Experimental and Analytical Study of Helical Cross-Flow Turbines for a Tidal Micropower Generation System

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MSME Thesis Defense

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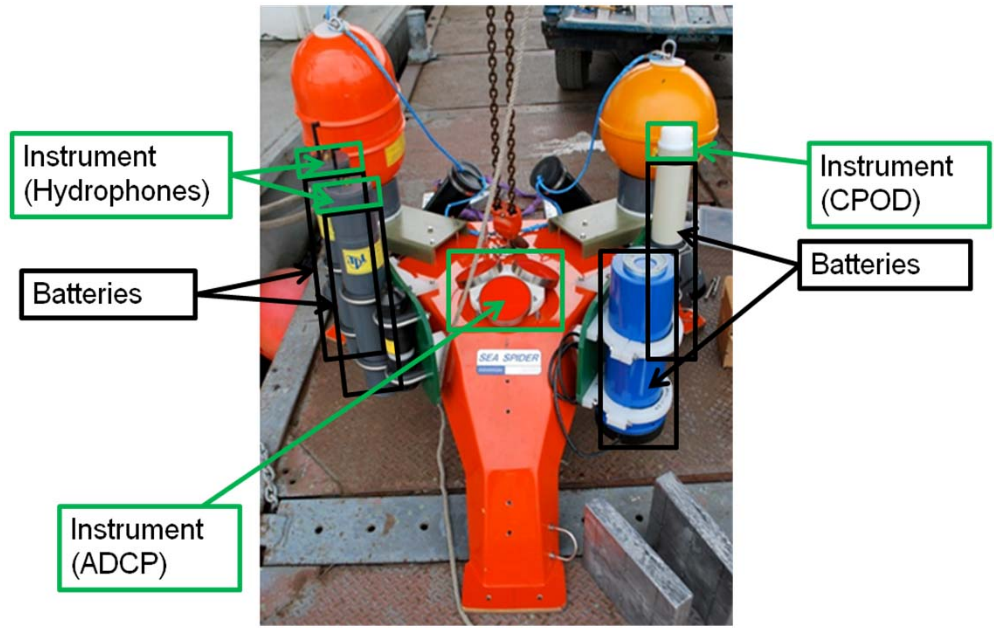
W OSU NNMREC

Outline

- Tidal Micropower System Overview
- Turbine Selection/Design Parameters
- Experimental Testing
- Modeling
- Conclusions and Future Work

Motivation for Micropower

- Admiralty Inlet – potential site of tidal turbine installation for commercial power
- NNMREC Environmental site characterization monitoring
    - Sea Spider bottom lander tripod
    - Instrumentation requires power
    - Currently battery- powered
    - Grid, solar and wind not feasible



Motivation for Micropower

	Battery Capacity (W-hr):		165	Cost ($/W-hr):	$ 1.15
Unit	Power Usage (W)	Deployment Duration (days)	Total W-hr	# of batteries Required	Battery Cost
Doppler Current Profiler	0.9	90	1944	**12**	**$ 2,280.00**

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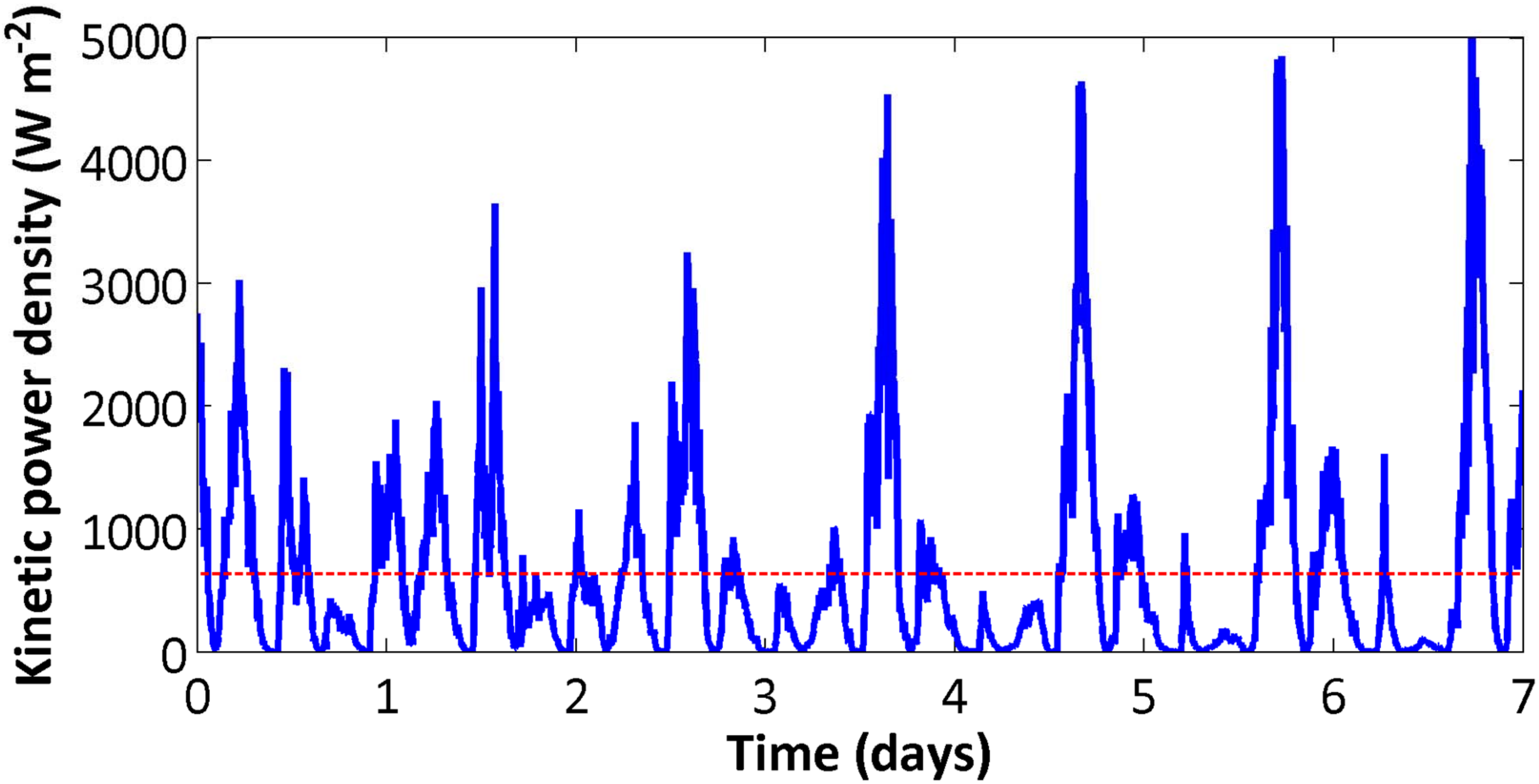
Doppler Current Profiler	0.9	**180**	3888	**24**	**$ 4,560.00**

Motivation for Micropower



$$KPD = \frac{1}{2}\rho {u_0}^3$$

u_0: *Inflow velocity*
ρ: *Fluid density*

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Motivation for Micropower

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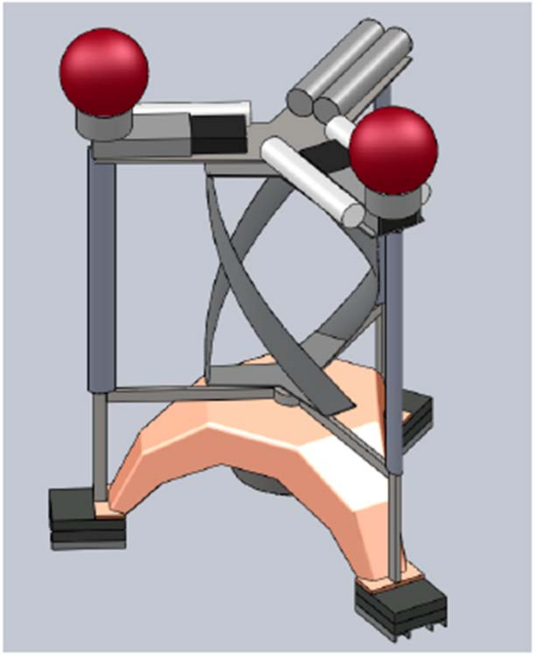
Imaging Sonar (20% duty cycle)	20.0	180	86400	**524**	**$99,560.00**
Imaging Sonar (20% duty cycle)	20.0	180	86400	**15**	**$ 2,850.00**

Micropower System Concept



Drawing courtesy of Stelzenmuller et al

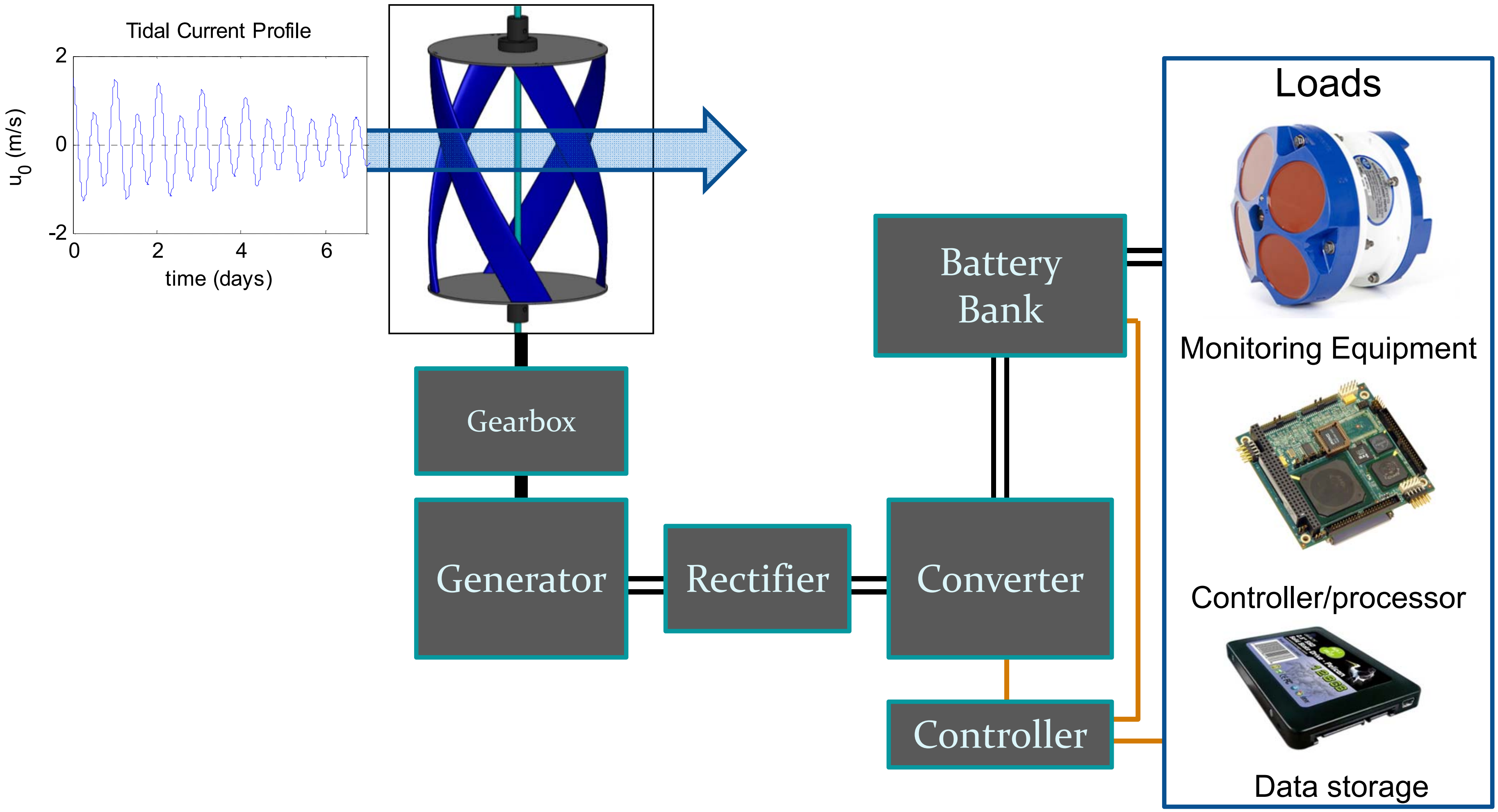
Micropower System – A tidal hydrokinetic power generation system to power remote instrumentation on the order of 20 W continuous in 1.5 m/s peak tidal currents.

Research Goals

Provide initial concept for a micropower tidal generation system

Provide detailed design, analysis and experimental testing one of the components: the hydrokinetic turbine

Micropower System Block Diagram



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Turbine Performance Metrics

- Efficiency – for power and torque production

$$C_P = \frac{T\omega}{\frac{1}{2}\rho D H u_0{}^3} \qquad C_Q = \frac{T}{\frac{1}{4}\rho D^2 H u_0{}^2}$$

- Starting torque magnitude and range – for self-start

$$C_{QS} = \frac{T}{\frac{1}{4}\rho D^2 H u_0{}^2} \qquad T \ vs \ \theta$$

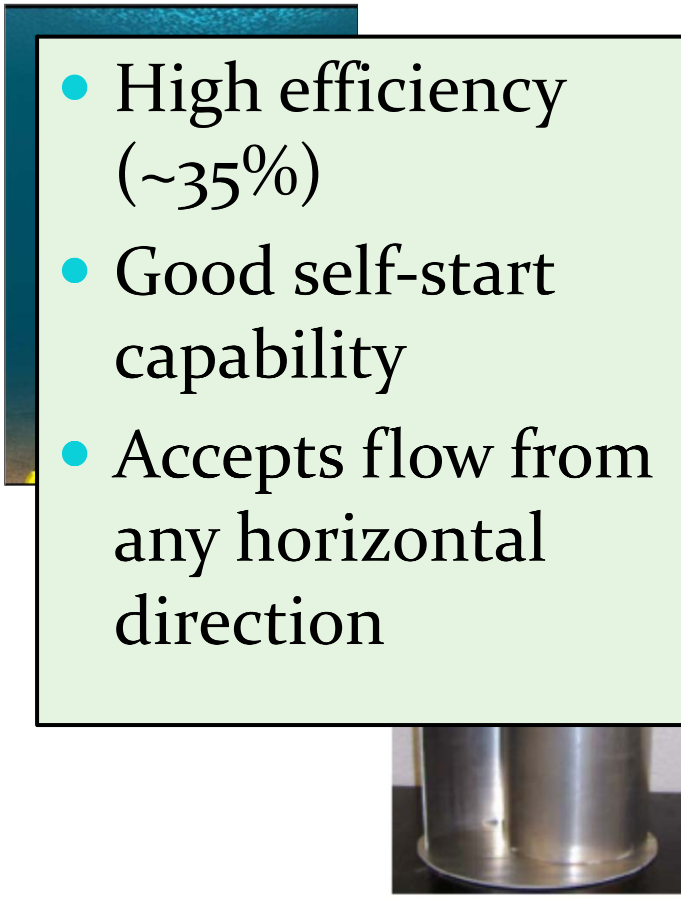
- Tip Speed Ratio and Rotation Rate – for generator integration

$$\lambda = \frac{\omega R}{u_0}$$

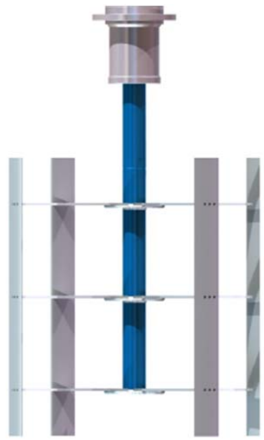
- Performance with respect to inflow orientation – for deployment flexibility

H: Height
D: Diameter
R: Radius
T: Torque
u_0: *Inflow velocity*
ρ: *Fluid density*
θ: *Azimuthal angle*
ω: *Angular velocity*

Turbine Design Concepts



- High efficiency (~35%)
- Good self-start capability
- Accepts flow from any horizontal direction



Darrieus Turbine

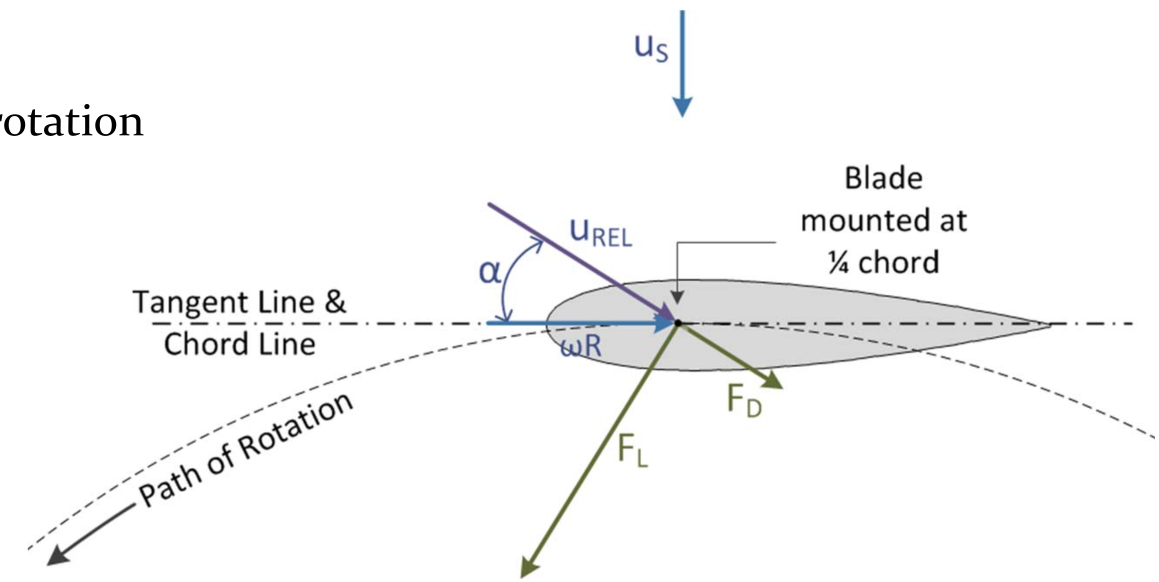
Hybrid Turbine

Helical Turbine

Sources: Polagye, 2011; engr.mun.ca/~tariq/jahangiralam.pdf; newenergycorp.ca;

Blade Element Theory

- Streamwise velocity (u_S)
- Tip velocity (ωR)
  - Induced by turbine's own rotation
- Relative velocity (u_{REL})
  - Resultant vector of u_S and ωR
- Angle of attack (α)
  - Angle between u_{REL} and chord line
- Lift - Drag Forces (F_L, F_D)
  - Generate turbine torque



$$C_L = \frac{F_L}{\frac{1}{2}\rho {u_{REL}}^2 A_P} = \frac{F_L}{\frac{1}{2}\rho {u_{REL}}^2 ch}$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho {u_{REL}}^2 A_P} = \frac{F_D}{\frac{1}{2}\rho {u_{REL}}^2 ch}$$

- Best lift-drag ratio when $-10 < \alpha < 10^\circ$

c: Blade length
h: Blade height
A_P: Planform area=ch

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Axial vs. Cross-Flow Turbines

Axial

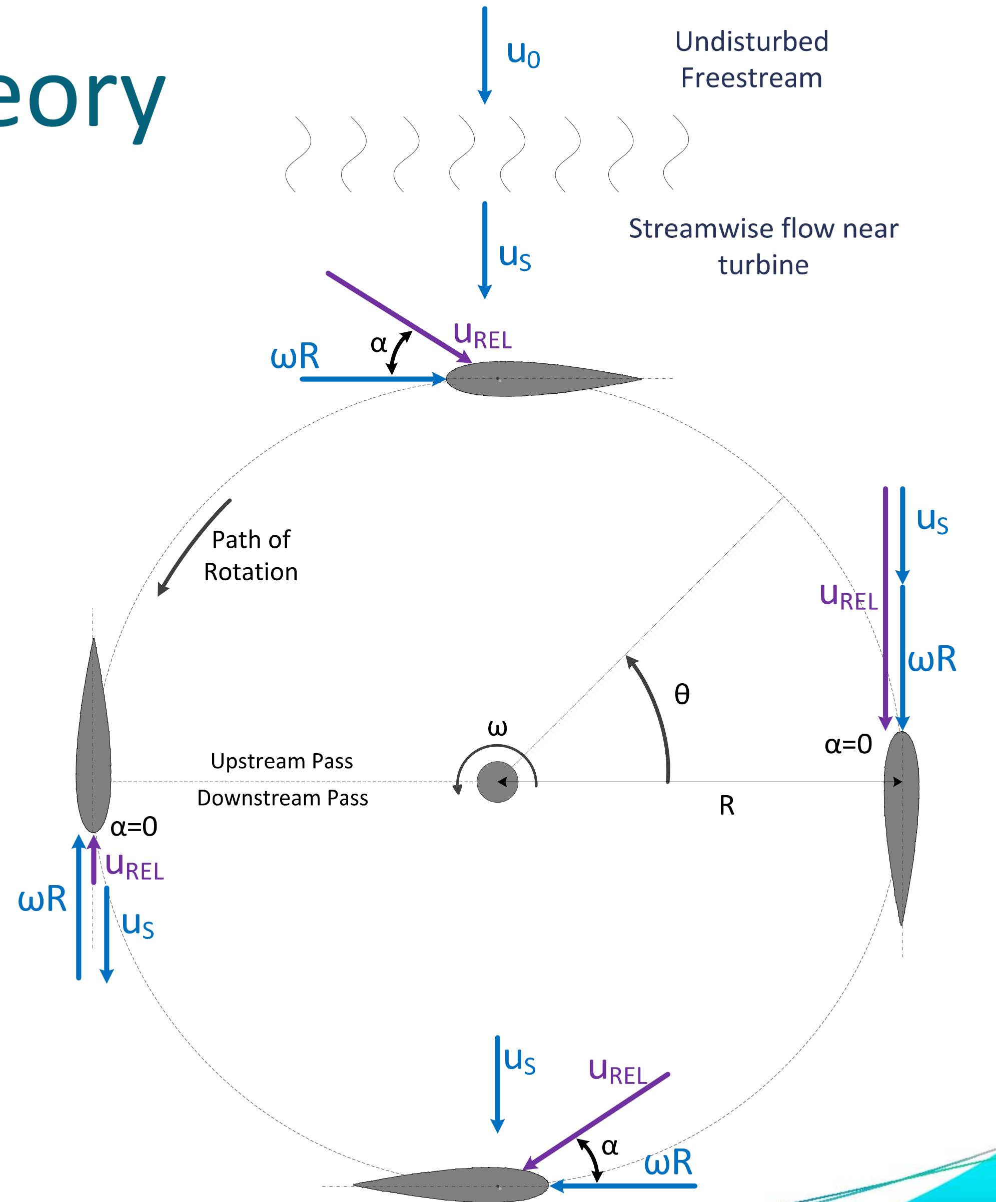
Tidal Flow is Parallel to Axis of Rotation

Cross-Flow

Tidal Flow is Perpendicular to Axis of Rotation

Blade Element Theory

- Angle of attack (α)
  - Constantly changing as turbine rotates
  - Often exceeds stall angle



