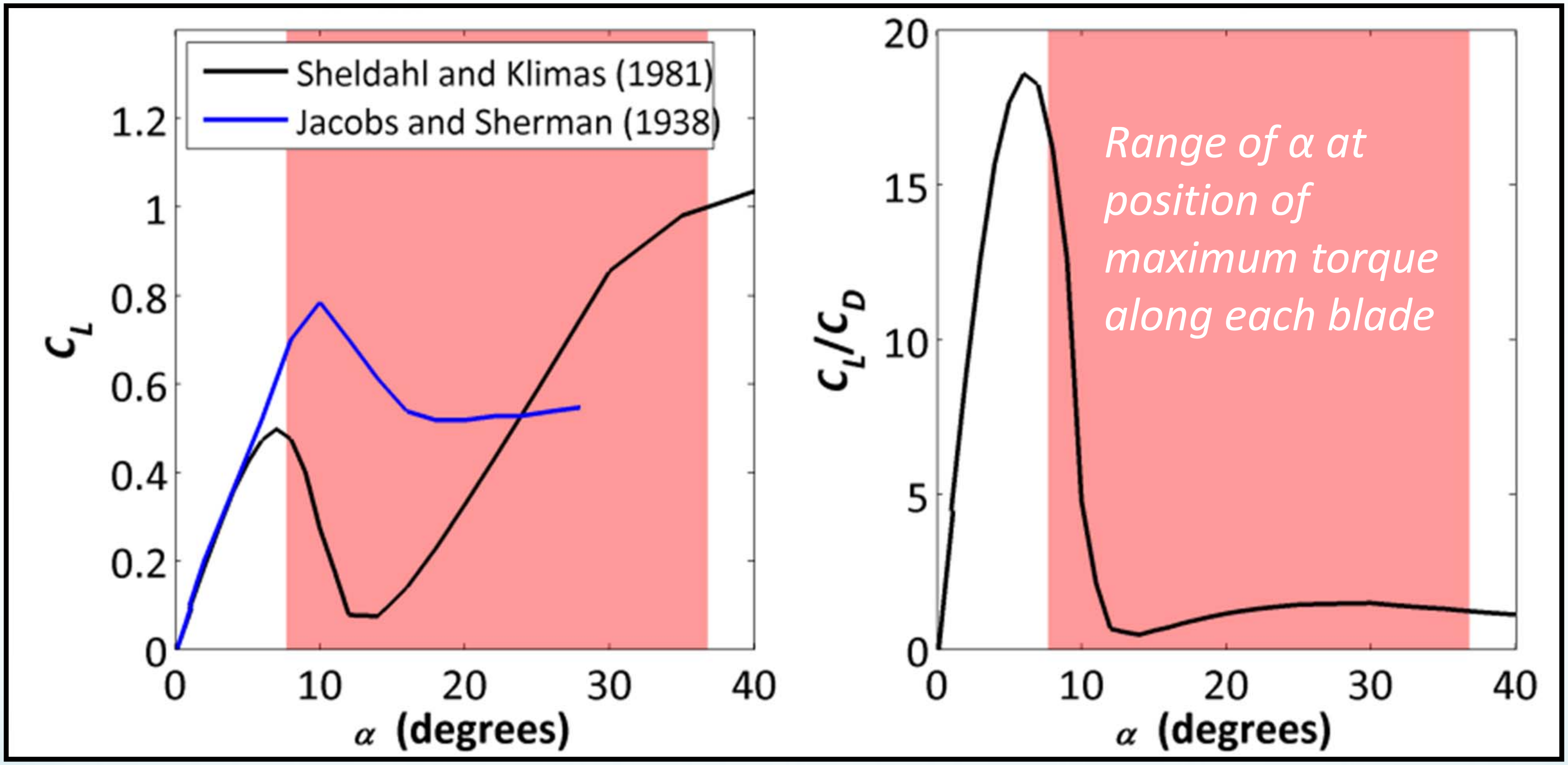
Significance of Dynamic Stall



$$Re_c = 5x10^4$$

Jacobs, E.N., and Sherman, A., 1937, "Airfoil section characteristics as affected by variations of the Reynolds number," Report No. 586, National Advisory Committee for Aeronautics.