Helical Turbine Parameters

- Blade Profile
- Blade Pitch
- Helical Pitch
- Aspect Ratio
- Solidity Ratio/ Chord-to-Radius Ratio
- Number of Blades
- Blade Wrap
- Attachment Design

Helical Turbine Parameters

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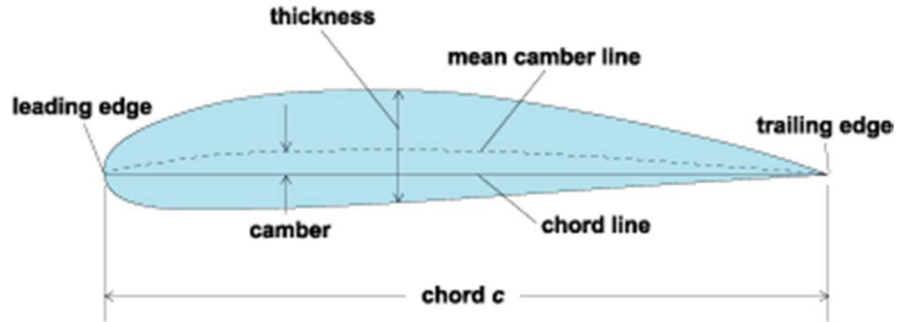

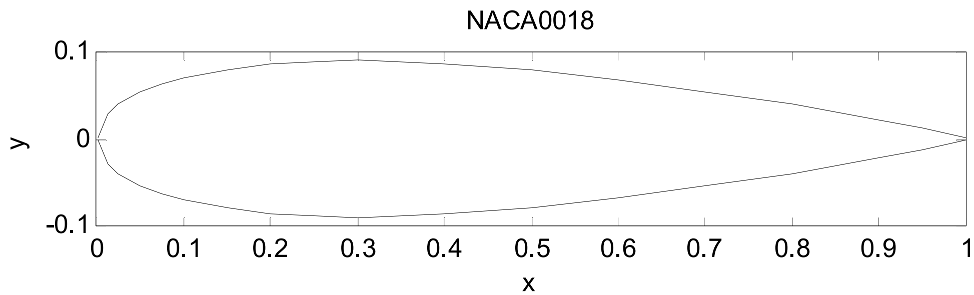

Source: answers.com

Helical Turbine Parameters

- Blade Profile
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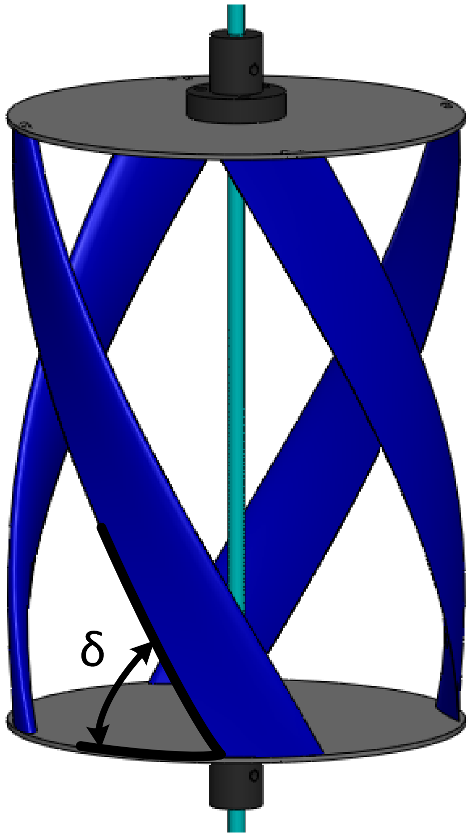
- Aspect Ratio
- Solidity Ratio/ Chord-to-Radius Ratio
- Number of Blades
- Attachment Design

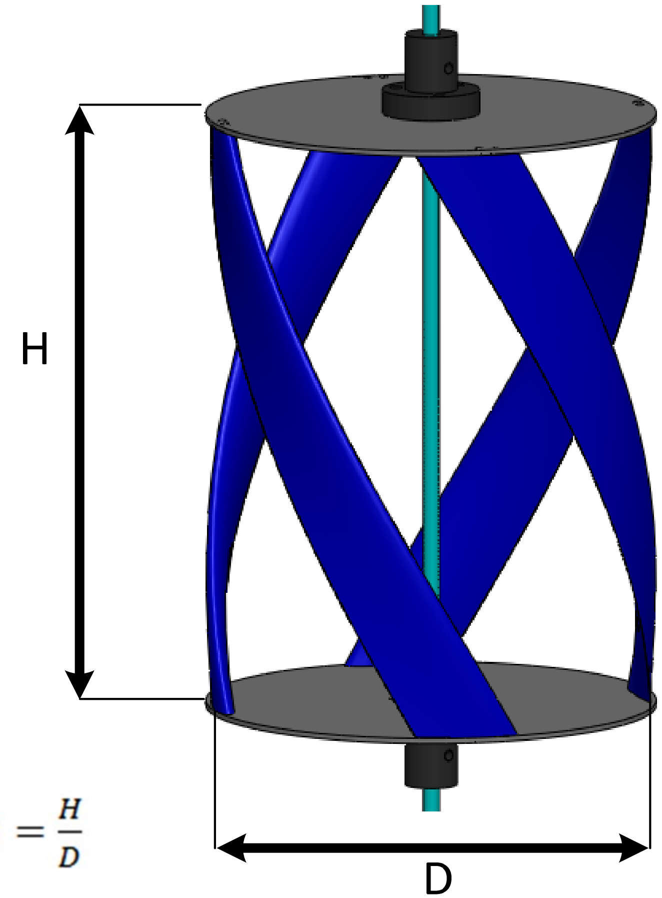


Helical Turbine Parameters

- Blade Profile
- Helical Pitch
- Aspect Ratio
- Solidity Ratio/ Chord-to-Radius Ratio
- Number of Blades
- Attachment Design

- Size limited by deployment constraints

$$AR = \frac{H}{D}$$



Helical Turbine Parameters

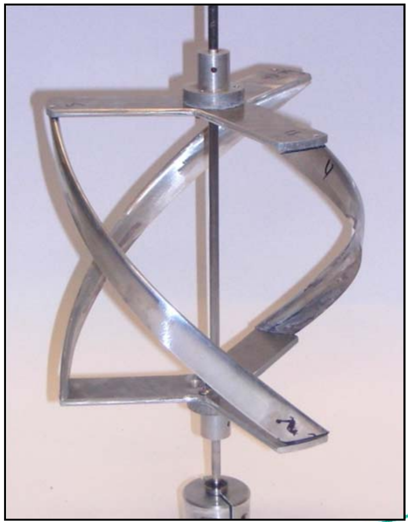
- Blade Profile
- Helical Pitch
- Aspect Ratio
- Solidity Ratio/ Chord-to-Radius Ratio
- Number of Blades (B)
- Attachment Design

$$\sigma = \frac{Bc}{\pi D}$$

$$\sigma_{C-R} = \frac{c}{R}$$

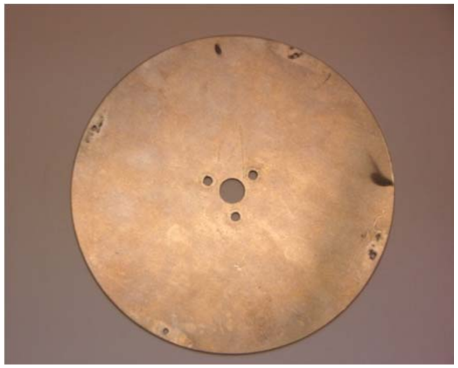
30% Solidity

15% Solidity



Helical Turbine Parameters

- Blade Profile
- Helical Pitch
- Aspect Ratio
- Solidity Ratio/ Chord-to-Radius Ratio
- Number of Blades
- Attachment Design



Parameter Optimization

Higher efficiency, Improved C_P, Manufacturability	**Helical Pitch**	Lower static torque variation
Improved C_P, Allows higher pitch	**Aspect Ratio**	Easier Deployment, Less blade stress, Less vibration
Better starting torque, Manufacturability	**Solidity Ratio**	Higher tip speed ratio
Allows increase in pitch and reduced aspect ratio	**Number of Blades**	Fewer parts, Less blade wake interference

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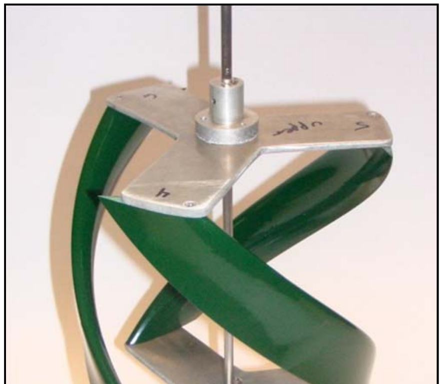
Turbine Prototypes

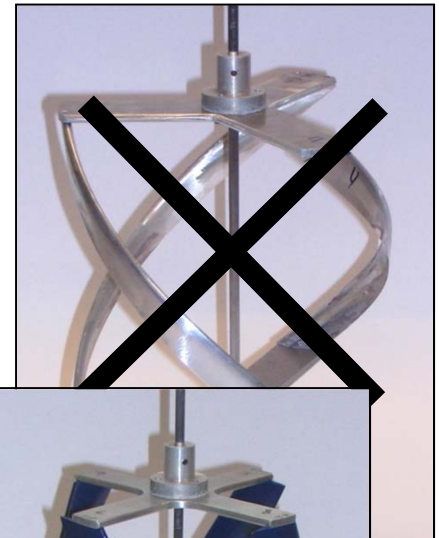
Baseline Configuration

3-Bladed Turbine

4-Bladed Turbine

Low Solidity Turbine



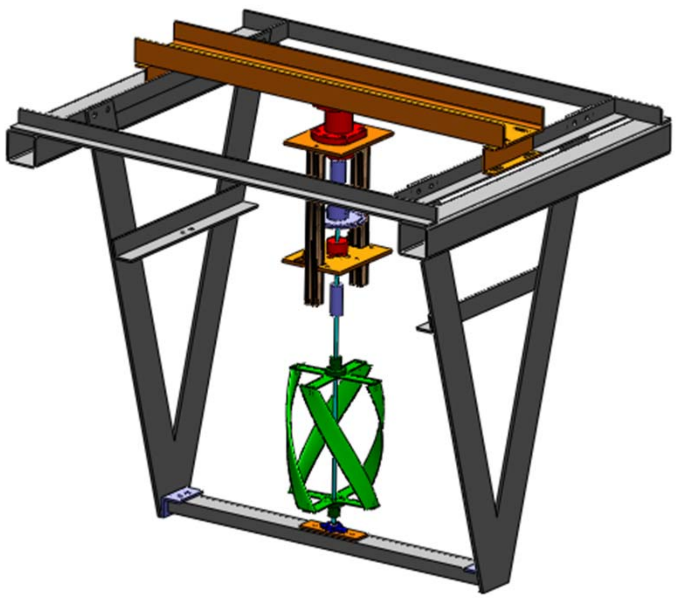


atio

Angle

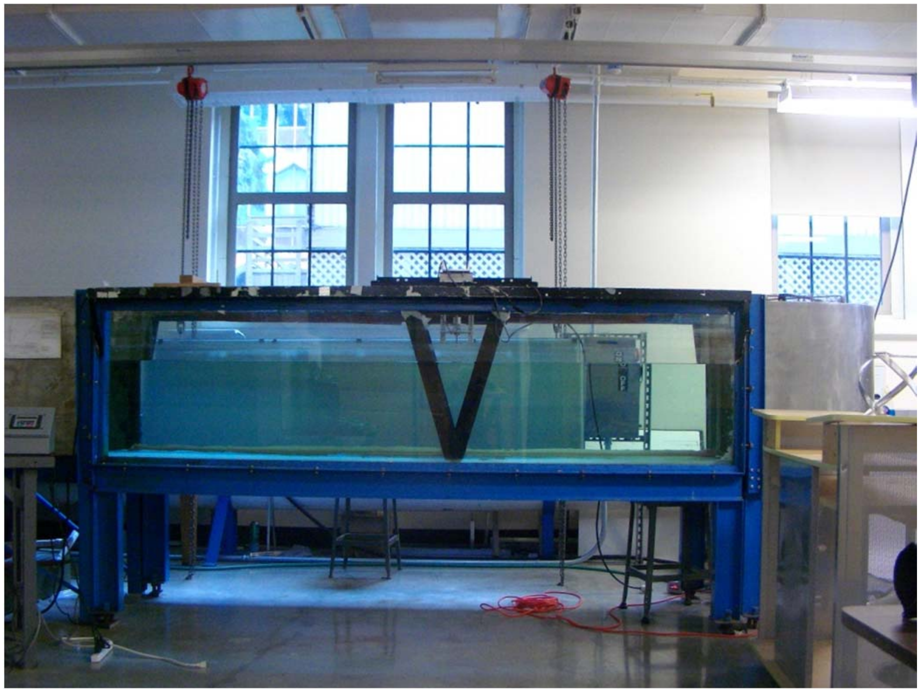
Tests Performed

- Baseline Configuration
  - Load Performance Test
  - Static Torque Test
  - Tilted Turbine Test
- Design Comparison Tests
  - Helical Pitch/No. of Blades
  - Strut Attachment Design
  - Shaft Design

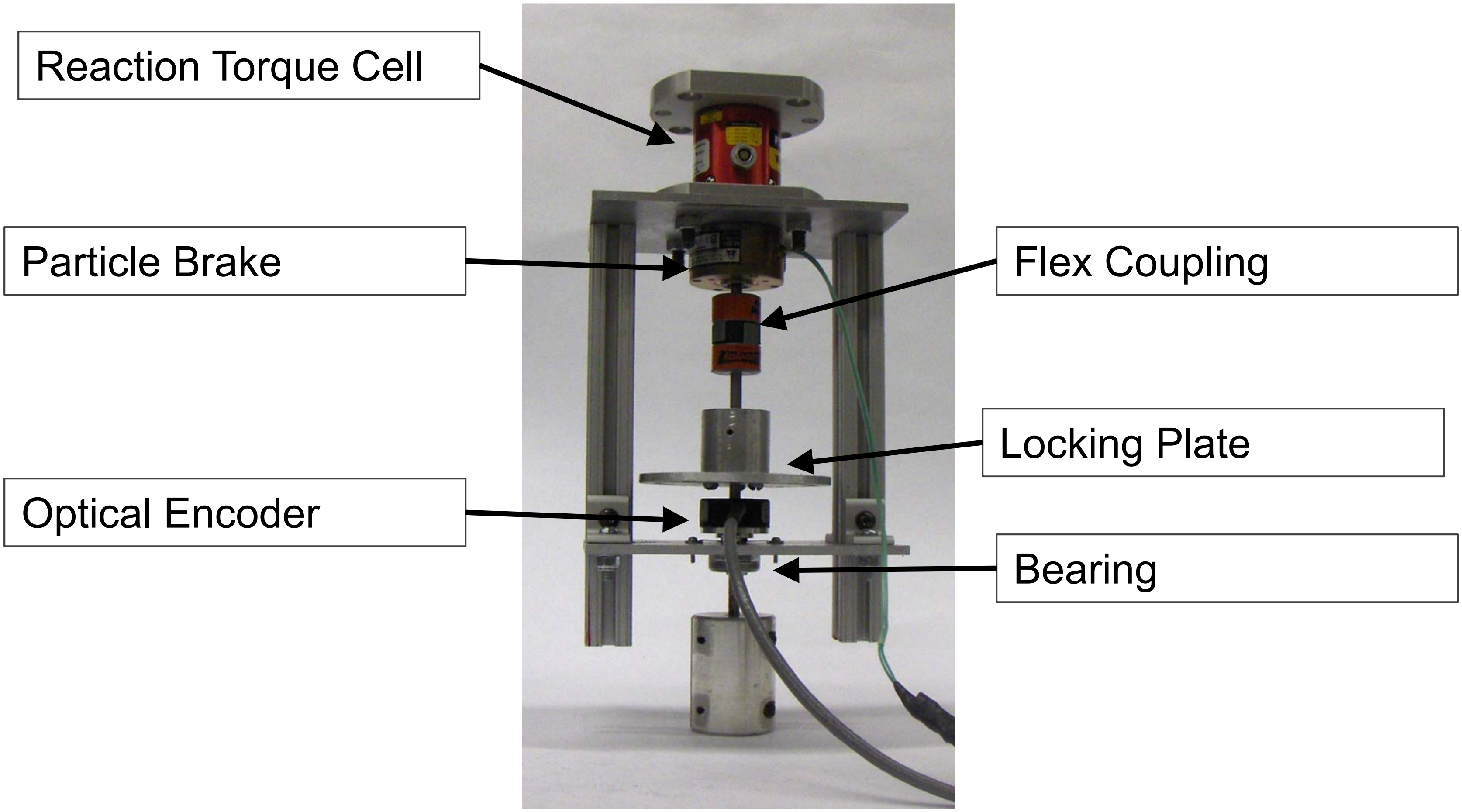


Flume Test Channel

- 3 meters length
- 72 cm wide
- Maximum 0.8 m/s flow rate
- Turbine located in center of flume width at 1.7 m from test channel inlet
- Acoustic Doppler Velocimeter (ADV) - to measure flume velocity



Test Instrumentation Module



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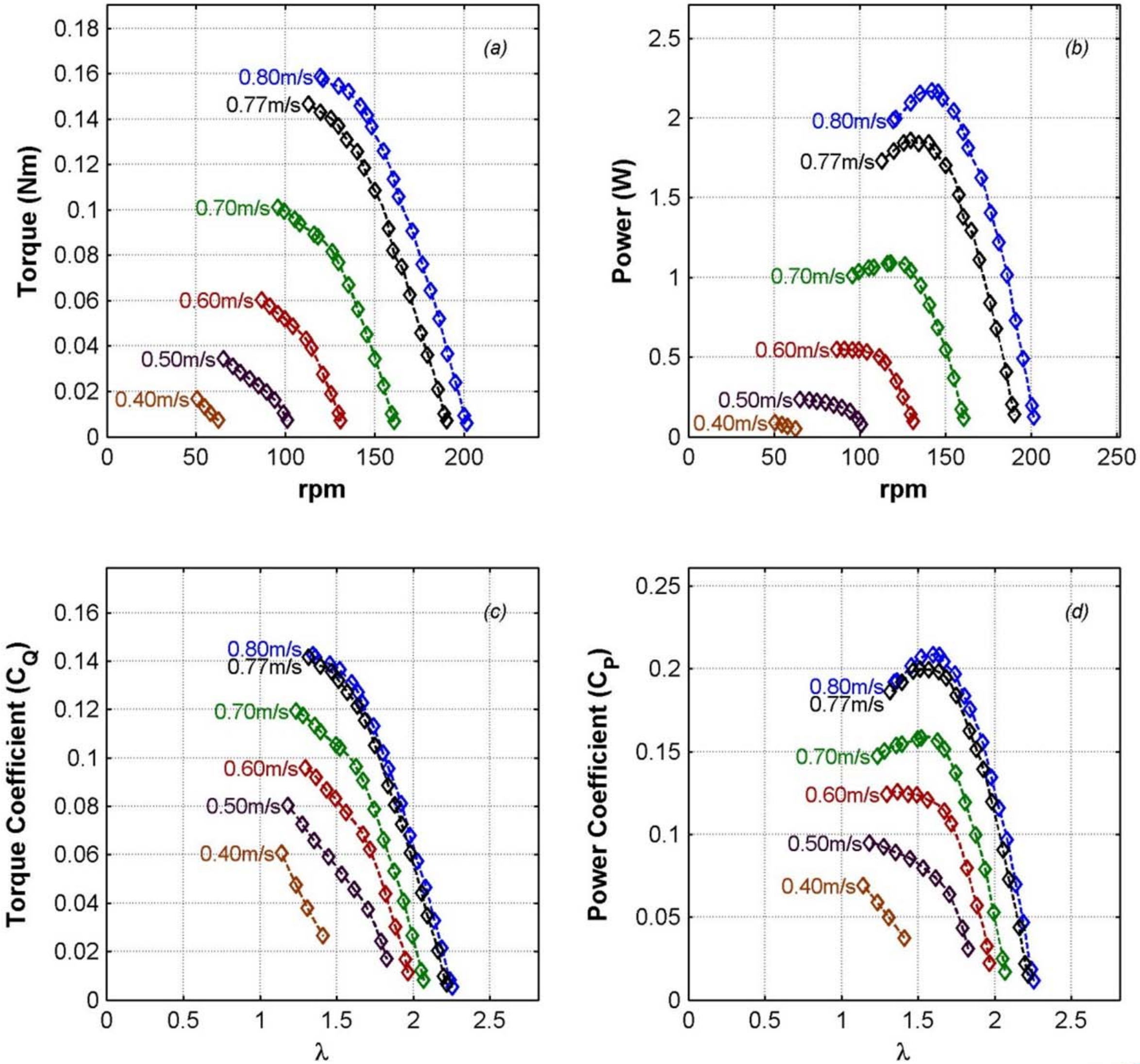
Turbine Operation

Load Performance Results

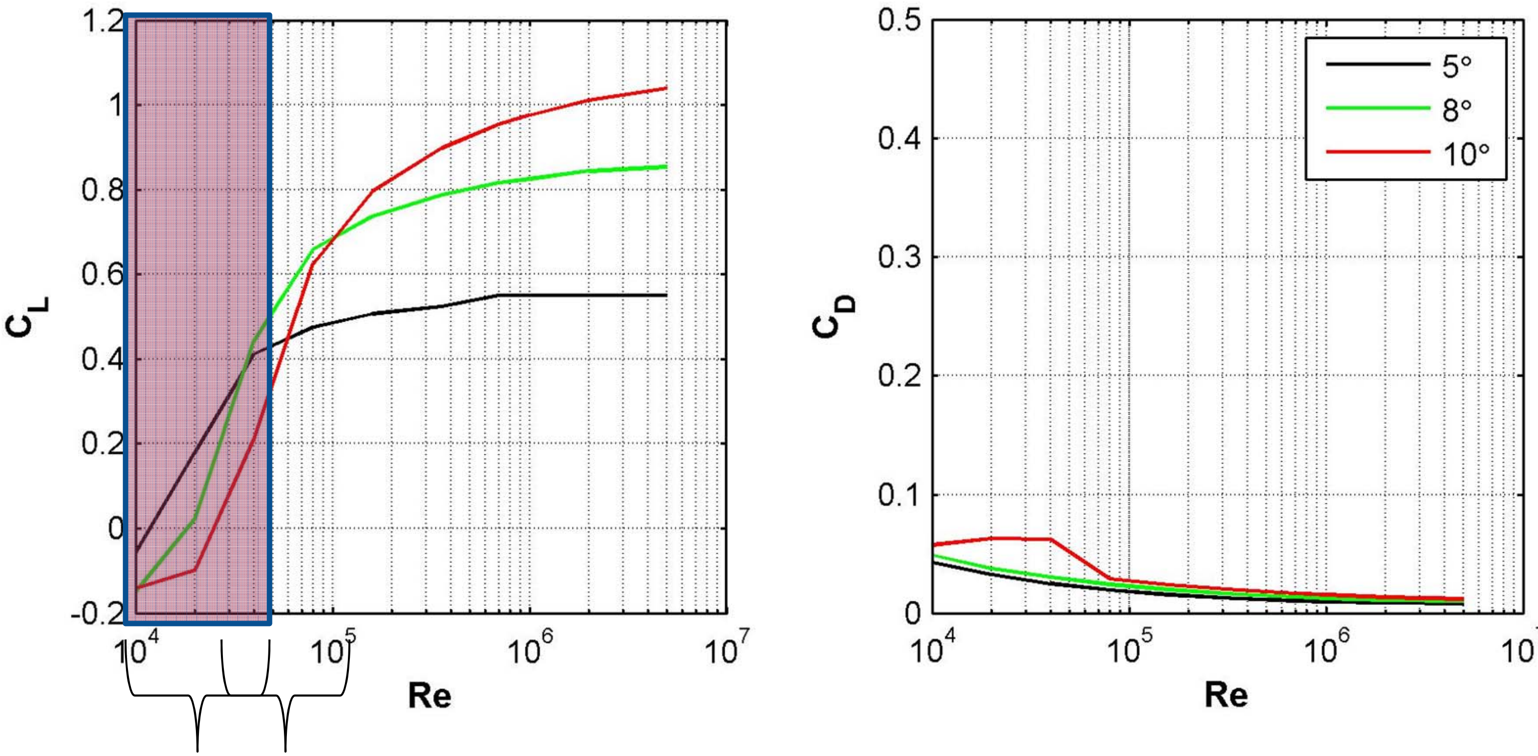
- Baseline Configuration

$$C_Q = \frac{T}{\frac{1}{4}\rho D^2 H u_0^{\,2}}$$

$$C_P = \frac{T\omega}{\frac{1}{2}\rho D H u_0^{\,3}} \qquad \lambda = \frac{\omega R}{u_0}$$



Lift and Drag for different α



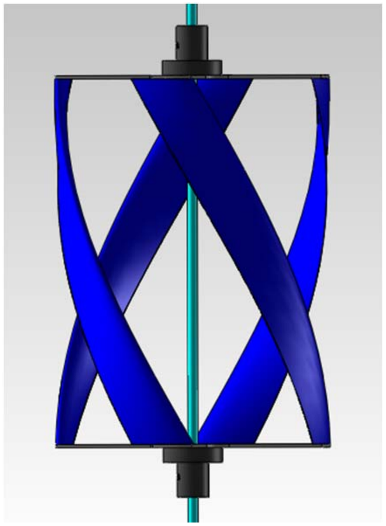
Region of Turbine Operation at 0.4-0.8 m/s

Region of increasing λ decreases average α

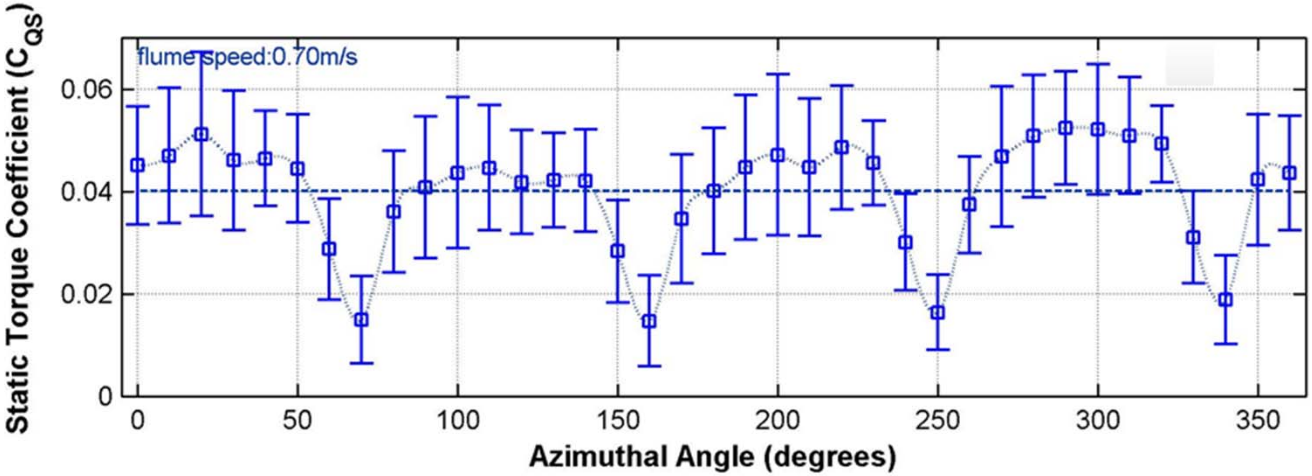
$$Re = \frac{u_{REL}c}{\upsilon}$$

Static Torque

- Baseline Configuration
- Flume: 0.7 m/s



0° view,
looking downstream

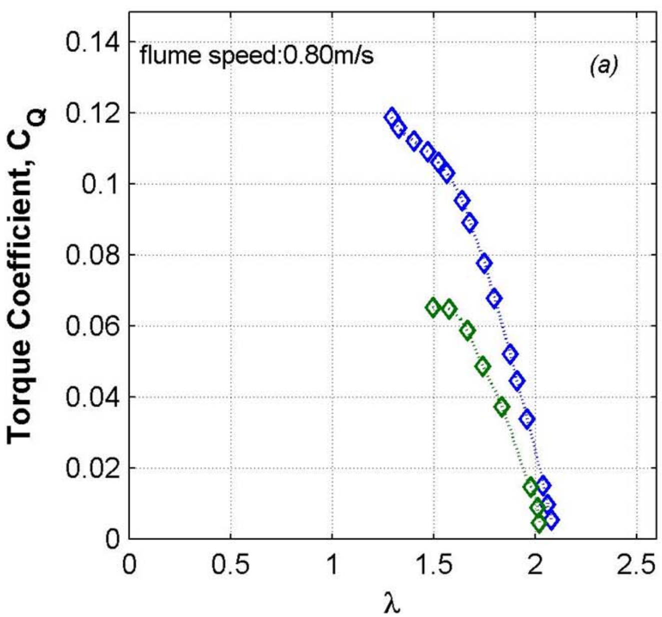


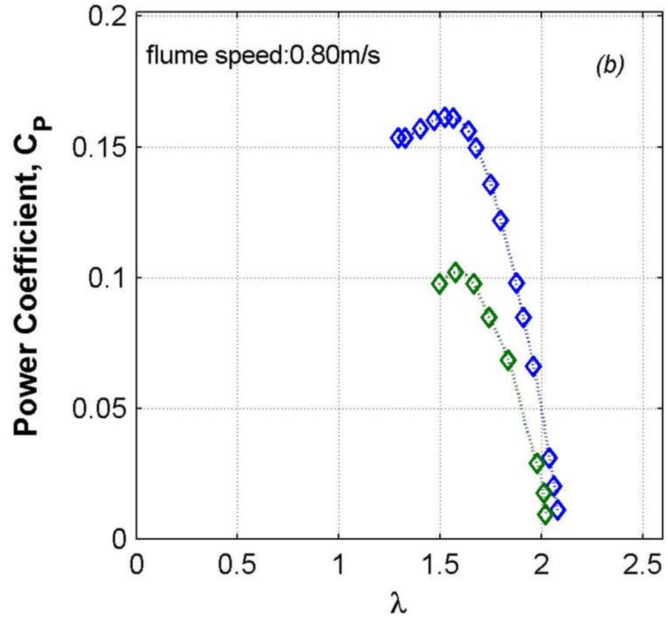
Turbine Design Comparison

Load Performance Test Results

3-Bladed Turbine

4-Bladed Turbine



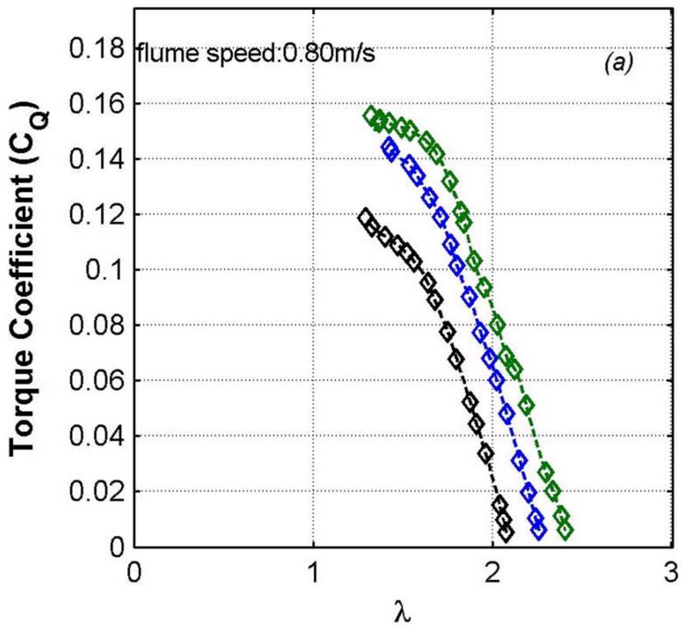


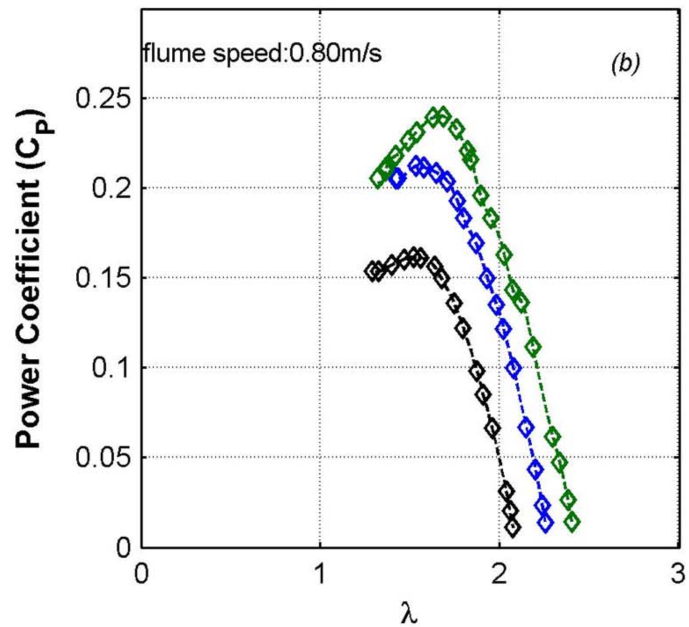
Strut Design Comparison

2 mm Spoke

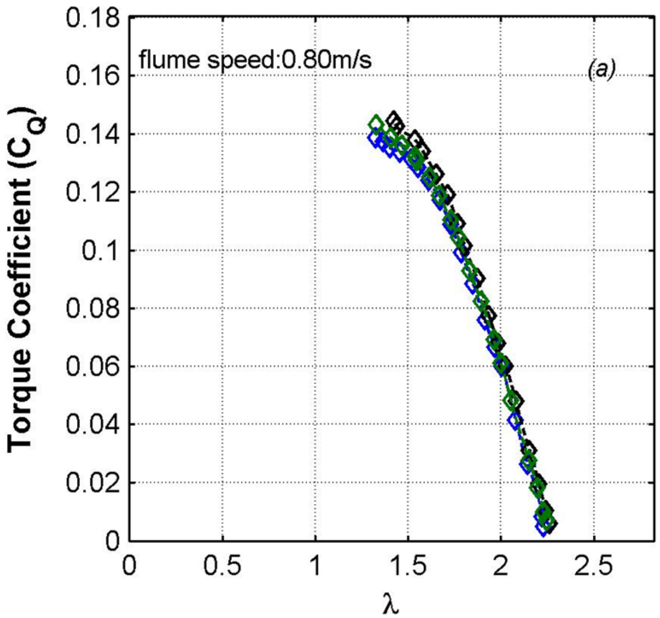
4.8 mm Spoke

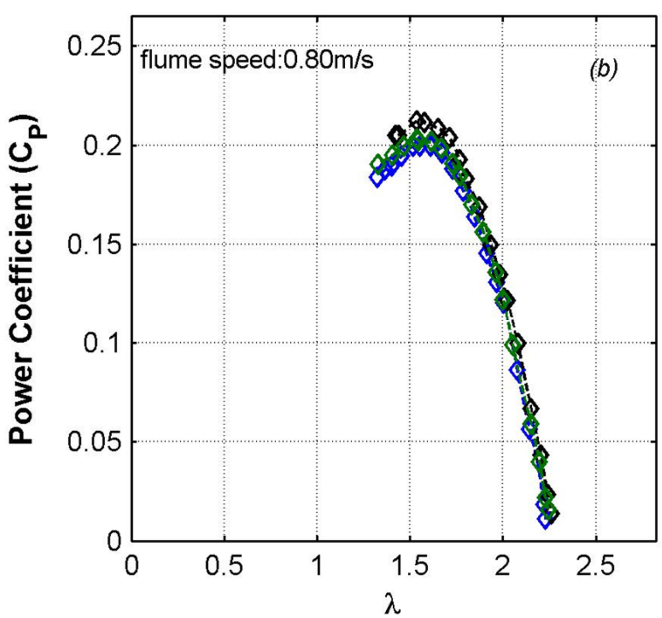
Circular Plate





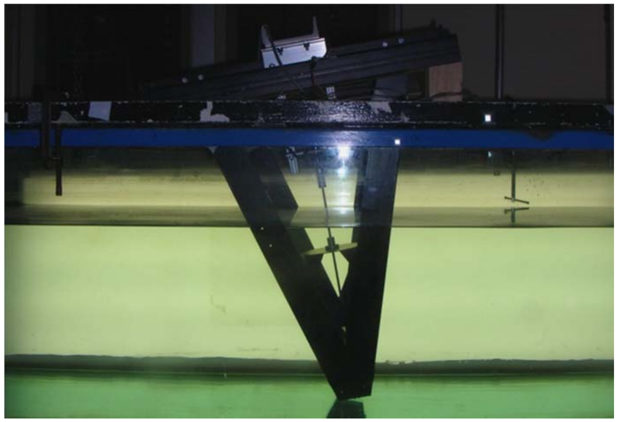
Shaft Diameter Comparison

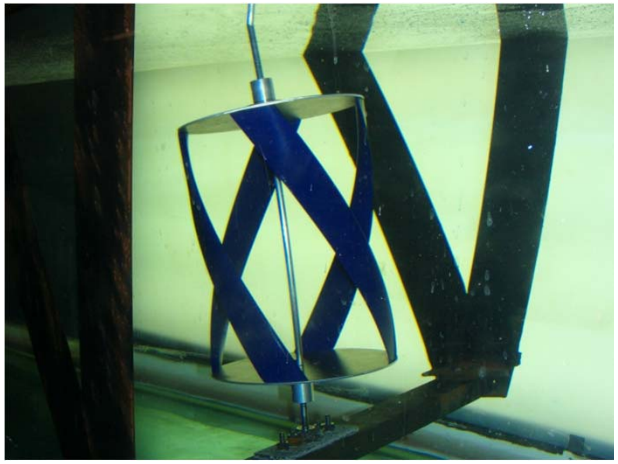




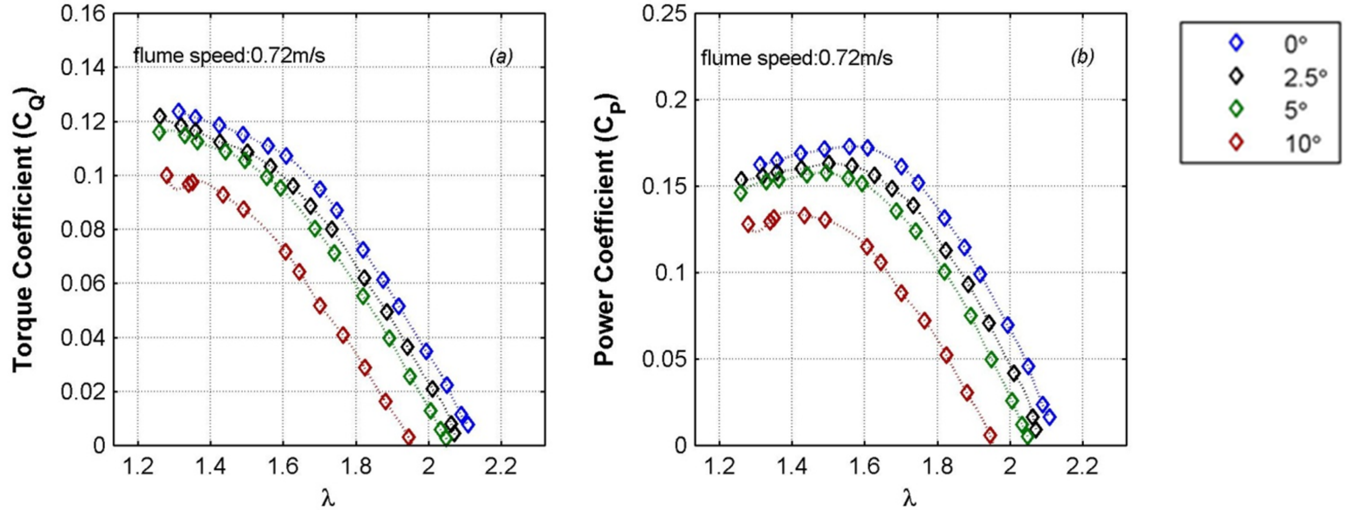
Tilted Turbine Test

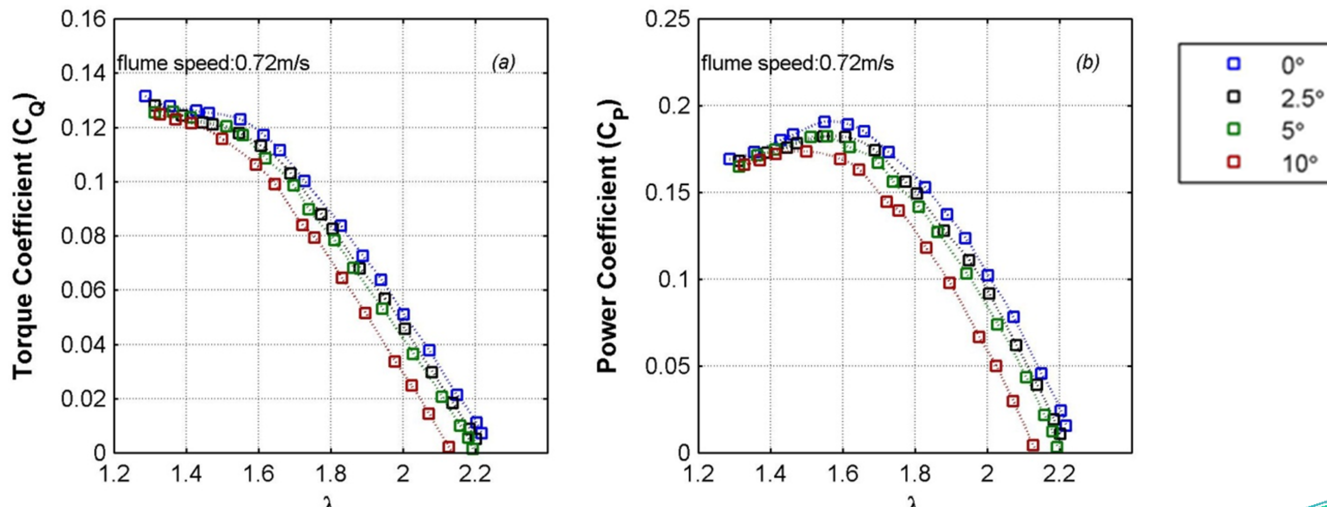
- Downstream end of turbine frame inclined
  - 0, 2.5, 5 and 10 degree inclinations
  - Performance test
  - Baseline spoke design and circular plate configurations





Tilted Turbine Test





Test Conclusions

- **Four-bladed turbine** is best design for optimum aspect ratio and performance
- **Good self-start** and performance with **high solidity**
- **Maximize helical pitch angle** to get better max C_P
- **No impact of shaft diameter** on performance
- **Circular plate** – best attachment design - eliminates profile drag, better tilt angle performance
- **Static torque is not uniform**
- **Higher inflow velocity** gives better C_P

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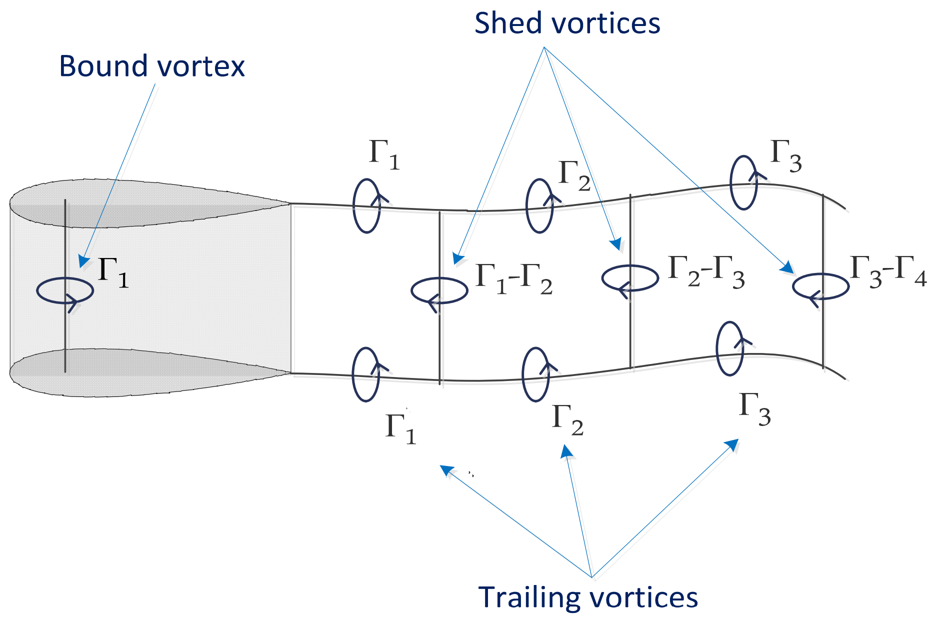
Vortex Model

- Free-vortex flow model
- Blade divided into several elements
- Blade element performance from C_L,C_D lookup tables
- Blades elements simulated as vortex generators
- Sum of velocity components gives u_{REL}



$$\Gamma = \int_A (\nabla \times \vec{u}) \cdot d\vec{A}$$

$$\vec{u}_{REL_i} = \vec{u}_{0_i} + \overrightarrow{\omega \mathrm{R}}_i + \sum_j \left(\vec{u}_{B\,i,j} + \vec{u}_{T\,i,j} + \vec{u}_{SHED\,i,j} \right)$$