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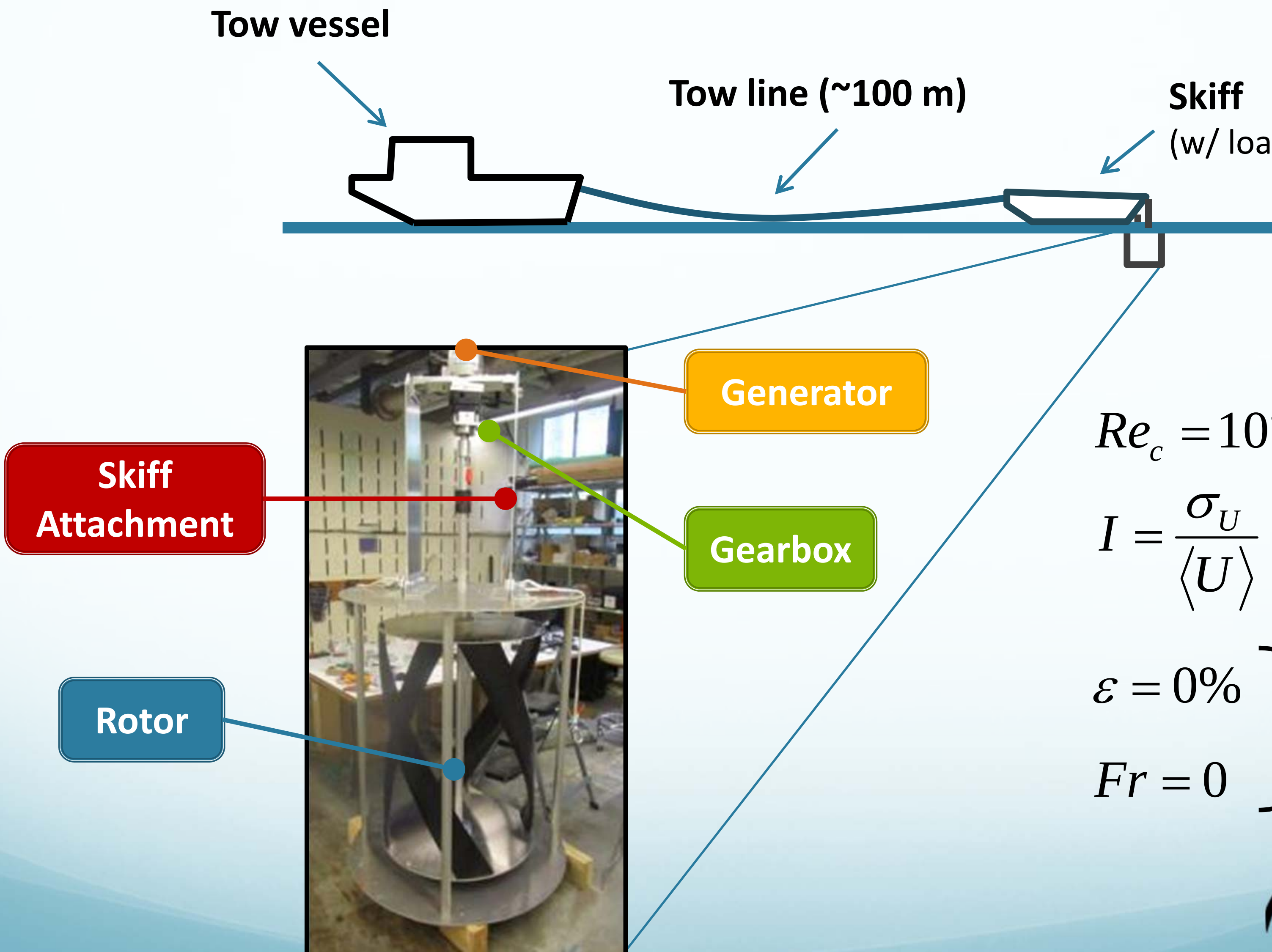
Field Experiments