Vortex Model

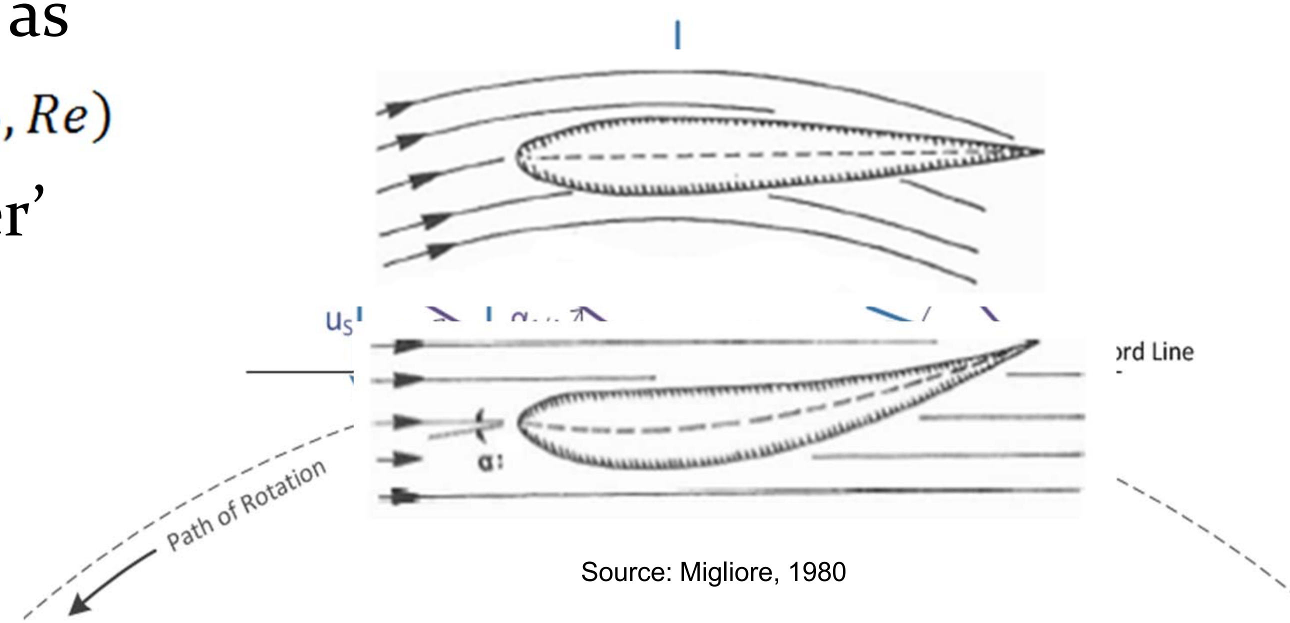
- Comparison to other model types -
  - Less computational time than CFD (days vs. minutes)
  - Compared to momentum models, the vortex model:
    - Can resolve helical geometry without yaw correction factors
    - Better resolves the wake
- Model Modifications
  - Helical geometry
  - Strut drag for circular plate and end spokes
  - Flow curvature effects
- Higher $\sigma_{C\text{-}R}$ than previously modeled

Flow Curvature

- Change in α from leading edge to trailing edge
- Important for high chord-to-radius ratio turbines
- Approximated as

$$C_L = f(\alpha + \alpha_C, Re)$$

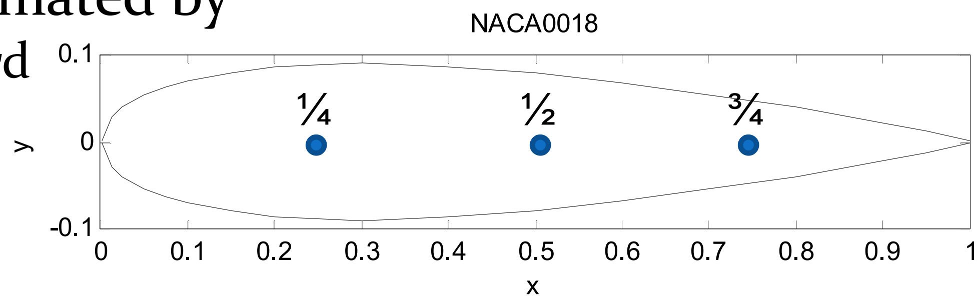
- 'Virtual camber'



Source: Migliore, 1980

Pitching and Dynamic Stall

- Lift, drag affected by pitch rate
  - $C_{L,D} = f(\alpha, Re)$ ‣ $C_{L,D} = f(\alpha, \dot{\alpha}, Re)$
  - 'Virtual incidence' – Approximated by
    - C_L calculated from α at ¾-chord
    - C_D calculated at α at ½-chord
    - Biases α positive

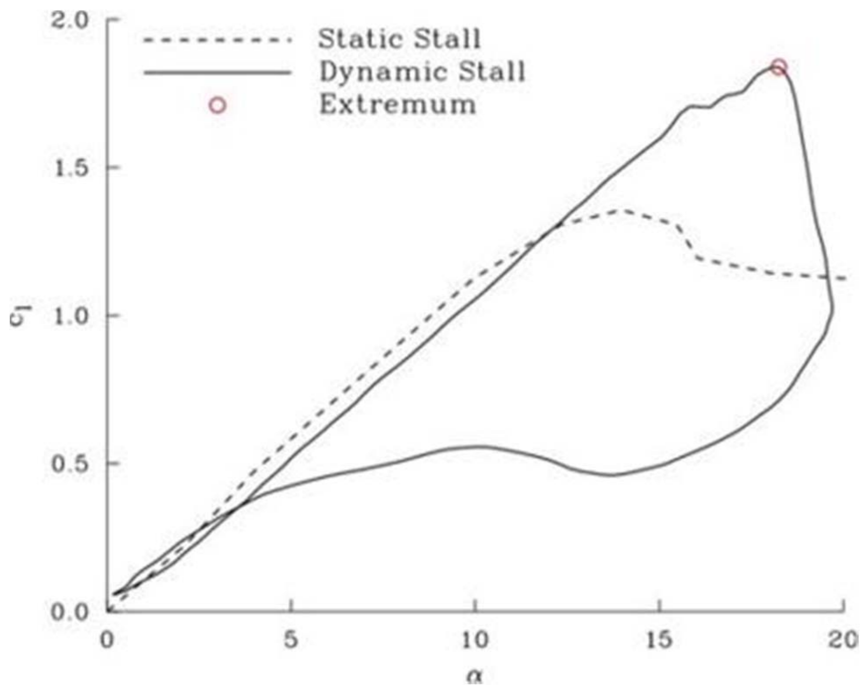


- Dynamic stall
  - Vortex forms at the leading edge of hydrofoil and tracks back along the chord
  - Lift is increased during tracking
  - Lift drops as vortex fully sheds

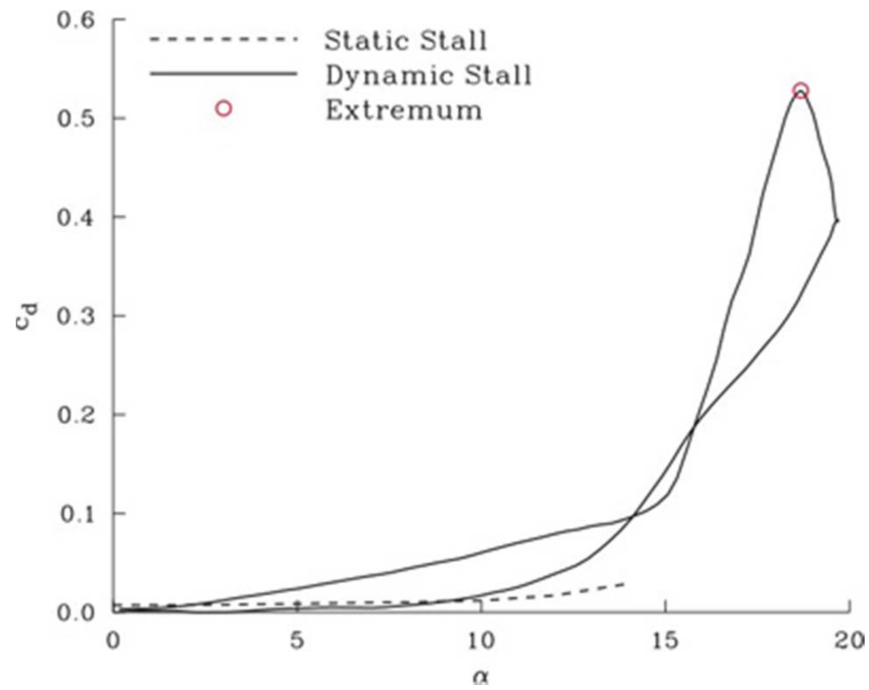
Source: Ekaterinaris & Platzer, 1997

Dynamic Stall

Lift

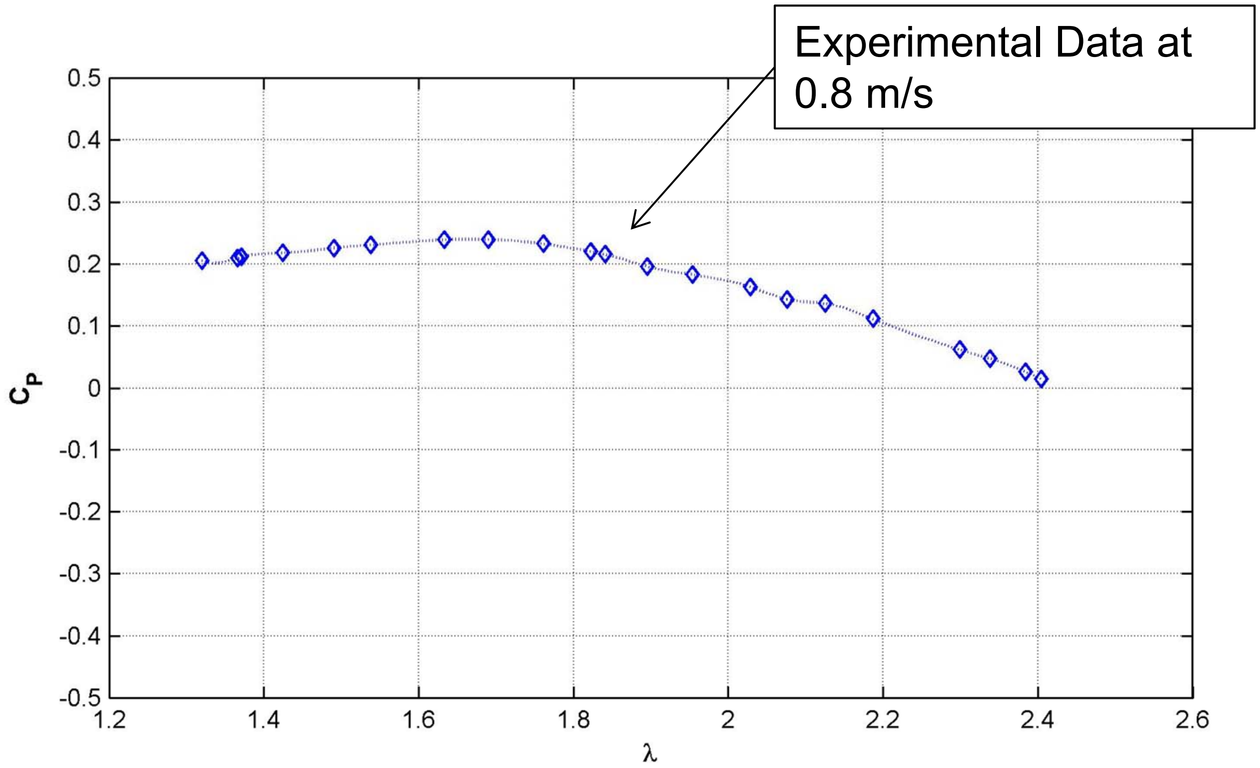


Drag



Source: NASA, 2009

Implementation of Secondary Effects



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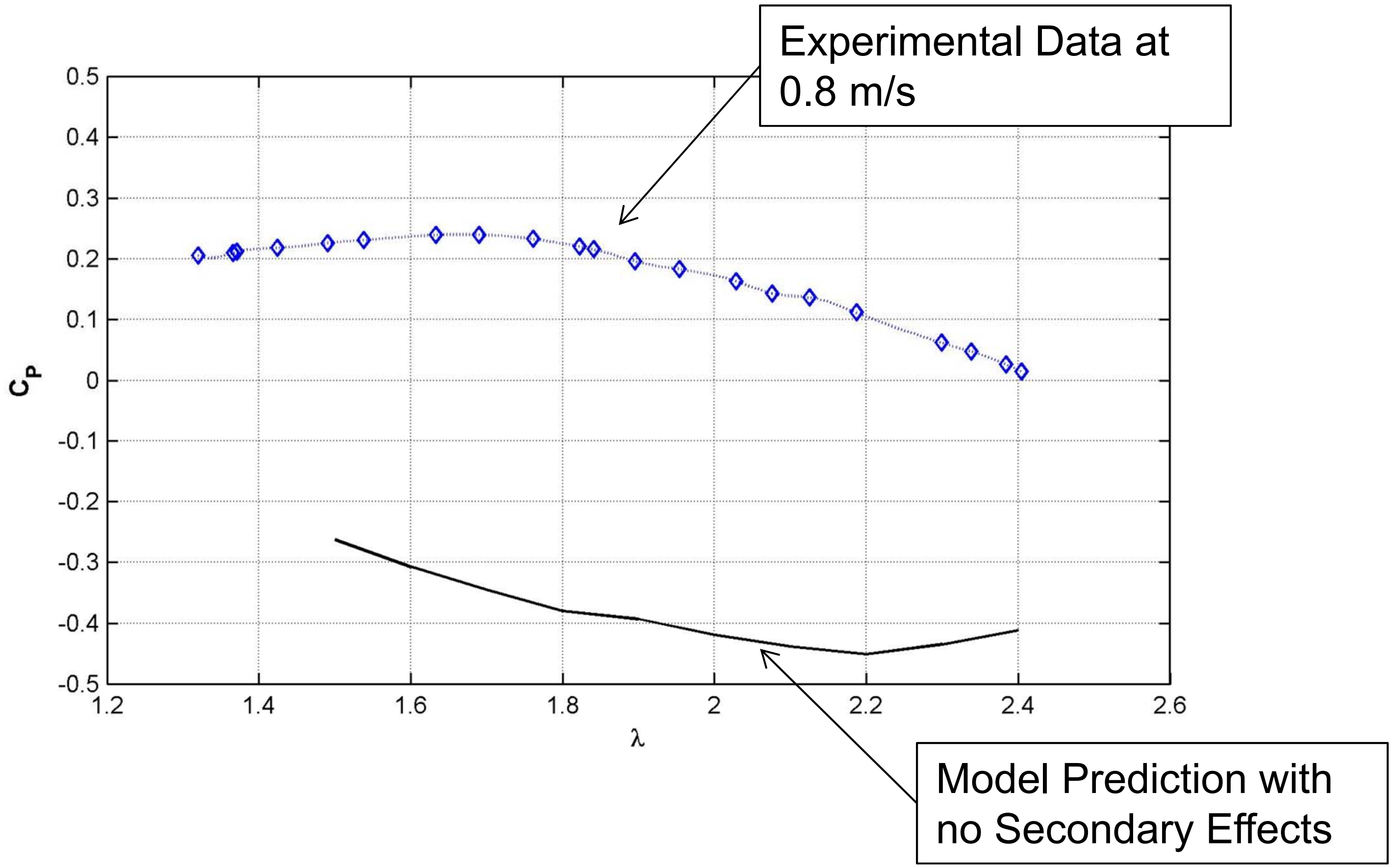
Implementation of Secondary Effects



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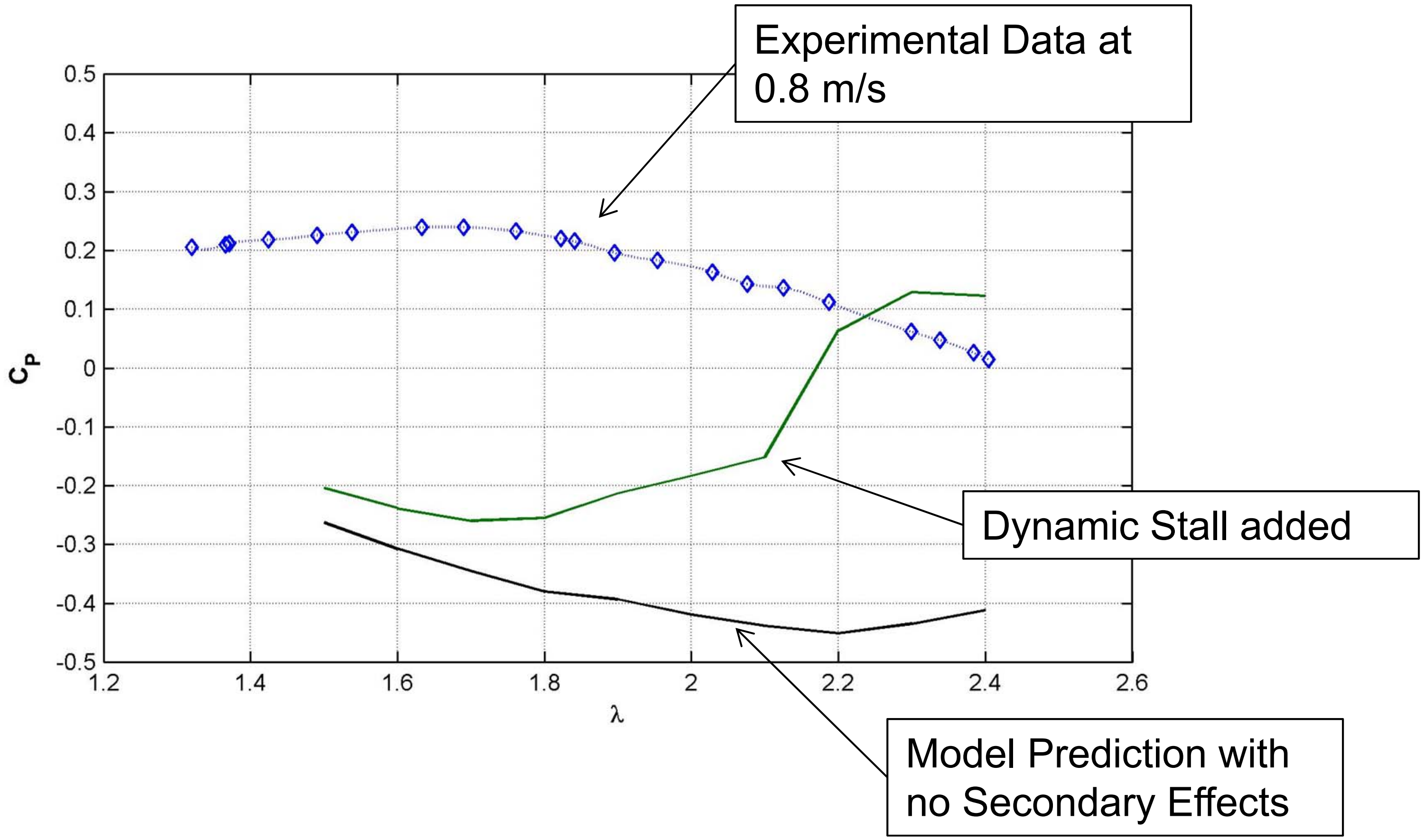
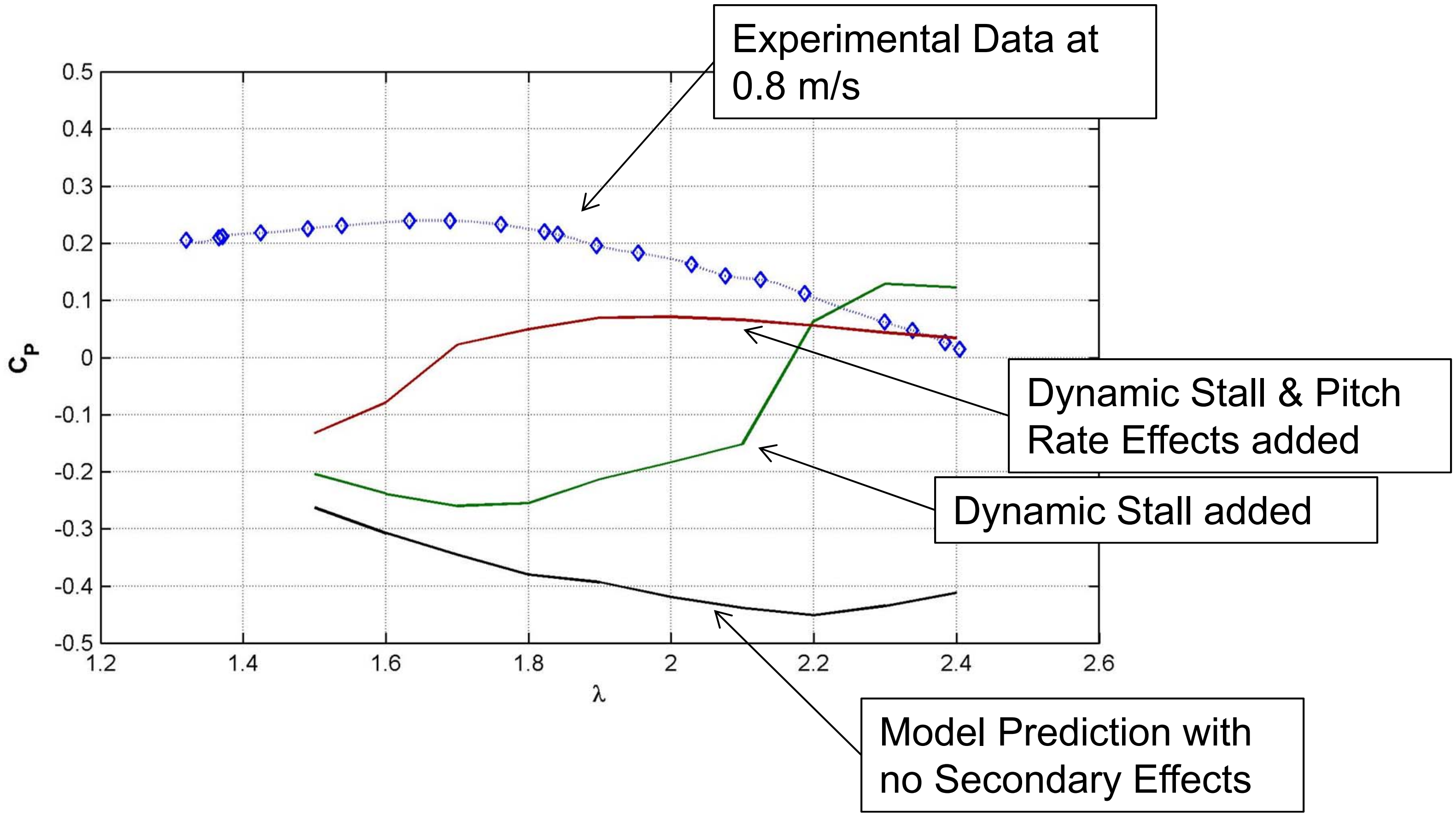


Implementation of Secondary Effects



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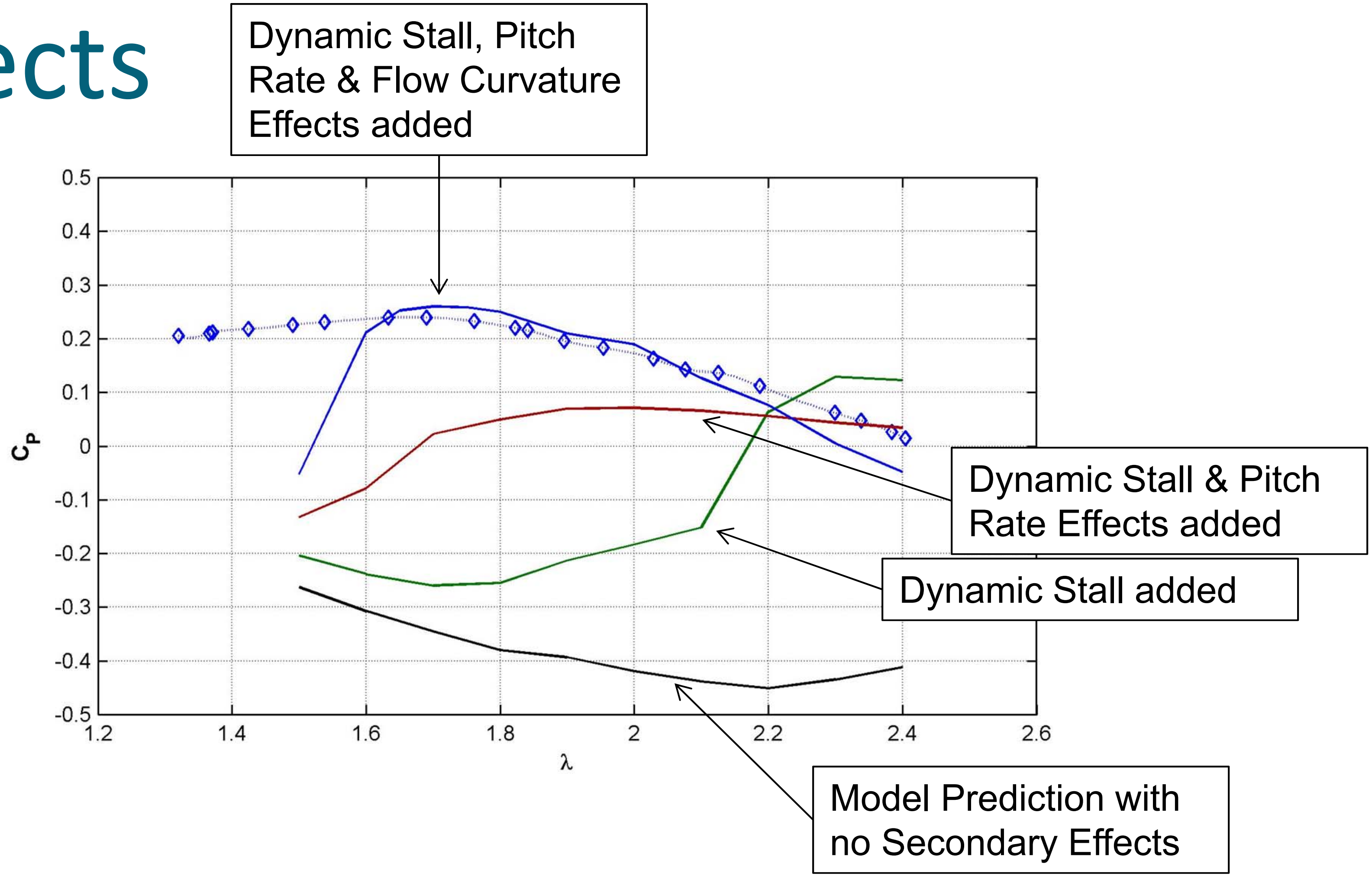
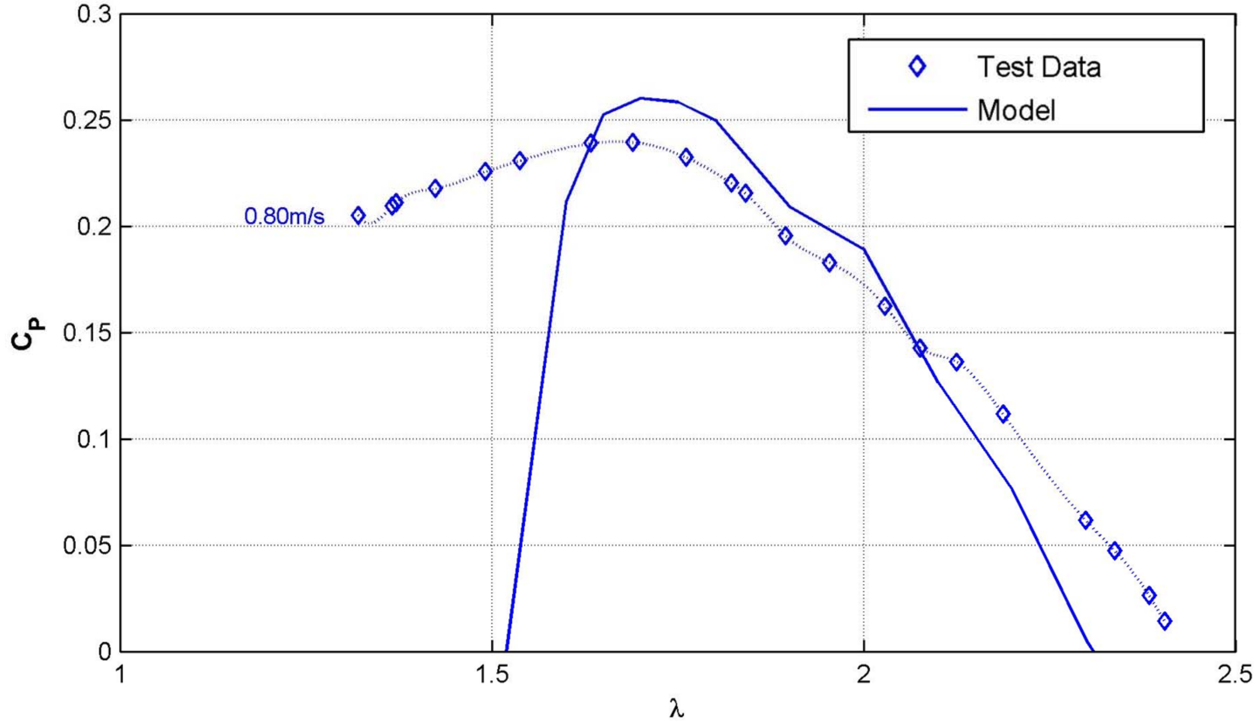
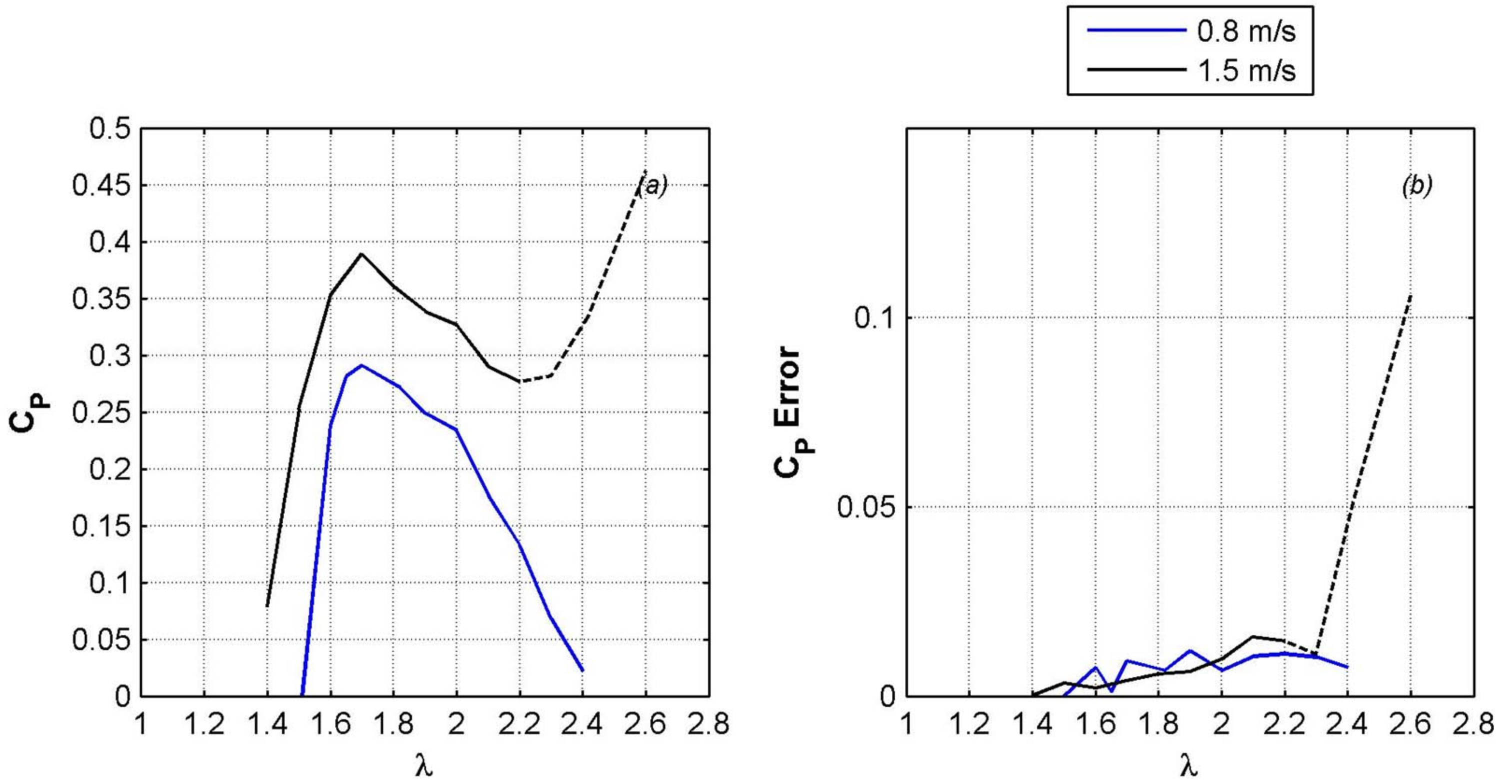


Model Prediction of Inflow Variation



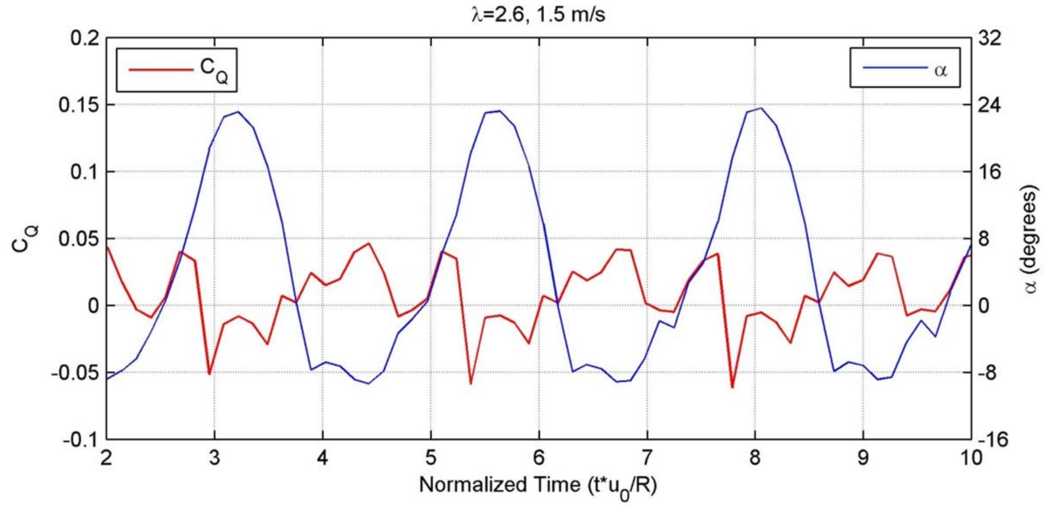
Extrapolation to 1.5 m/s



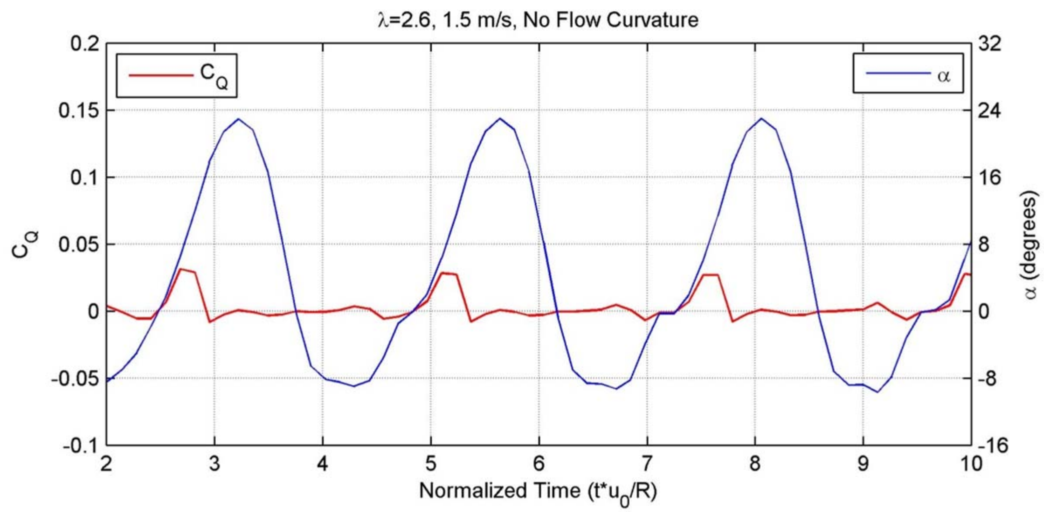
$$C_{P_{ERROR}} = max\left(C_{P_{(N-4):N}}\right) - min\left(C_{P_{(N-4):N}}\right)$$

Analysis of High Tip Speed Ratio

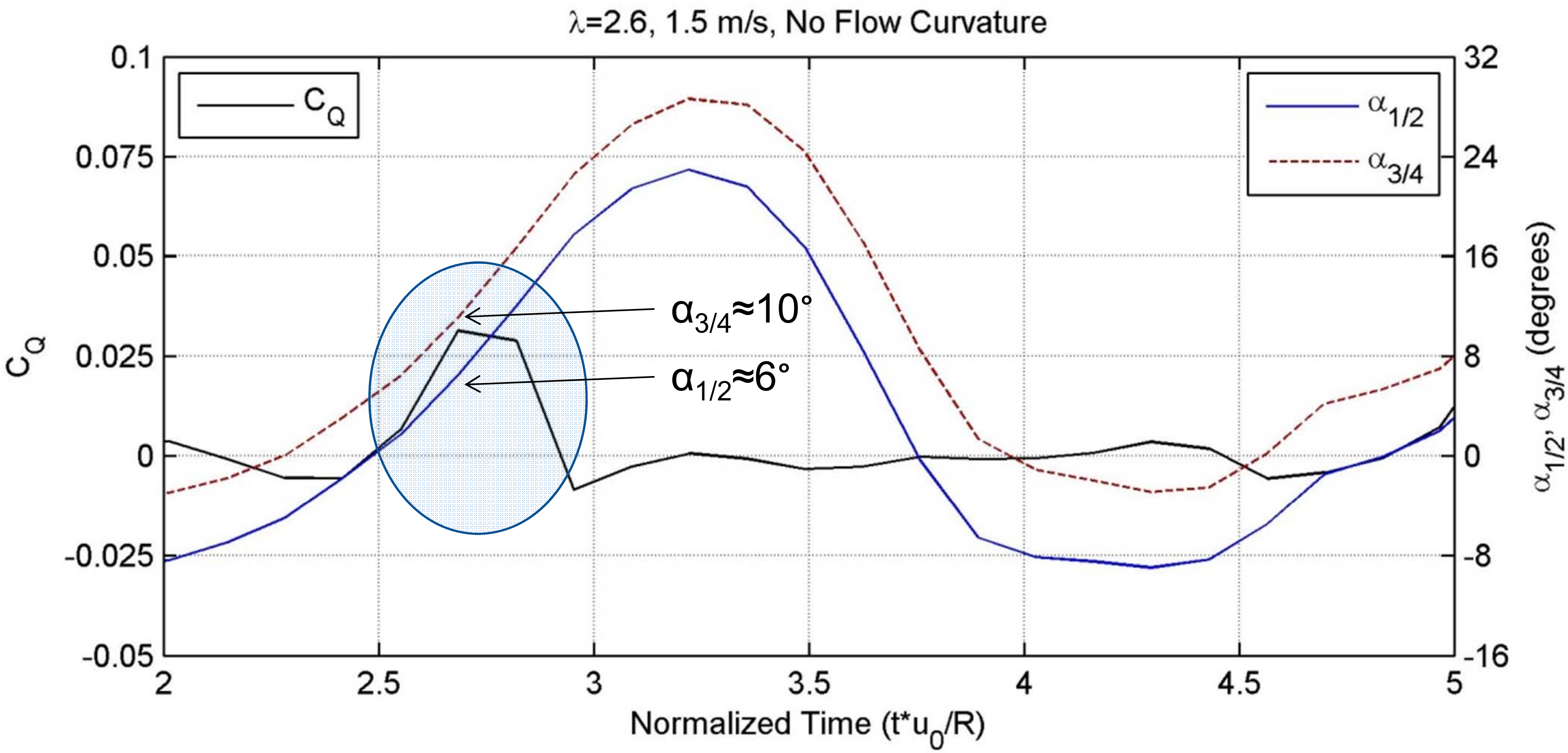
Flow curvature active
C_P=0.46



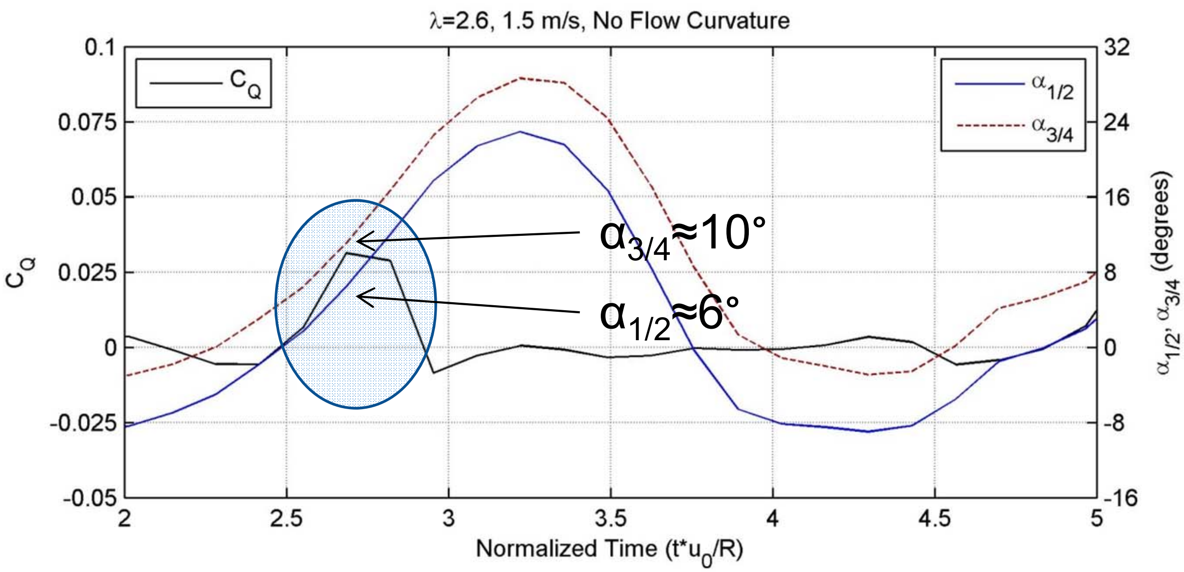
Flow curvature disabled
C_P=0.43

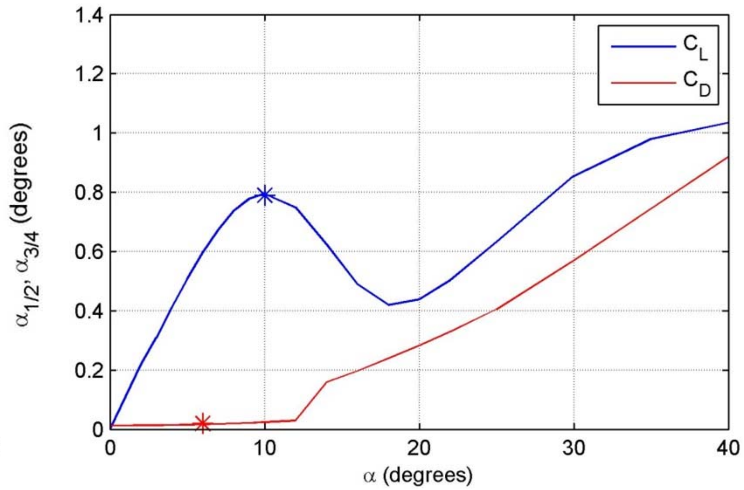


Analysis of High Tip Speed Ratio



Analysis of High Tip Speed Ratio





Due to high chord-to-radius ratio:

- Flow curvature adds instability to model output
- Pitch rate effects and dynamic stall over-amplifying performance
  - This effect has been documented in previous literature (Dai *et al.*, 2011), (Cardona, 1984)

Project Conclusions

- Demonstrated need for and viability of a tidal micropower system
- Designed a turbine for a micropower system
  - 24% efficient at 0.8 m/s (and increasing with flume speed)
  - Good self-start and flow orientation capabilities
  - Optimized select helical turbine design parameters
- Modified a vortex model to accept helical turbine design
  - Demonstrated importance of secondary effects
  - Demonstrated general trends in performance
  - Need for further study of secondary effects for high chord-to-radius ratio turbines

Future Work

- Testing of the full-scale turbine
- Design of system drive train and control
  - Turbine-Generator matching
  - Selection of battery type
- Improving turbine efficiency
- Improved turbine modeling
  - Examination and refinement of secondary effects
  - Other model types (CFD, etc.)