$$Re_c = 10^4 - 10^5$$

$$I = \frac{\sigma_U}{\langle U \rangle} = 4\%$$

$$\varepsilon = 0\%$$

$$Fr = 0$$

No Blockage

Turbine Operation

Micropower Turbine

Tow Test 2

8/23/12

Cut-in to 4 knots

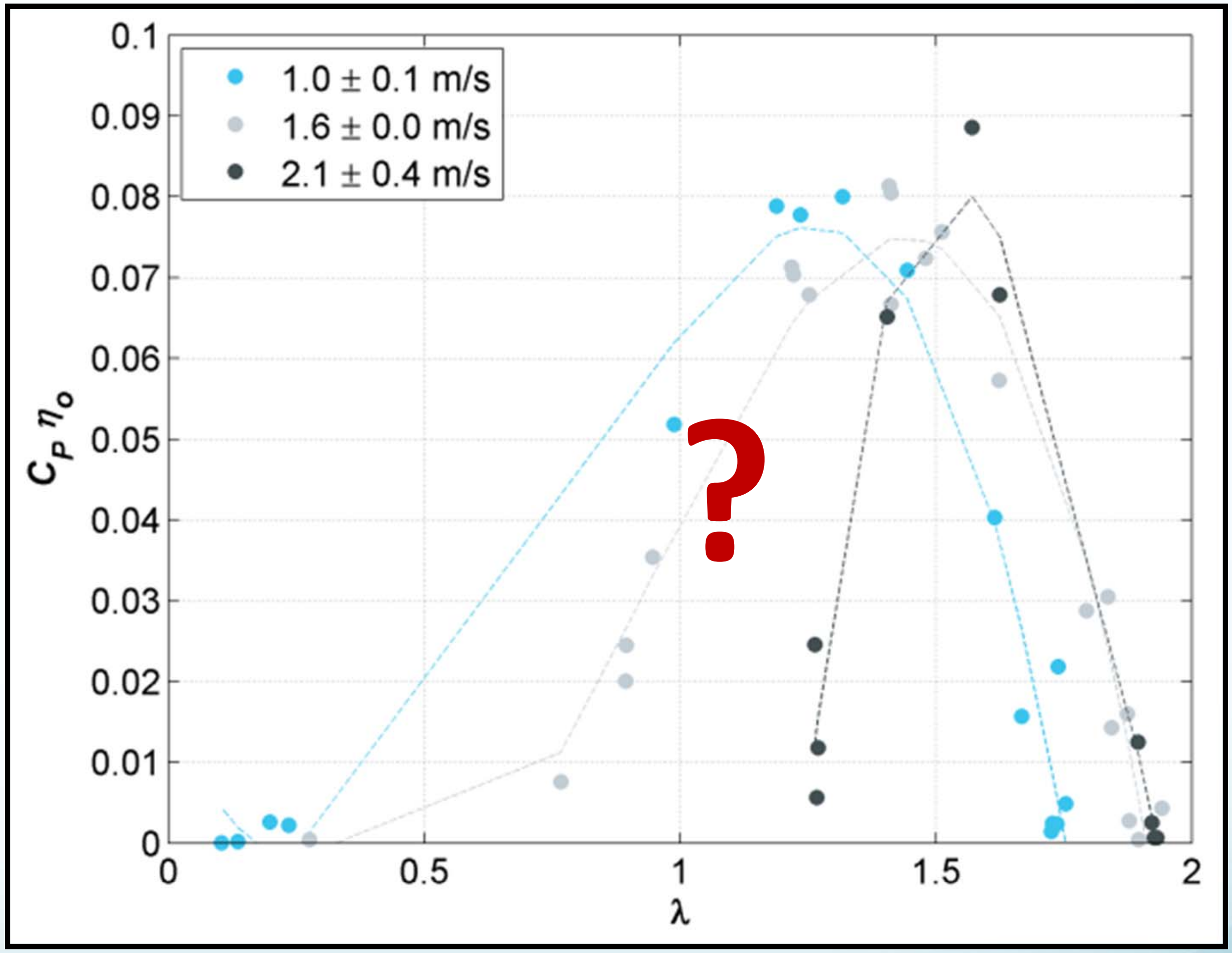
Field Performance

Electrical Power

$$C_P\eta_o = \frac{P_e}{\rho U_\infty^3 RH}$$

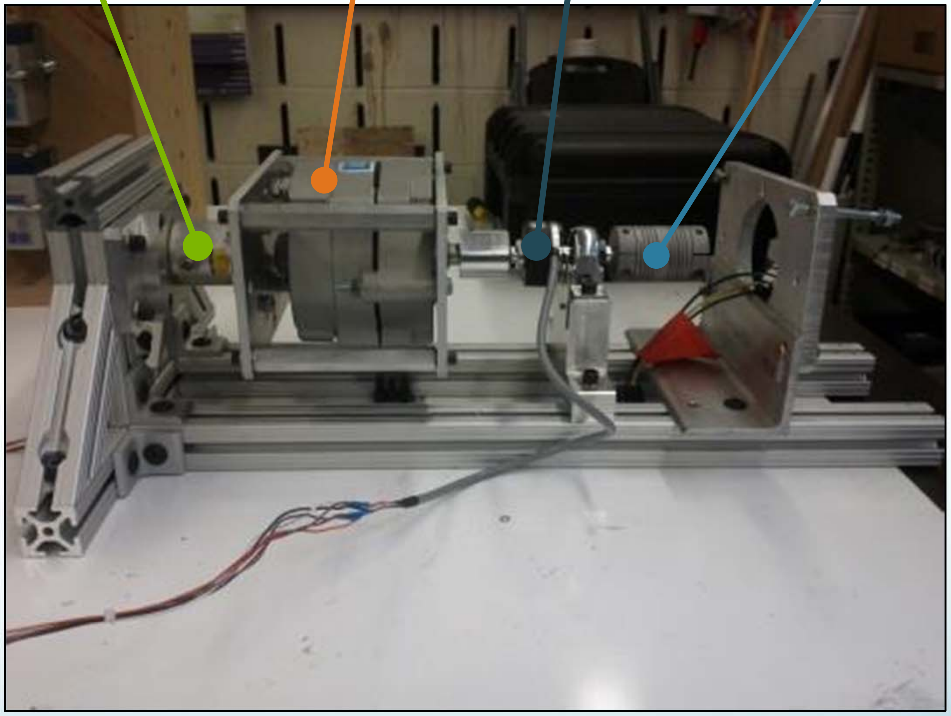
Radius

Height

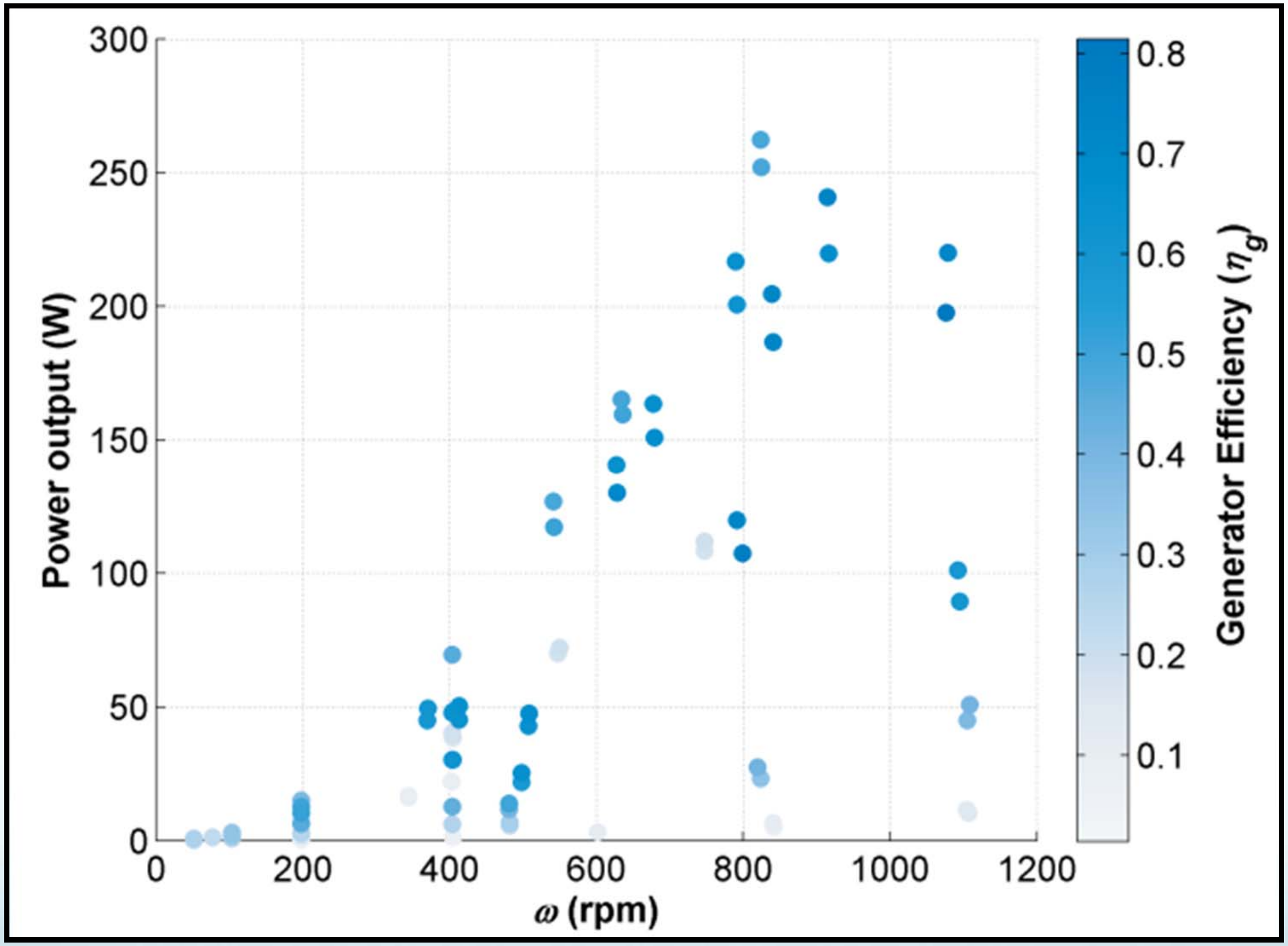


Laboratory Dynamometer