Acknowledgements

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- Dr. Jim Thomson & APL
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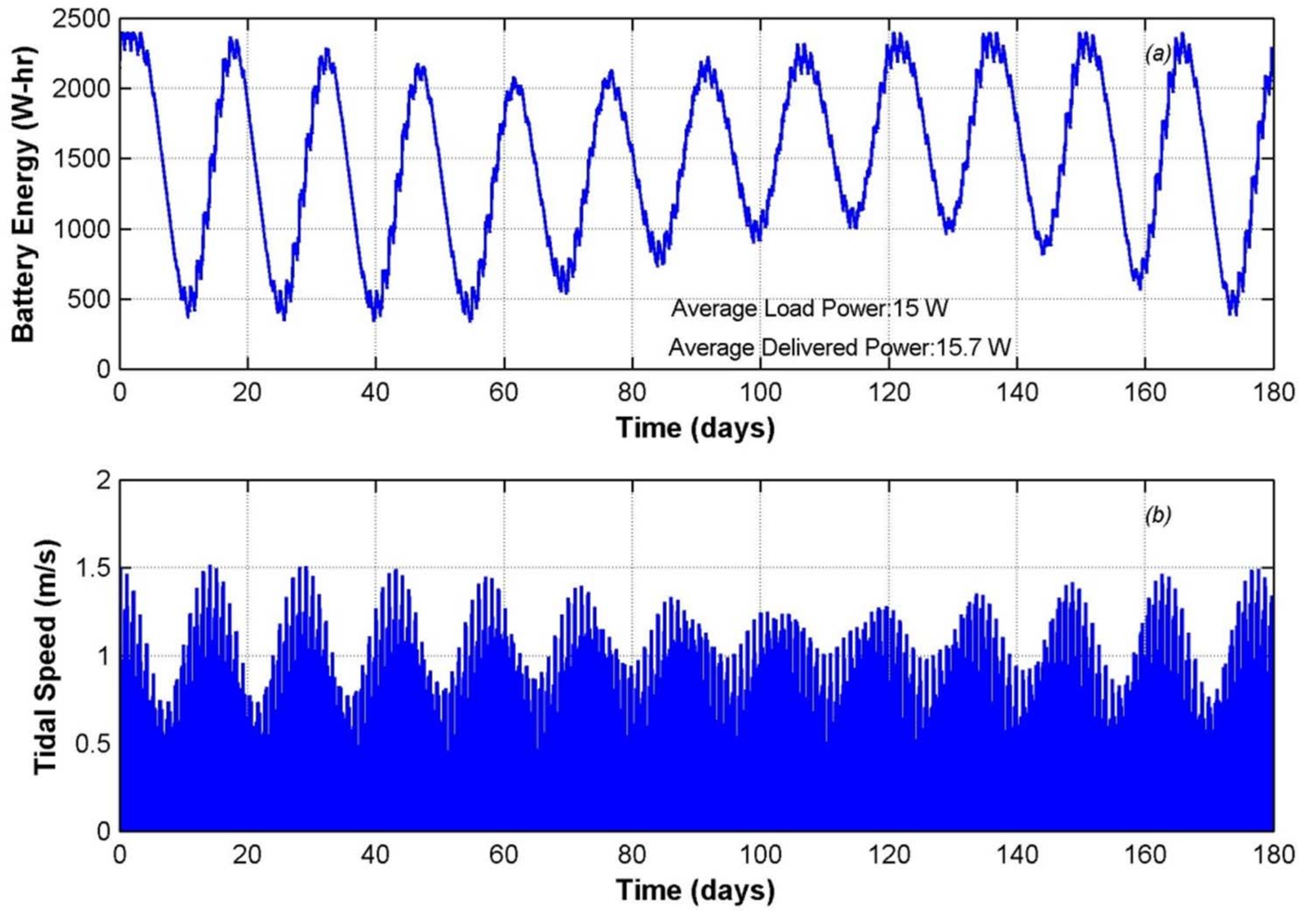
- NNMREC Organization
- Sandia National Labs
- Marie

Questions?

Backup Slides

System Performance



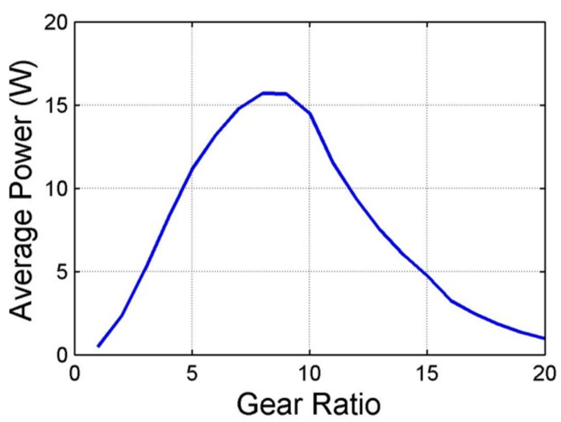
System Performance

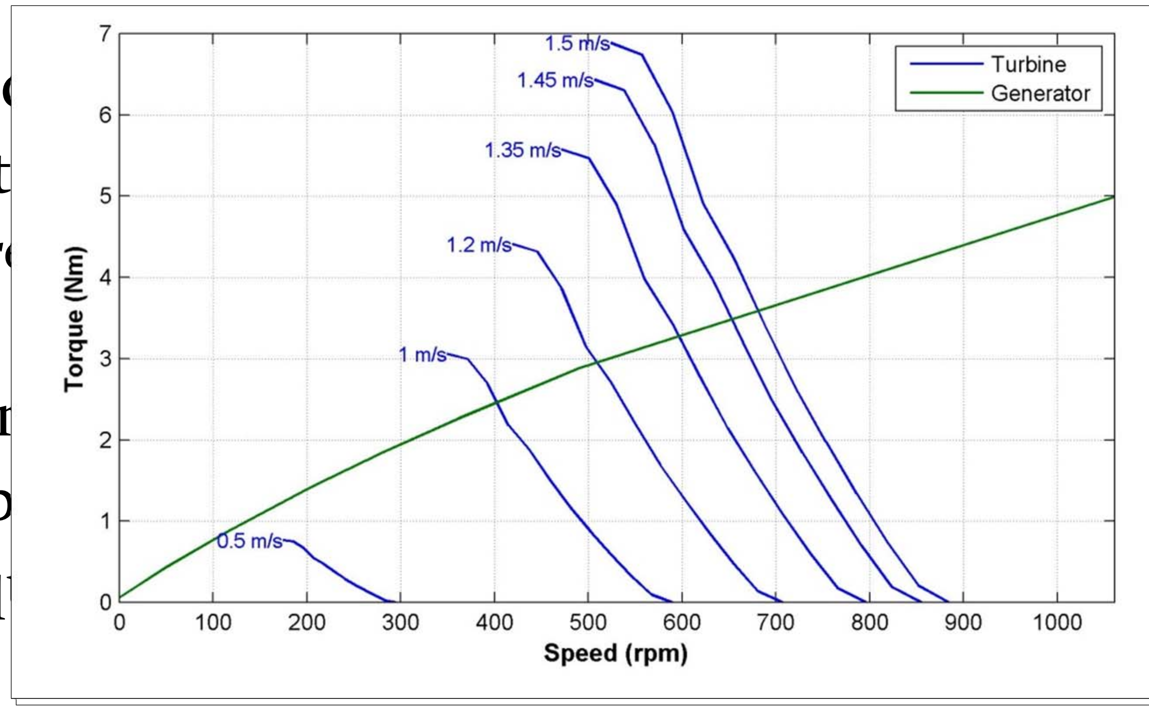
- Turbine-generator matching

$$\omega_{GEN} = G\omega_{TURB}$$

$$T_{GEN} = \frac{\eta}{G} T_{TURB}$$

- Desired generator c
  - Low speed operat





Battery Information

Characteristic	Sealed Lead-Acid	NiMH	NiCd	Lithium-Ion
Energy Density (Wh/L) [1]	Low 50-90	High 430	Low 15-100	High 570
Cycle Life (cycles) [1]	Low 200-500	Medium 300-1000	High 1500	High 1000+
Memory Effect [4]	Low No effect	Medium Less than NiCd	High Periodic discharge required	Low No effect
Charging Time [2]	High 8-16 hours	Medium 2-4 hours	Low about 1 hour	Medium 1-4 hours
Cost [3] ($/kWh)	Low $8.50	Medium $18.50	Low-Medium $11.00	High $24
Toxicity [2]	Very high	Low	Very high	Low
Transportation Limitations [4]	No	No	No	Yes
Comments [1,4]	Slow charging time; low energy density	Generates heat during high rate charge or discharge; tolerant of overcharge oroverdischarge	Rugged; lowest cost per cycle; some limitations on use due to toxicity	Transportation limitations; requires complex circuit to operate safely; limited availability for high-power applications

Data Source:

[1] Reddy & Linden (2011) [2] Buchmann (2010d) [3] Buchmann (2011b) [4] Buchmann (2010e)

Helical Turbines

- Lift-style device
- Advantages:
  - Easily self-starts
  - Fairly high efficiency (~35%)
  - No torque oscillation
- Disadvantages:
  - Difficult to manufacture
  - Less efficient than straight-blade turbine

Blade Element Theory

- Lift - Drag Force

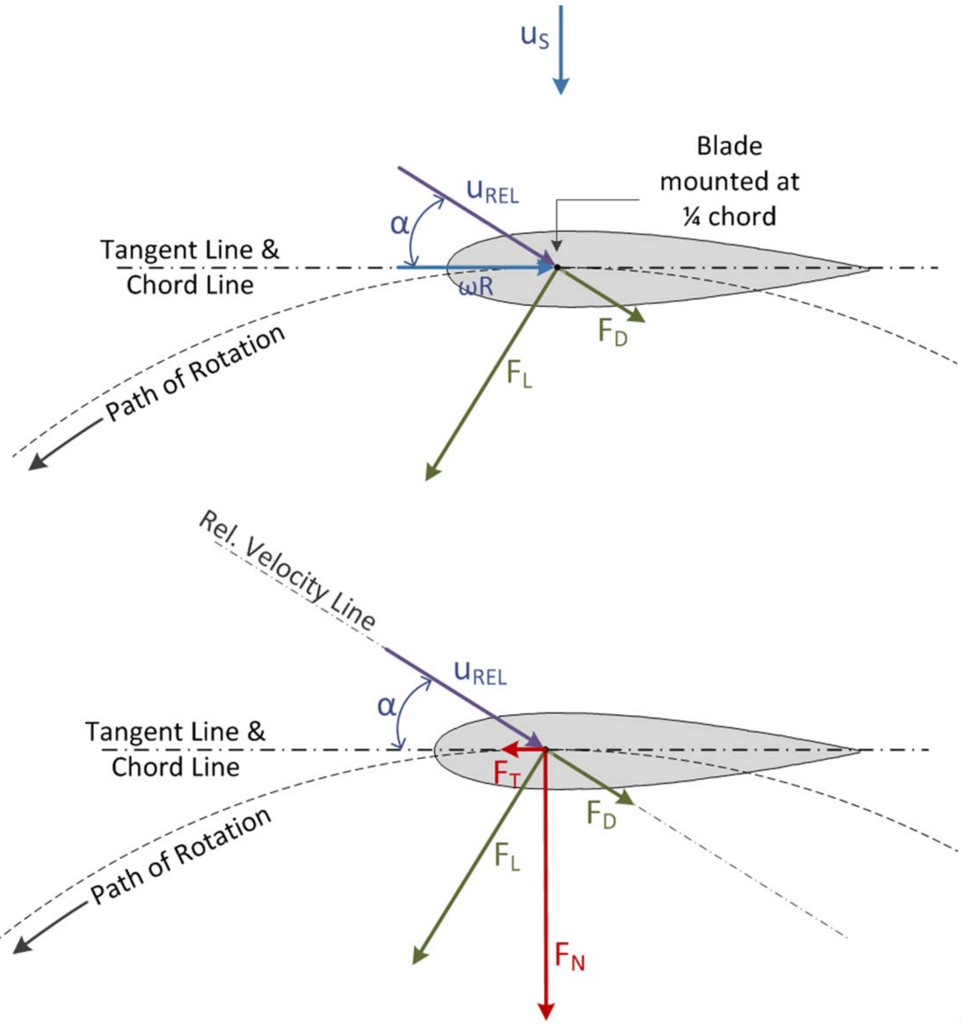
$$C_L = \frac{F_L}{\frac{1}{2}\rho u_{REL}{}^2 A_P} = \frac{F_L}{\frac{1}{2}\rho u_{REL}{}^2 ch}$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho u_{REL}{}^2 A_P} = \frac{F_D}{\frac{1}{2}\rho u_{REL}{}^2 ch}$$

- Normal - Tangential Force

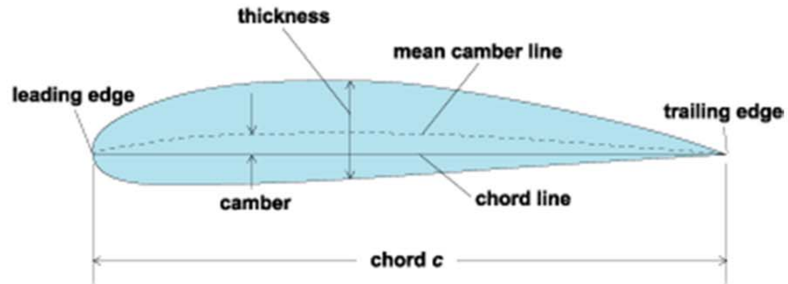
$$C_T = \frac{F_T}{\frac{1}{2}\rho u_{REL}{}^2 A_P} = \frac{F_T}{\frac{1}{2}\rho u_{REL}{}^2 ch}$$

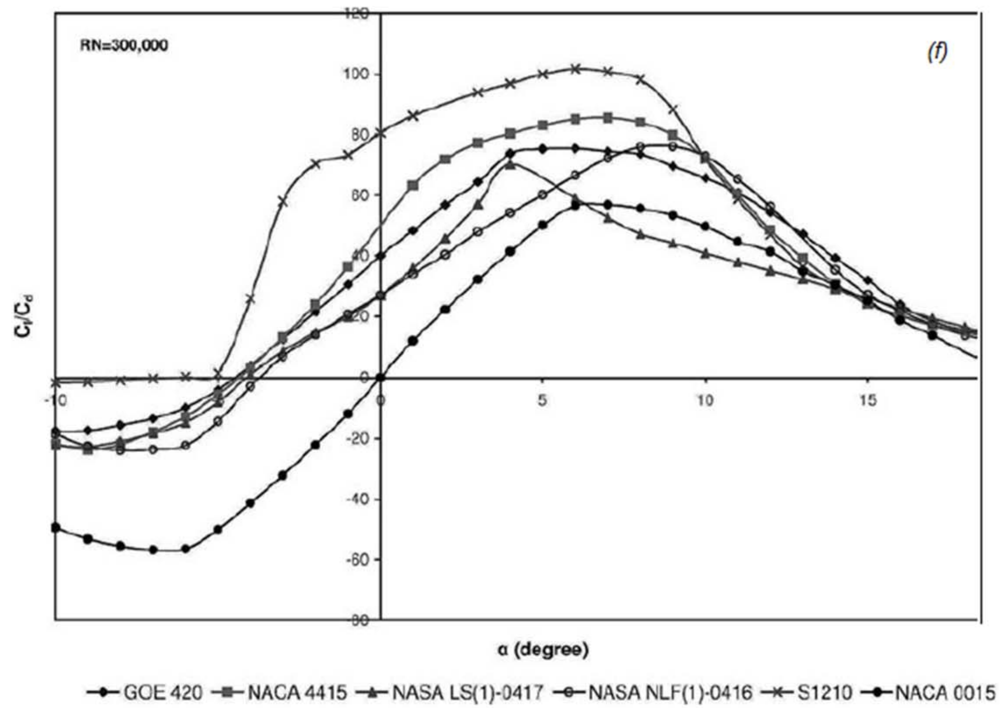
$$C_N = \frac{F_N}{\frac{1}{2}\rho u_{REL}{}^2 A_P} = \frac{F_N}{\frac{1}{2}\rho u_{REL}{}^2 ch}$$

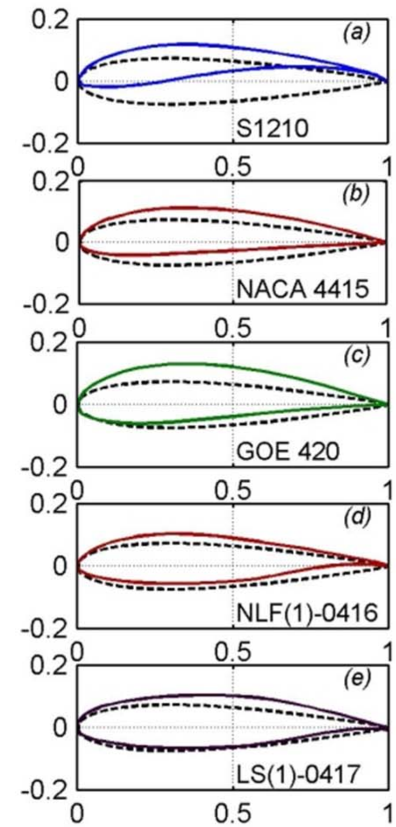


Helical Turbine Parameters

- Blade Profile

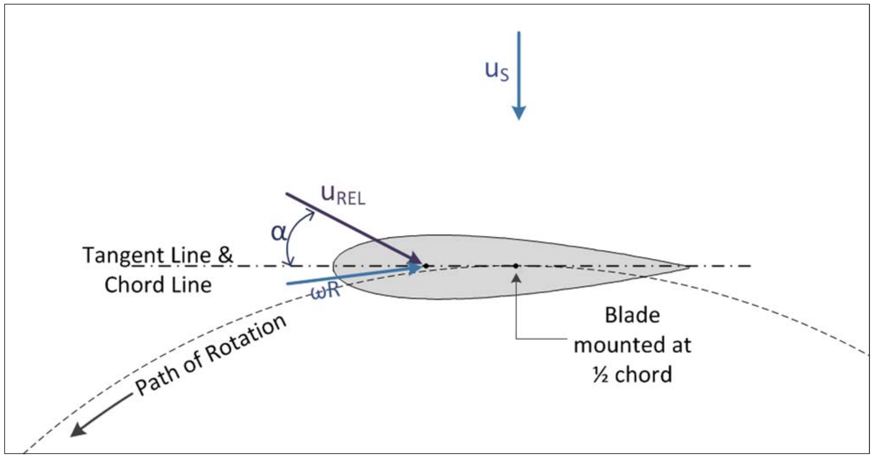


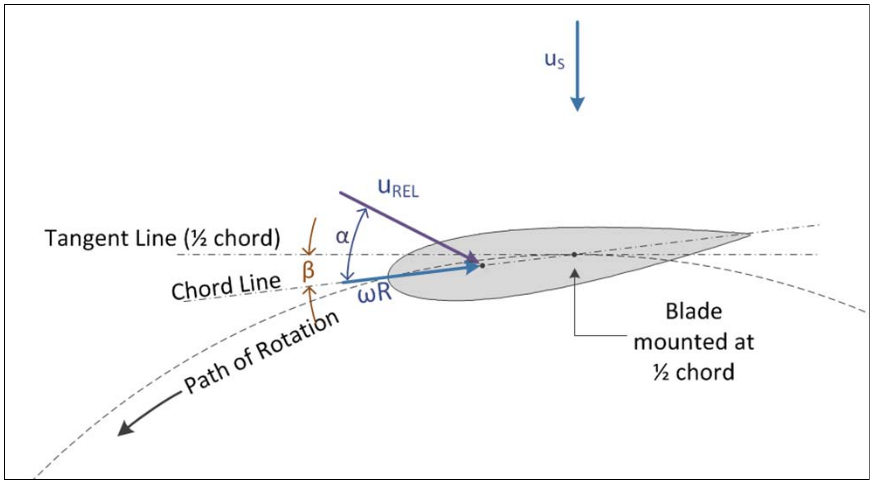




Helical Turbine Parameters

- Blade Profile
- Blade Pitch
- Helical Pitch
- Aspect Ratio
- Solidity Ratio/ Chord-to-Radius Ratio
- Number of Blades
- Blade Wrap
- Strut/shaft Design

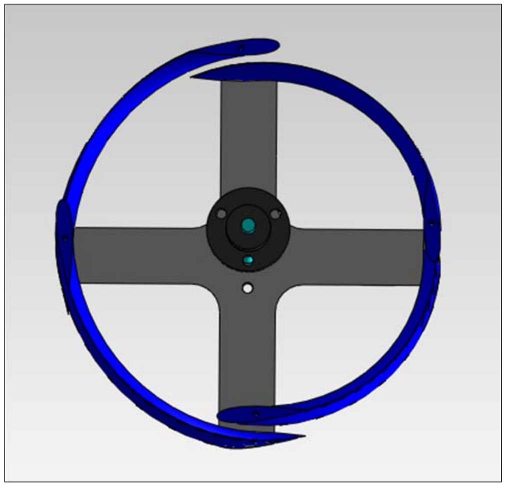




Helical Turbine Parameters

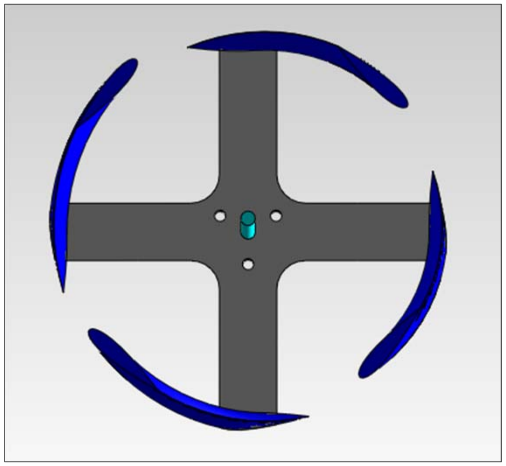
- Blade Profile
- Blade Pitch
- Helical Pitch
- Aspect Ratio
- Solidity Ratio/ Chord-to-Radius Ratio
- Number of Blades
- Blade Wrap
- Strut/shaft Design

100% Wrap



$$\varpi = \frac{BH}{\pi D \tan \delta}$$

50% Wrap



Test Matrix

Turbine Geometry			Performance test					Static Torque		Dynamic Torque		Startup - Shutdown	Tilted Turbine		Wake Measure-ment
		Flume Velocity (m/s):	0.8	0.7	0.6	0.5	0.4	0.7		0.78	0.7	0-0.7	0.72		0.78
Turbine Design	Strut Design	Shaft Diameter (mm)	--	--	--	--	--	Single blade length	Full Revolution	--	--	--	Load Per-formance	Static Torque	--
Single Blade, from 4-bladed turbine	Circular Plates	6.4		X					X	X					
4-bladed turbine	4.8 mm, 4-leg spokes	6.4	X	X					X						
	2.0 mm, 4-leg spokes	No shaft	X	X				X							
		6.4	X	X	X	X	X		X	X		X	X	X	X
		12.7	X	X				X							
	Circular Plates	6.4	X	X	X	X	X	X					X	X	
3-bladed turbine	4.8 mm, 3-leg spokes	6.4	X	X	X	X			X		X				
Low Solidity Turbine	4.8 mm, 3-leg spokes	6.4	X	X											

X: Test Completed

Test Calculations

$$\varepsilon = \frac{A_{TURBINE}}{A_F} = \frac{DH}{w_F(h_0)}$$

$$Fr = \frac{u_0}{\sqrt{g h_0}}$$

$$Re_M = \frac{\rho u_0 D}{\mu}$$

$$Re_B = \frac{\rho u_{REL} c}{\mu}$$

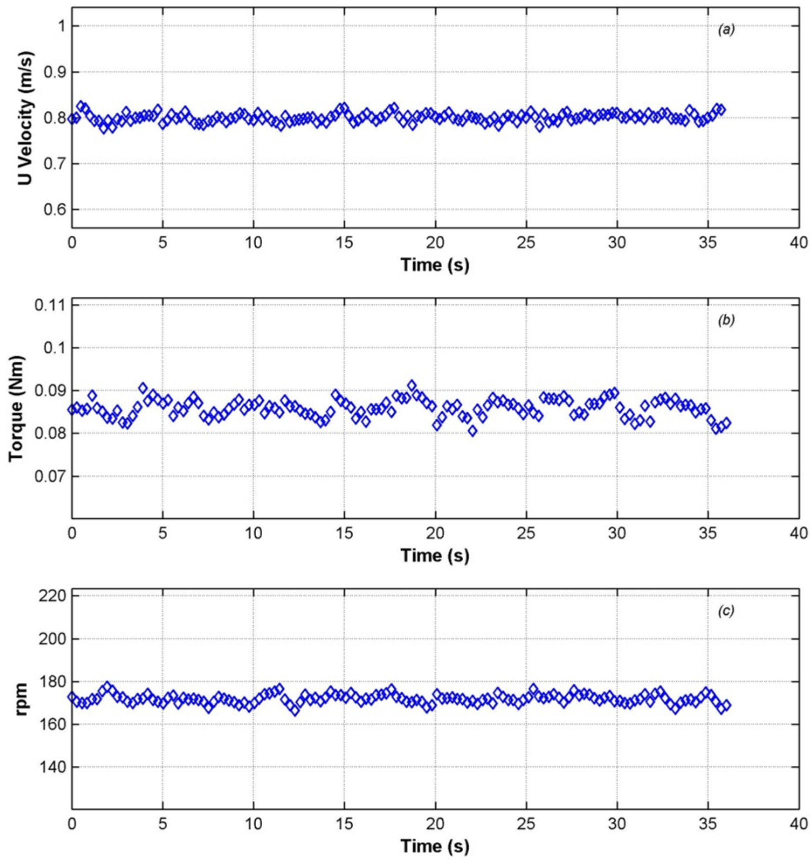
$$C_Q = \frac{T}{\frac{1}{4}\rho D^2 H {u_0}^2} \qquad C_P = \frac{T\omega}{\frac{1}{2}\rho D H {u_0}^3}$$

$$C_{QS} = \frac{T}{\frac{1}{4}\rho D^2 H {u_0}^2} \qquad \lambda = \frac{\omega R}{u_0}$$

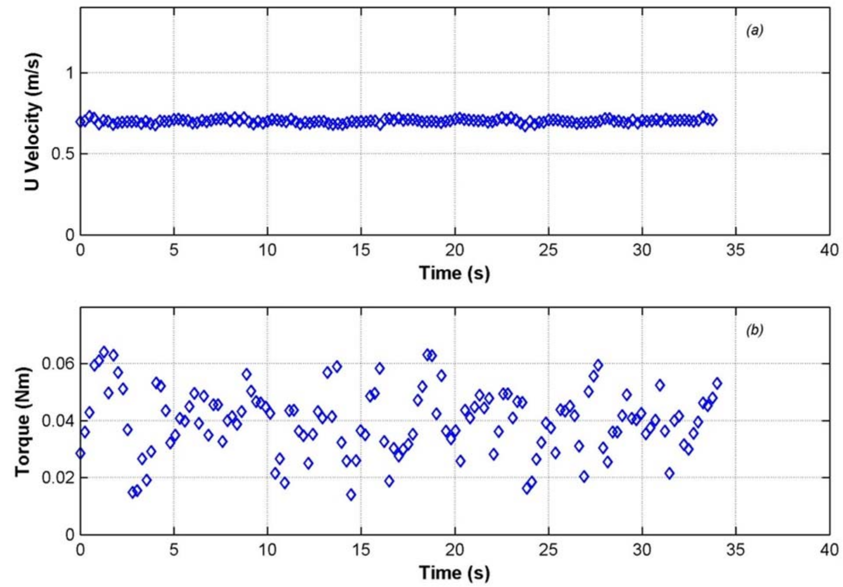
Parameter	Symbol	Data Range	
Flume Speed (m/s)	u_0	0.4	0.8
Static Water Height (cm)	h_{sw}	50	46
Dynamic Water Height (cm)	h_0	49	42
Water Column Cross-Sectional Area (m^2)	A_F	0.371	0.318
Turbine Cross-Sectional Area (m^2)	A_C	0.040	0.040
Blockage Ratio	ε	0.108	0.126
Froude Number	Fr	0.182	0.394
Max Blade Reynold's Number (4-Bladed Turbine)	Re_B	4.0E+04	9.5E+04
Min Blade Reynold's Number (4-Bladed Turbine)	Re_B	3.6E+03	2.2E+04
Machine Reynold's Number (4-Bladed Turbine)	Re_M	7.7E+04	1.5E+05

Typical Test Results

Load Performance Test

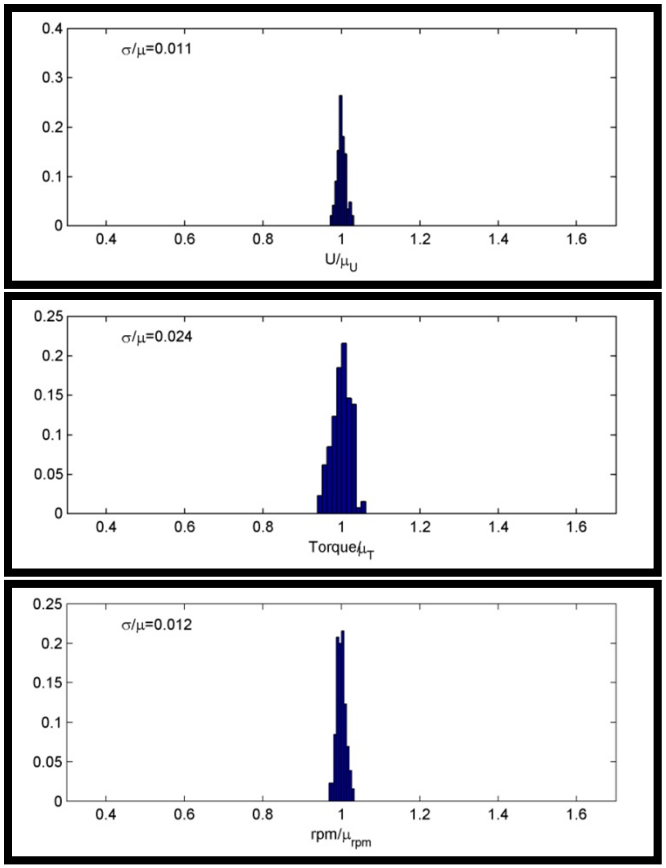


Static Torque Test

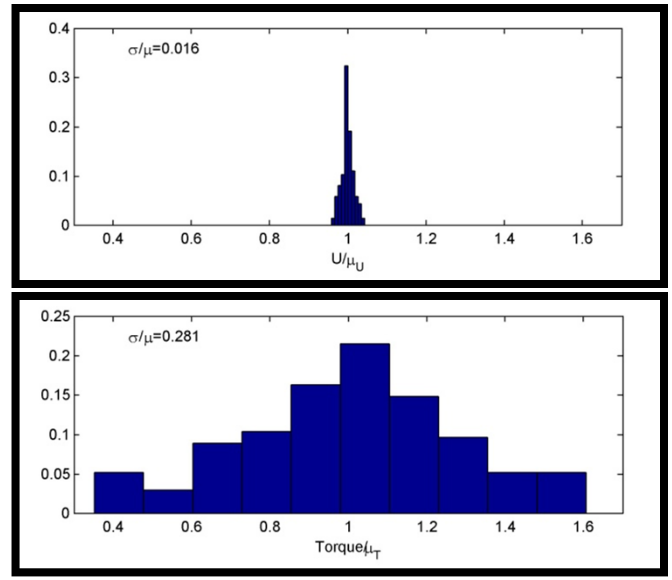


Typical Test Results

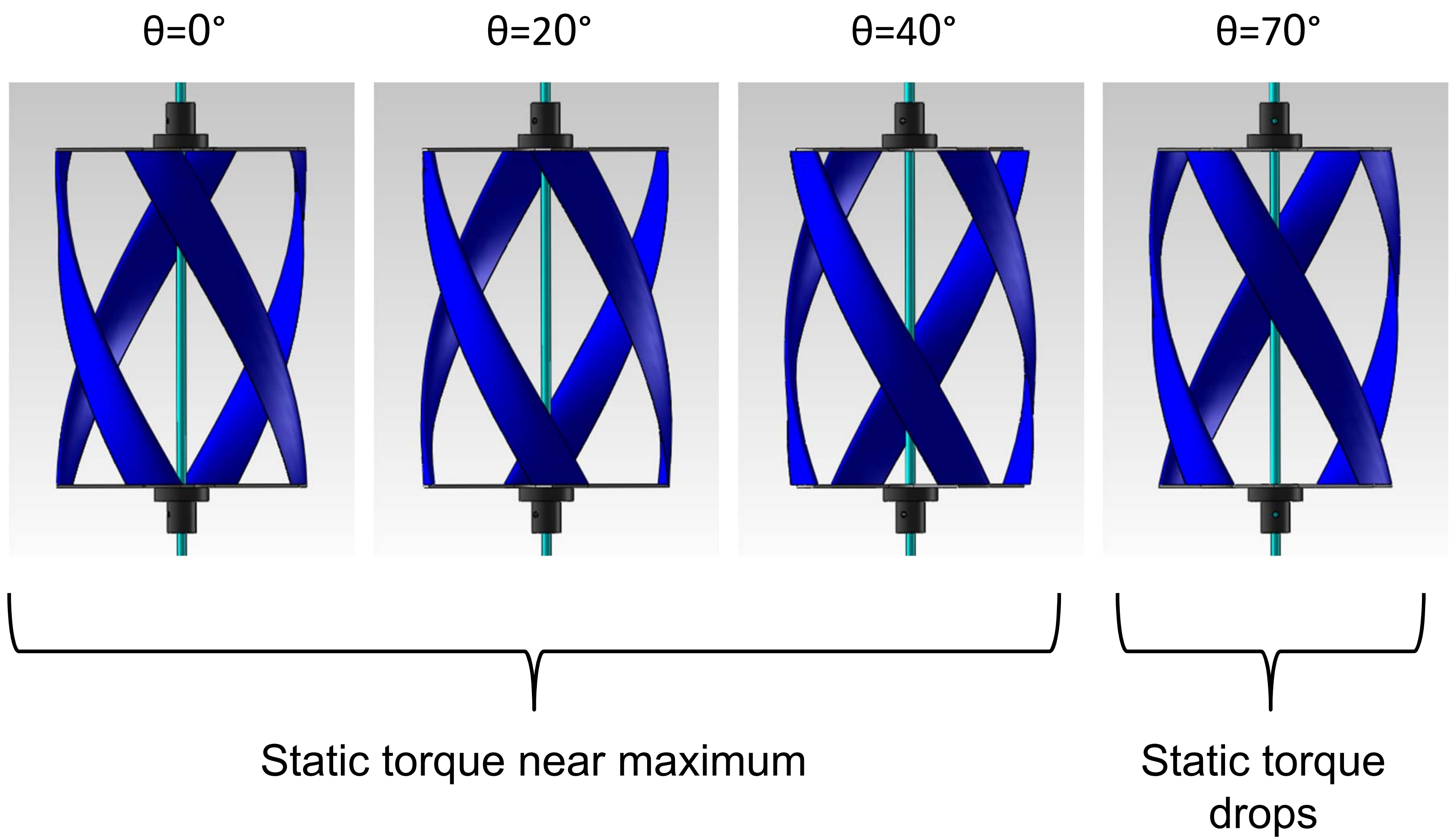
Load Performance Test



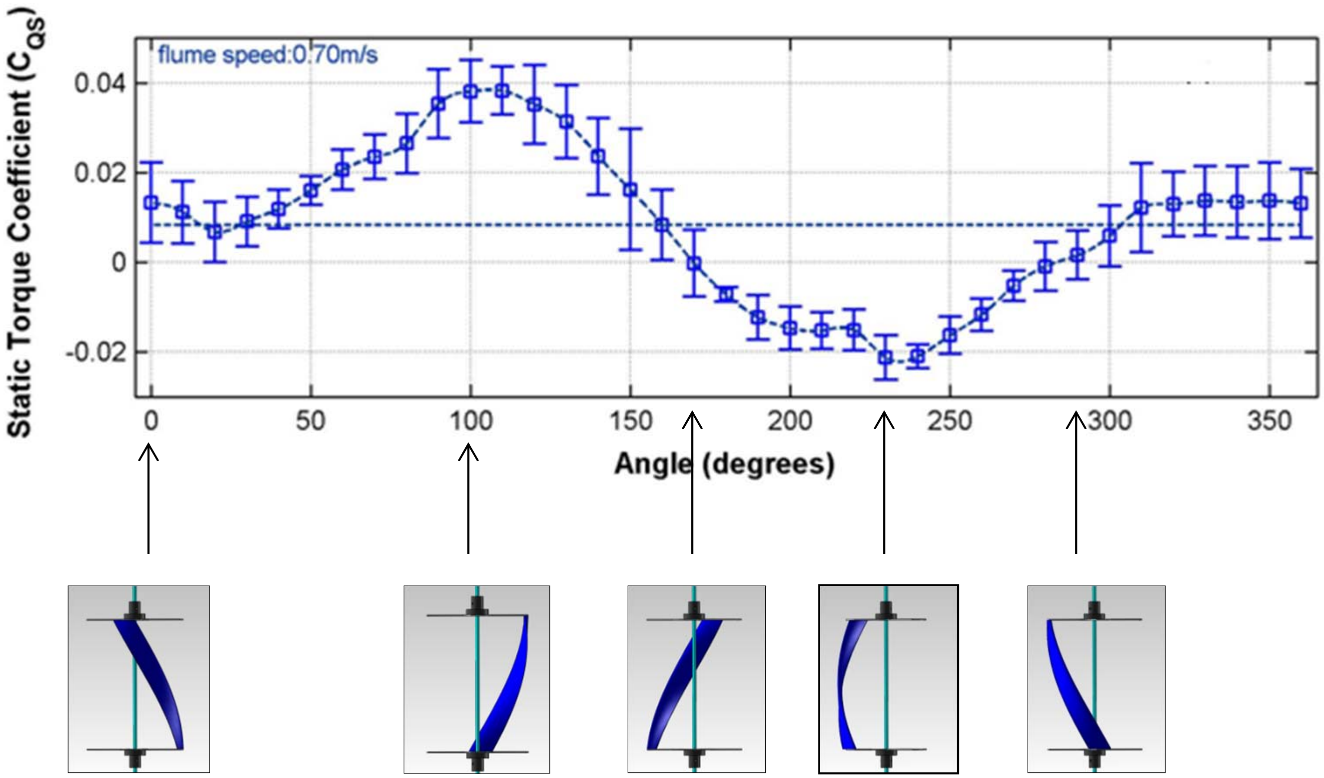
Static Torque Test



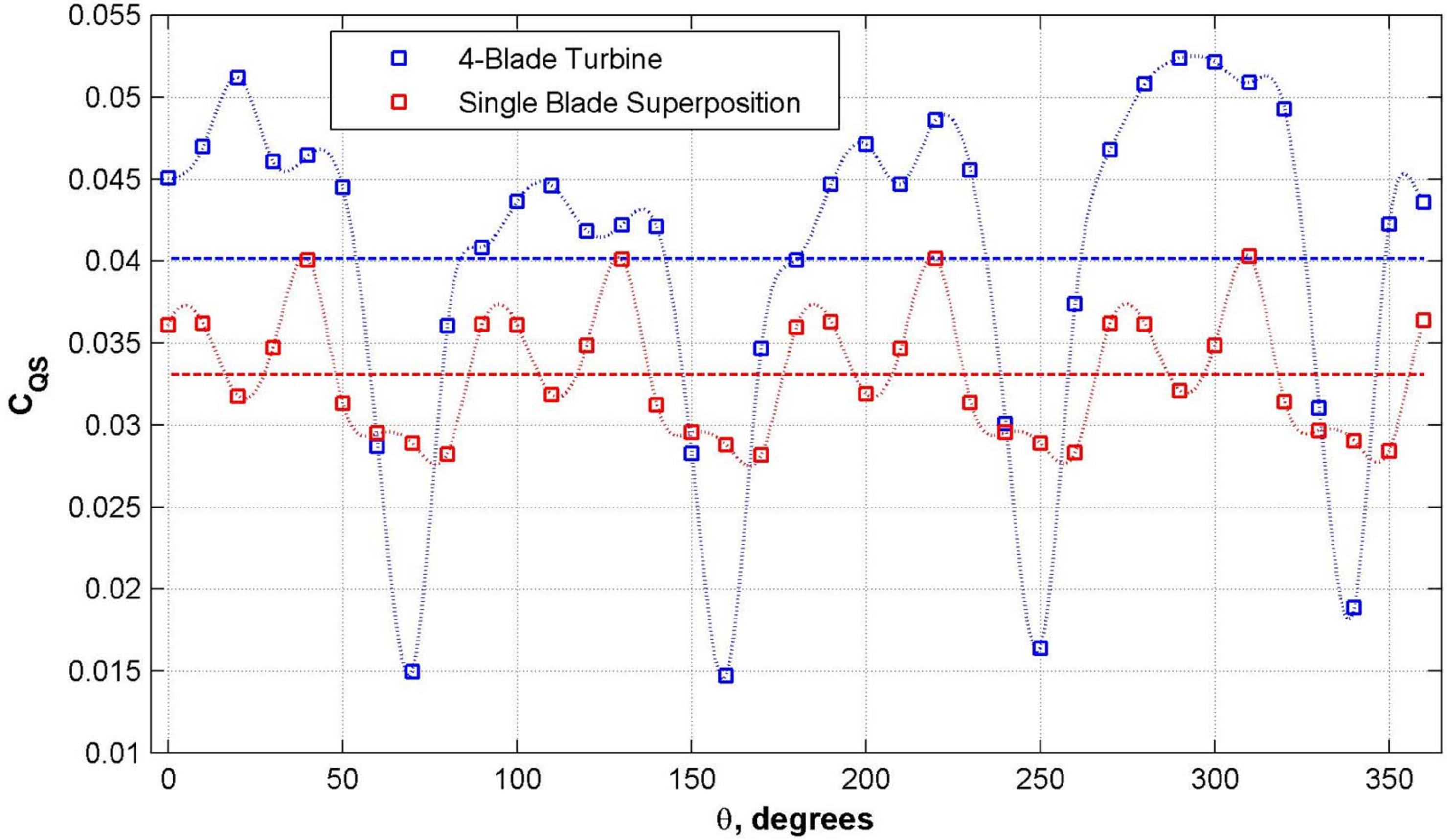
Streamwise View



Single Blade Static Torque



Single Blade Torque Superposition



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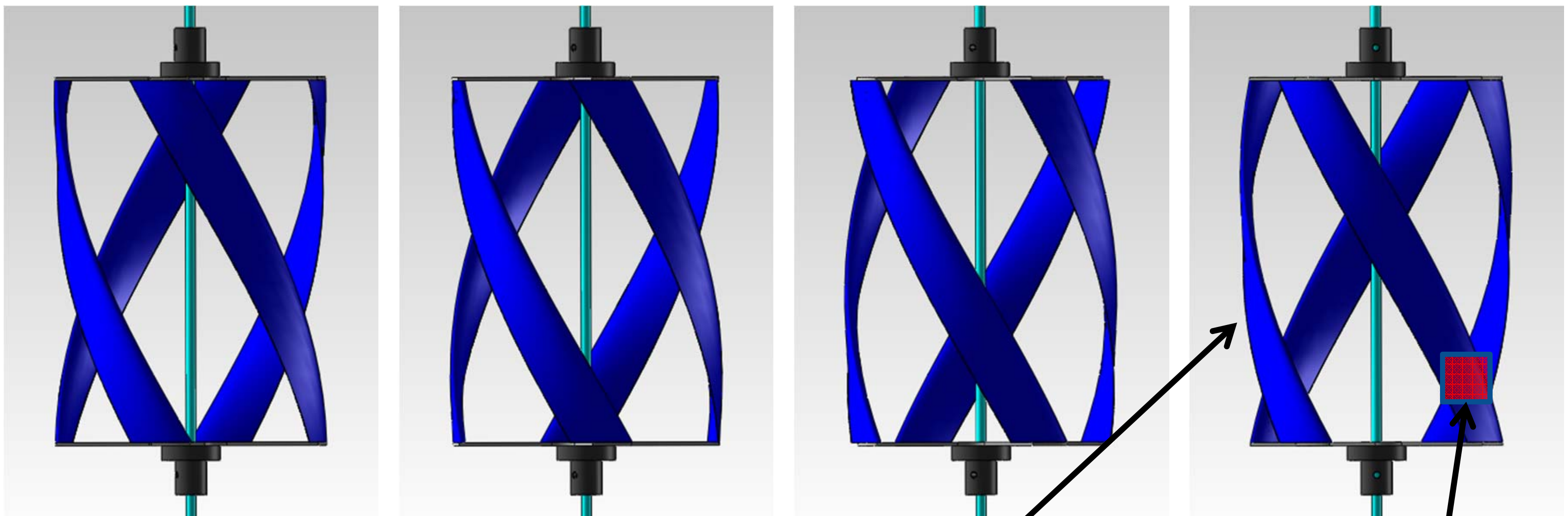
Streamwise View