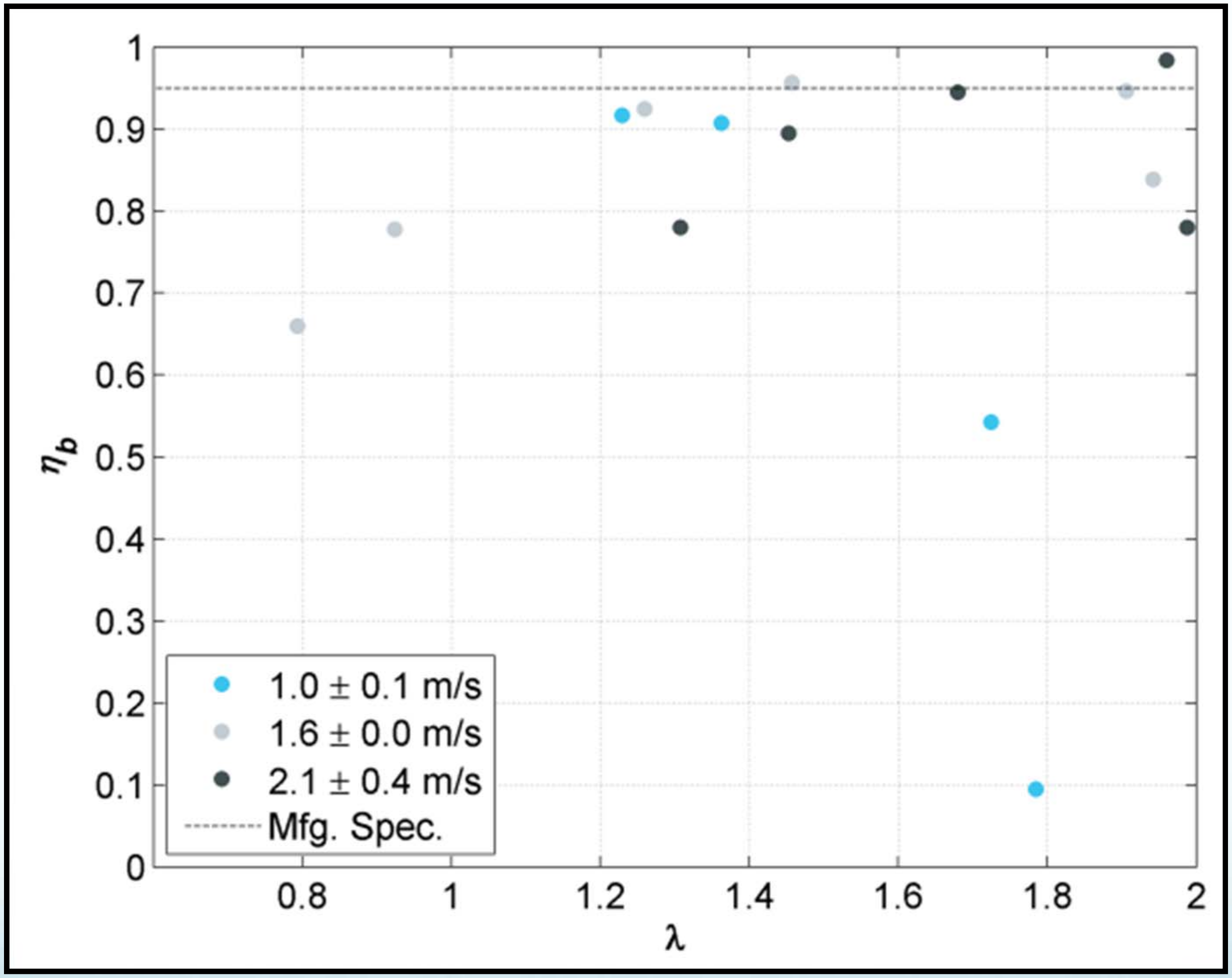
- Generator connected to field testing load bank
- Motor driven by variable frequency drive (3 phase AC)
- Evaluate generator and gearbox efficiency under same conditions as field test (loads and rpm)