θ=0° θ=20° θ=40° θ=70°



Unobstructed (-T) blade

Partial obstruction of (+T) blade at location of best drag

Static torque near maximum

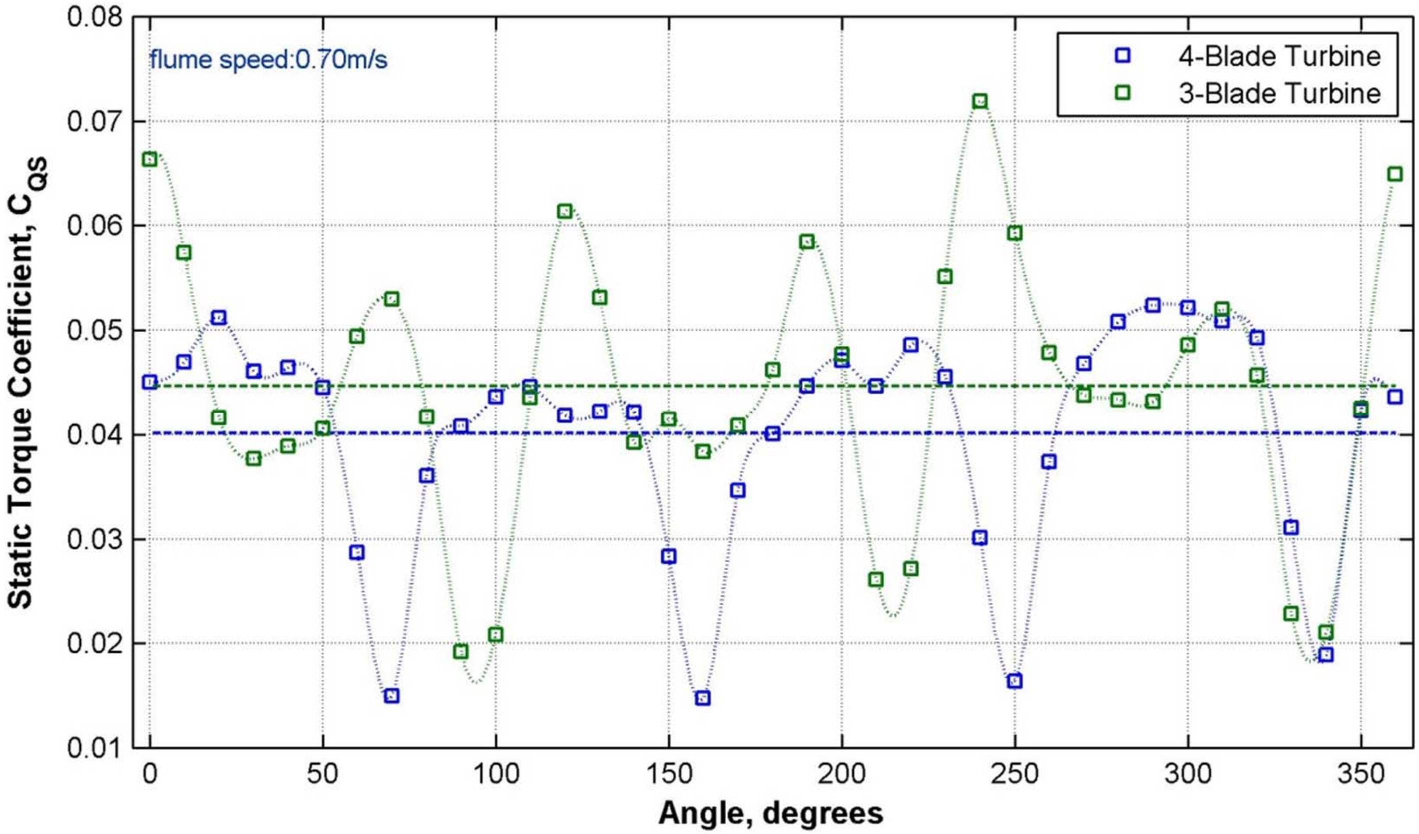
St

Turbine Design Comparison

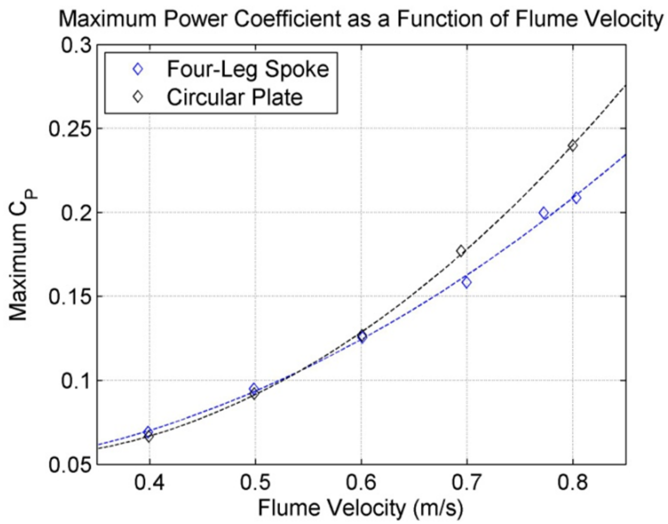
3-Bladed Turbine

4-Bladed Turbine

Static Torque Test Results



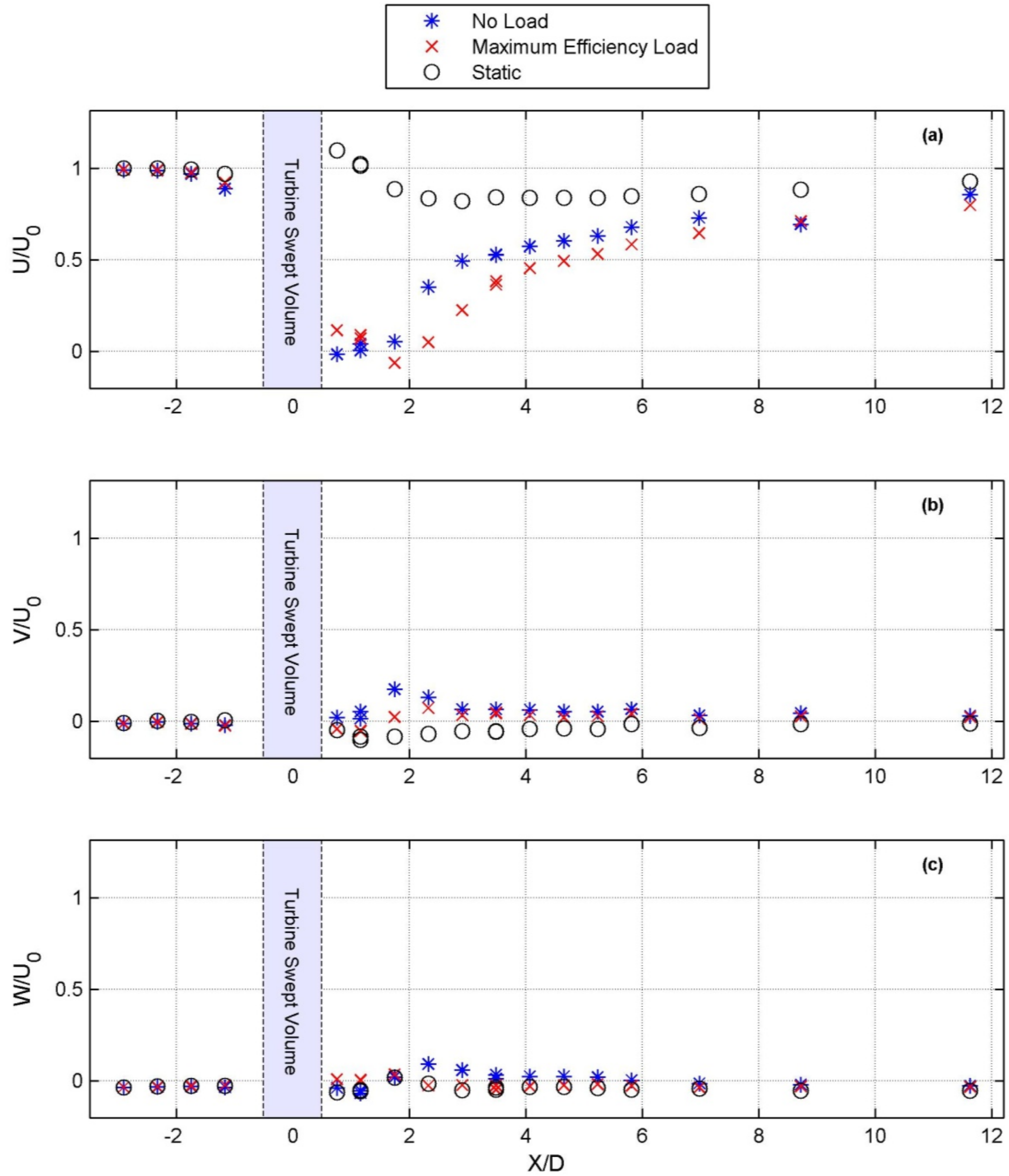
Tilted Turbine Test



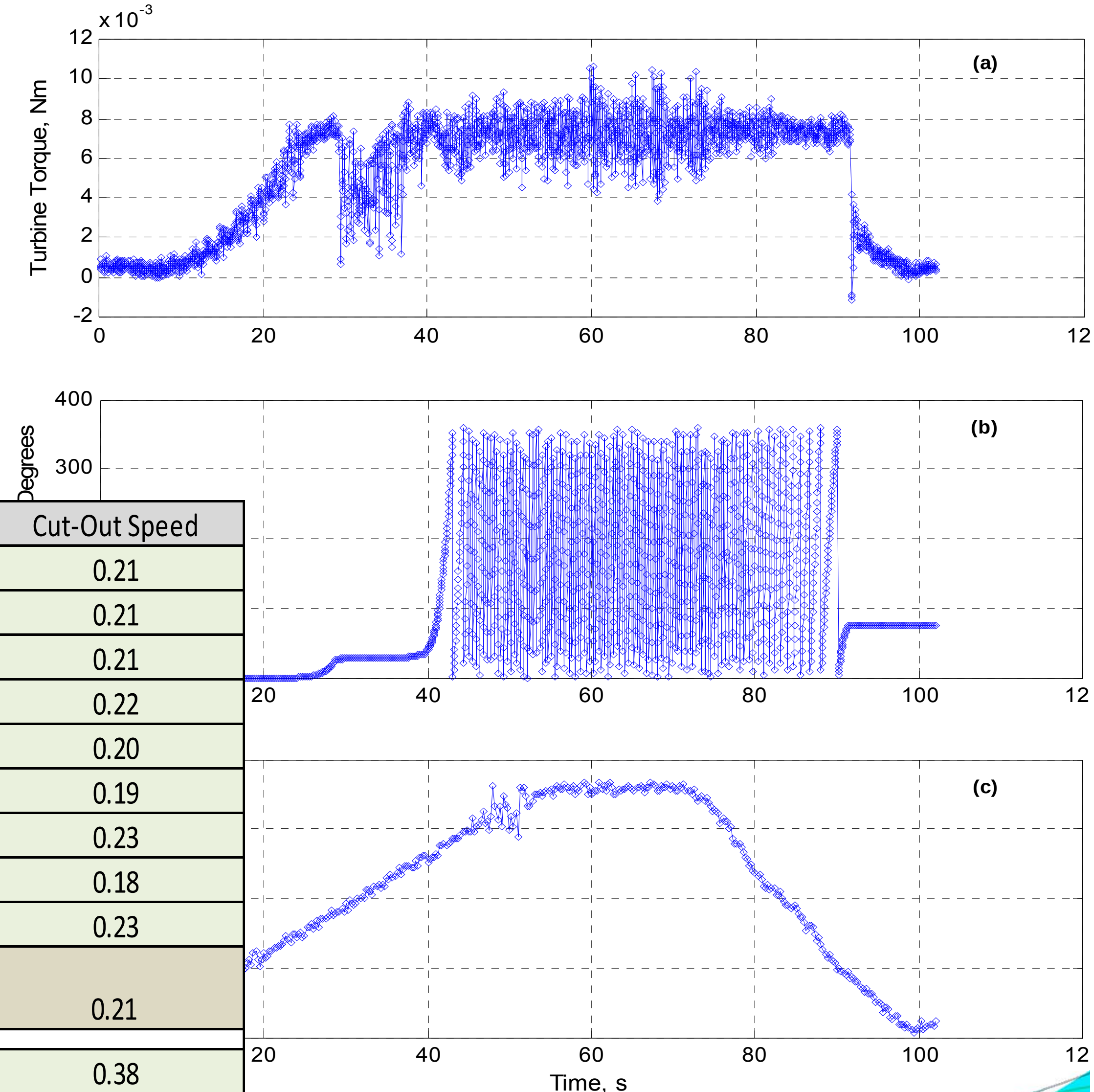
Strut Design	Tilt Angle (degrees)	Tilt Velocity	Predicted C_P Loss from cos(Tilt)	Actual C_P Loss
2 mm, 4-Leg Spoke	0	0.720	0.0%	0.0%
	2.5	0.719	-0.2%	-5.6%
	5	0.717	-0.7%	-8.8%
	10	0.709	-2.8%	-23.0%
2 mm Circular Plate	0	0.720	0.0%	0.0%
	2.5	0.719	-0.2%	-4.5%
	5	0.717	-0.8%	-4.4%
	10	0.709	-3.3%	-8.9%

Wake Measurement Test

- Baseline Configuration
- Flume: 0.78 m/s
- Wake measurements along turbine centerline



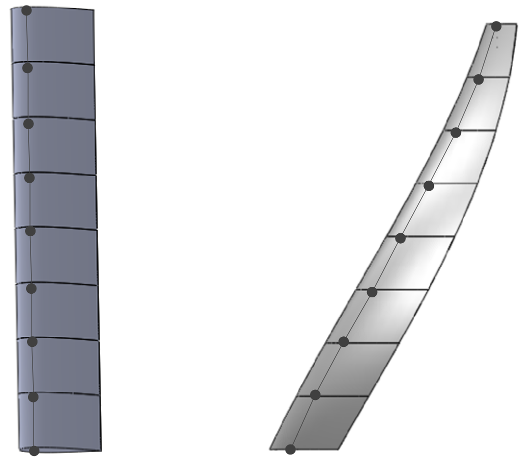
Start-up Shutdown Test Profile



Starting Angle	Load Torque (Nm)	Cut-In Speed (m/s)	Cut-Out Speed
0	0.006	0.47	0.21
10	0.006	0.47	0.21
20	0.006	0.47	0.21
30	0.006	0.58	0.22
40	0.006	0.60	0.20
50	0.006	0.57	0.19
60	0.006	0.60	0.23
70	0.006	0.55	0.18
80	0.006	0.47	0.23
Average cut-in/cut-out speed at 0.006 Nm load torque:		0.53	0.21
0	0.021	0.71	0.38

Vortex Model

- Blade is divided into segments, revolution into time steps
- 8 elements per blade
- 15 revolutions to establish wake
- Vortex influences the flow of surrounding blades



Model Solution

- Sum of velocity components gives u_{REL}

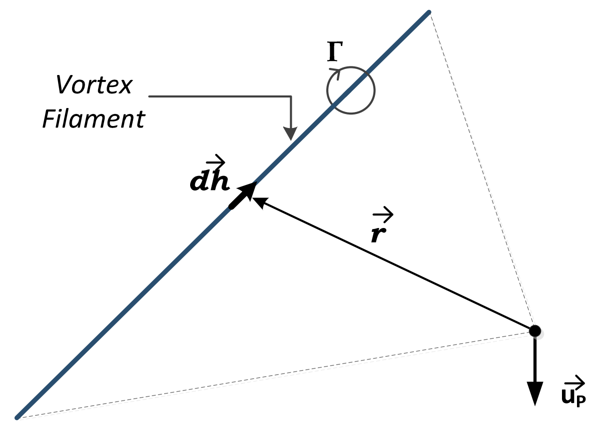
$$\vec{u}_{REL_i} = \vec{u}_{0_i} + \vec{u}_{TIP_i} + \sum_j \left(\vec{u}_{B_{i,j}} + \vec{u}_{T_{i,j}} + \vec{u}_{SHED_{i,j}} \right)$$

- Total change in circulation over time is zero (Kelvin's theorem):

$$\frac{D\Gamma}{Dt} = 0$$

- Vortex-induced velocity at a point is found by Biot-Savart Law:

$$\vec{u}_P = \frac{\Gamma}{4\pi} \int \frac{\vec{r}\, x\, d\vec{h}}{|\vec{r}|^3}$$



- Circulation strength is found from Kutta-Joukowski theorem:

$$\Gamma_B = \frac{1}{2} C_L c u_{REL}$$

- Predictor-corrector to solve system of equations

Boeing Vertol Dynamic Stall Model

$$\alpha_{REF\,(L,D)} = \alpha - K_1 \gamma \sqrt{\frac{c\dot{\alpha}}{2u_{REL}}}\, sign(\dot{\alpha}). \quad C_L = \left(\frac{C_{L_{REF}}}{\alpha_{REF} - \alpha_{ZL}}\right)\alpha \qquad C_D = C_{D_{REF}}$$

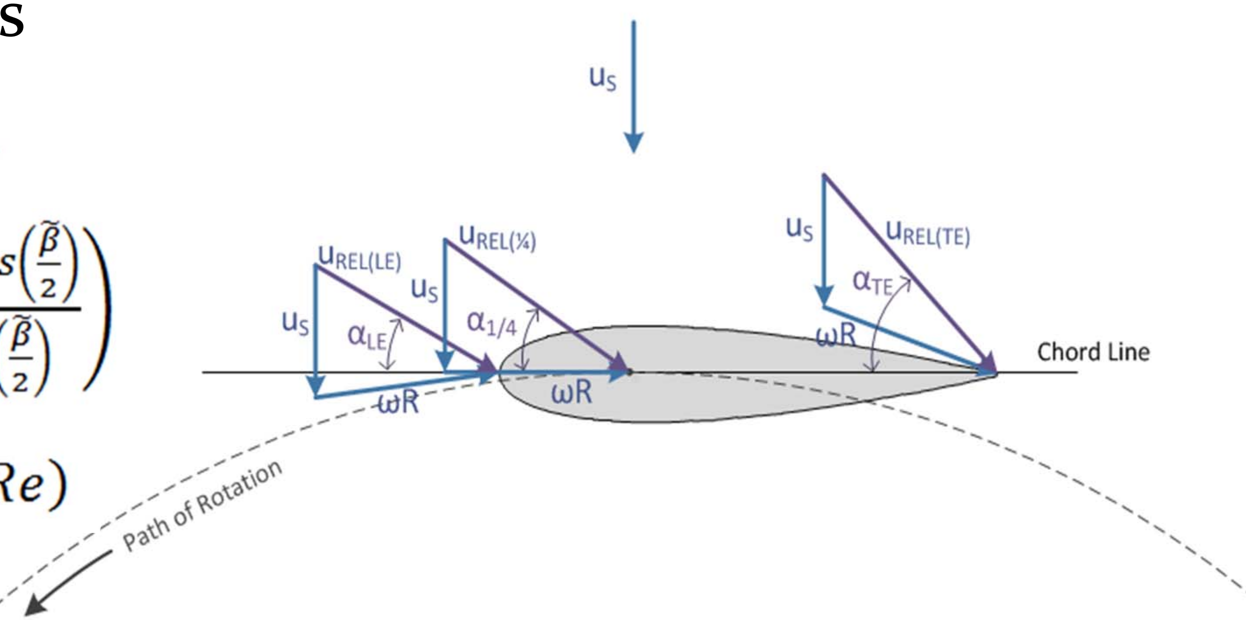
Flow Curvature

- Change in α from leading edge to trailing edge
- Important for high chord-to-radius ratio turbines
- Approximated as

$$\tilde{\beta} = \alpha_{TE} - \alpha_{LE}$$

$$\alpha_C = tan^{-1}\left(\frac{1 - cos\left(\frac{\tilde{\beta}}{2}\right)}{sin\left(\frac{\tilde{\beta}}{2}\right)}\right)$$

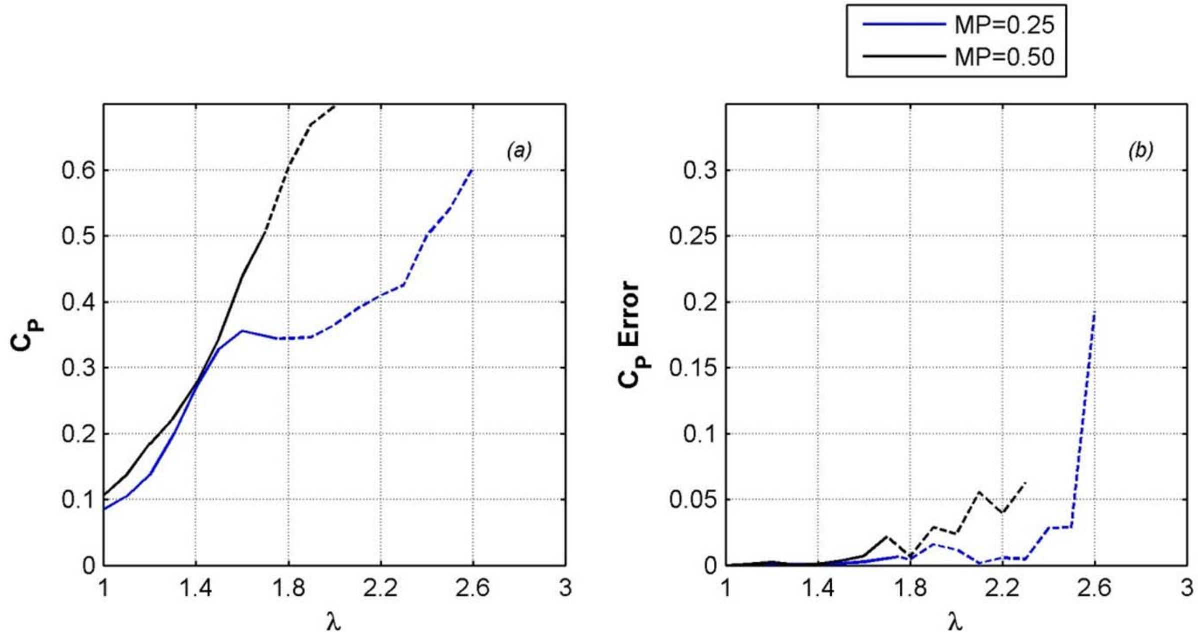
$$C_L = f(\alpha + \alpha_C, Re)$$



- 'Virtual camber'

Full-Scale Turbine Prediction

All Secondary Effects Active



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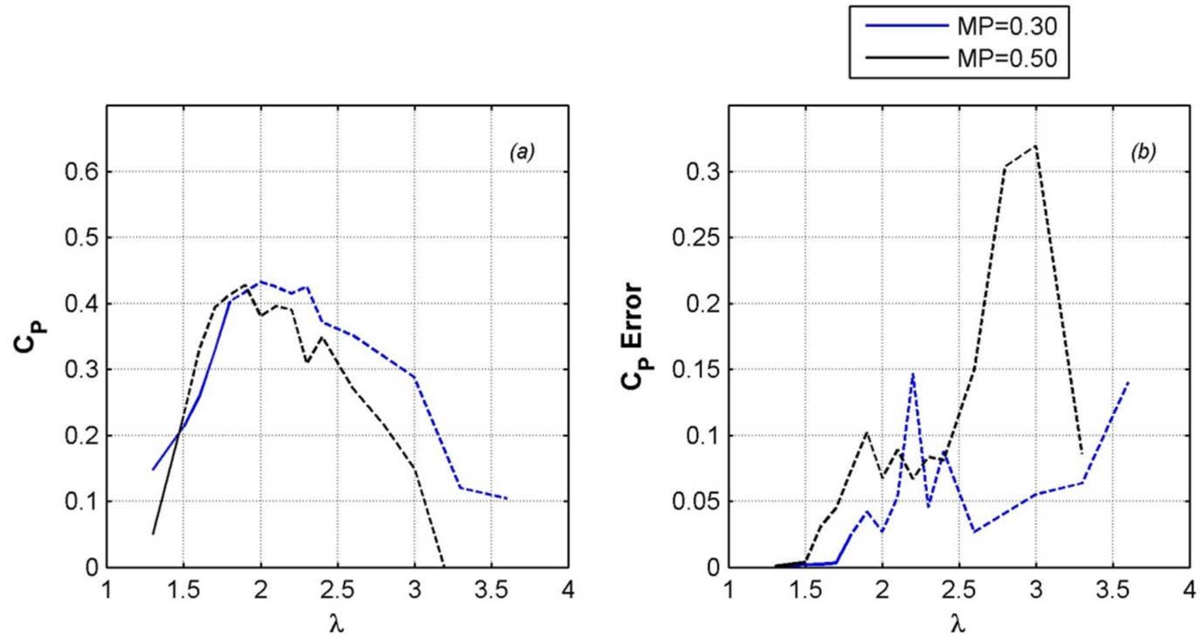
Full-Scale Turbine Prediction

Dynamic Stall only



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Model Prediction of Strut Drag

- u_o=0.8 m/s