Generator Efficiency

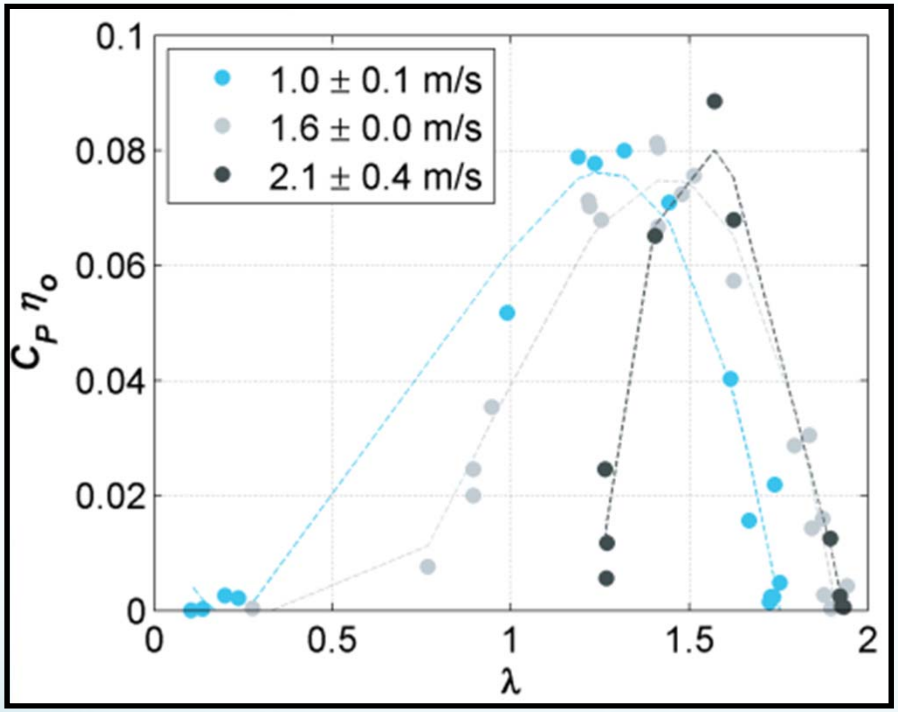


Gearbox Efficiency

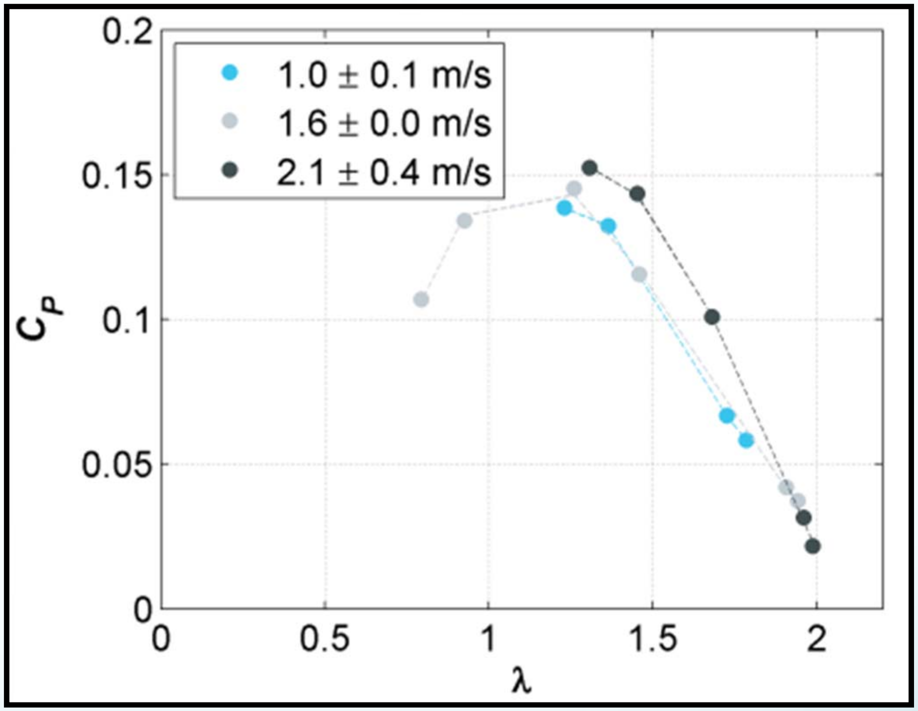


Field Performance

System Performance

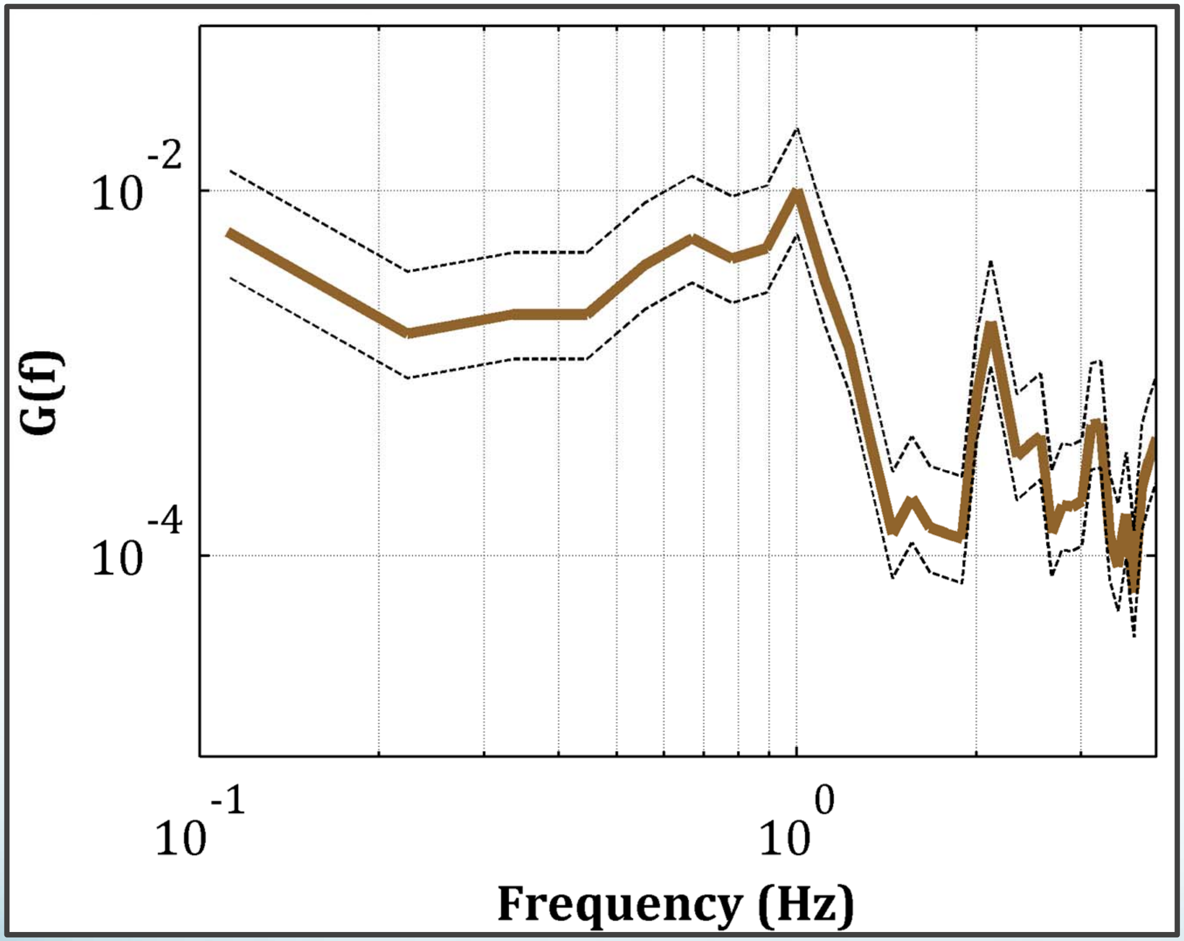


Rotor Performance



Rotor performance (without blockage) in line with expectations from prior work by Bachant and Wosnik (2011), accounting for higher solidity

Response to Turbulent Perturbations



$$U_\infty = 1.5\,\mathrm{m/s}$$

Maximum C_P

$$G(f) = \frac{S_{P_eP_e}(f)}{S_{PP}(f)}$$

$$f_c = \frac{U}{L}$$ Taylor's hypothesis

$$f_c = 2\ \mathrm{Hz}$$ Smallest engulfing gust

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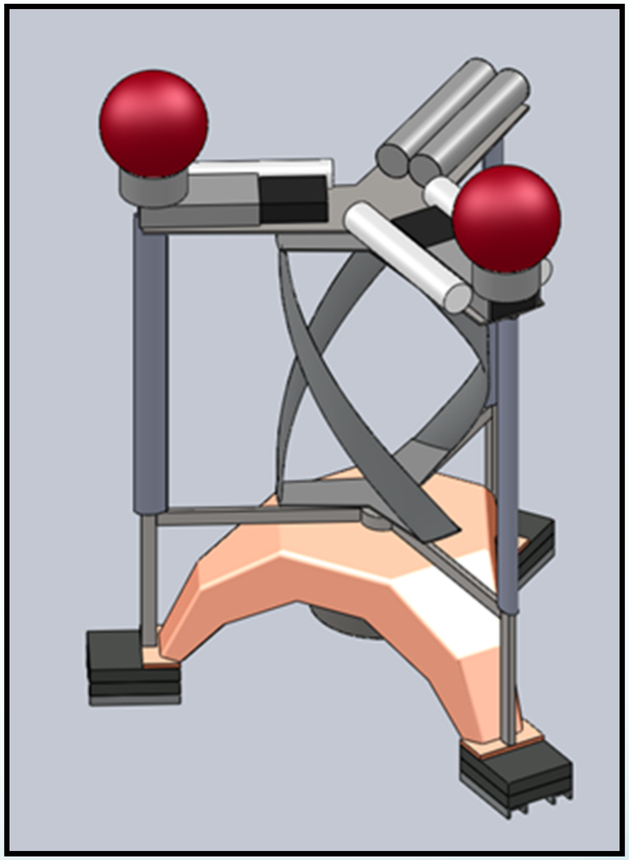
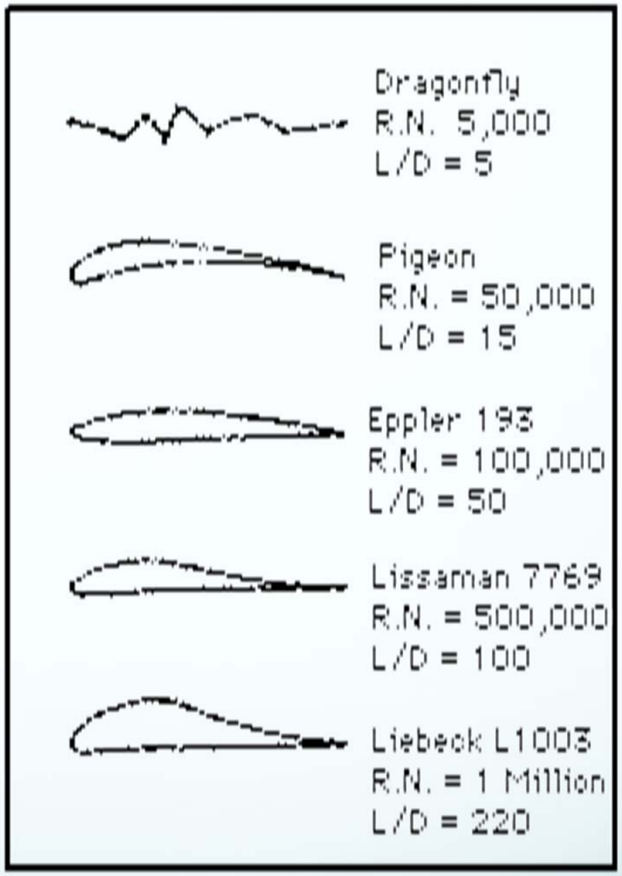
Tidal Micropower Feasibility

- **Self-starting without external excitation**
- **Accommodate currents with time varying direction**
- **High efficiency conversion of kinetic power to electrical power**
  - Low balance of system efficiency
  - Relatively low rotor efficiency



Design Refinements

- **Improved Rotor Efficiency**
  - — Decrease solidity to increase λ
  - — Asymmetric foil with higher C_L/C_D at $Re_c \sim 10^4 - 10^5$ (similar Re_c to UAVs)
- **Submersible Direct-Drive Generator**
  - — With existing drivetrain, optimal λ depends on inflow velocity (undesirable for control)
  - — Eliminate rotary seal
  - — Minimize thermal management challenge



http://adg.stanford.edu/aa241/airfoils/airfoilhistory.html

Acknowledgements

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