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

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Northwest National Marine Renewable Energy Center

MSME Thesis Defense
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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

<table>
<thead>
<tr>
<th>Unit</th>
<th>Power Usage (W)</th>
<th>Deployment Duration (days)</th>
<th>Total W-hr</th>
<th># of batteries Required</th>
<th>Battery Cost</th>
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</thead>
<tbody>
<tr>
<td>Doppler Current Profiler</td>
<td>0.9</td>
<td>90</td>
<td>1944</td>
<td>12</td>
<td>$ 2,280.00</td>
</tr>
</tbody>
</table>

**Battery Capacity (W-hr): 165**  
**Cost ($/W-hr): $ 1.15**
### Motivation for Micropower

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<tr>
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<td>0.9</td>
<td><strong>180</strong></td>
<td>3888</td>
<td>24</td>
<td>$4,560.00</td>
</tr>
</tbody>
</table>

- **Battery Capacity (W-hr):** 165
- **Cost ($/W-hr):** $1.15
Motivation for Micropower

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

*\( u_0 \): Inflow velocity
*\( \rho \): Fluid density
# Motivation for Micropower

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<tr>
<td>Imaging Sonar (20% duty cycle)</td>
<td>20.0</td>
<td>180</td>
<td>86400</td>
<td>524</td>
<td>$99,560.00</td>
</tr>
<tr>
<td>Imaging Sonar (20% duty cycle)</td>
<td>20.0</td>
<td>180</td>
<td>86400</td>
<td>15</td>
<td>$ 2,850.00</td>
</tr>
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</table>

Battery Capacity (W-hr): 165

Cost ($/W-hr): $ 1.15
Micropower System Concept

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

- Tidal Current Profile
- time (days)
- $u_0$ (m/s)

- Gearbox
- Generator
- Rectifier
- Converter
- Battery Bank
- Controller
- Monitoring Equipment
- Controller/processor
- Data storage
- Loads

NNMREC
Outline

• Micropower System Overview
• Turbine Selection/Design Parameters
• Experimental Testing
• Modeling
• Conclusions and Future Work
Turbine Performance Metrics

- Efficiency – for power and torque production
  \[ C_P = \frac{T\omega}{\frac{1}{2}\rho DHu_0^3} \quad C_Q = \frac{T}{\frac{1}{4}\rho D^2 Hu_0^2} \]

- Starting torque magnitude and range – for self-start
  \[ C_{QS} = \frac{T}{\frac{1}{4}\rho D^2 Hu_0^2} \quad T \text{ vs } \theta \]

- Tip Speed Ratio and Rotation Rate – for generator integration
  \[ \lambda = \frac{\omega R}{u_0} \]

- Performance with respect to inflow orientation – for deployment flexibility

\[ H: \text{ Height} \]
\[ D: \text{ Diameter} \]
\[ R: \text{ Radius} \]
\[ T: \text{ Torque} \]
\[ u_0: \text{ Inflow velocity} \]
\[ \rho: \text{ Fluid density} \]
\[ \theta: \text{ Azimuthal angle} \]
\[ \omega: \text{ Angular velocity} \]
Turbine Design Concepts

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

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

- Streamwise velocity ($u_s$)
- Tip velocity ($\omega R$)
  - Induced by turbine’s own rotation
- Relative velocity ($u_{REL}$)
  - Resultant vector of $u_s$ and $\omega R$
- Angle of attack ($\alpha$)
  - Angle between $u_{REL}$ and chord line
- Lift - Drag Forces ($F_L$, $F_D$)
  - Generate turbine torque

\[
C_L = \frac{F_L}{\frac{1}{2} \rho u_{REL}^2 A_P} = \frac{F_L}{\frac{1}{2} \rho u_{REL}^2 c h}
\]

\[
C_D = \frac{F_D}{\frac{1}{2} \rho u_{REL}^2 A_P} = \frac{F_D}{\frac{1}{2} \rho u_{REL}^2 c h}
\]

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

$c$: Blade length
$h$: Blade height
$A_P$: Planform area $= ch$
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 ($\alpha$)
  - 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

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

Source: answers.com
Helical Turbine Parameters

- Blade Profile
- Helical Pitch
- 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

\[
\sigma = \frac{Bc}{\pi D}
\]

\[
\sigma_{C-R} = \frac{c}{R}
\]
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**
- **Improved $C_p$, Allows higher pitch**
- **Better starting torque, Manufacturability**
- **Allows increase in pitch and reduced aspect ratio**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helical Pitch</td>
<td>Lower static torque variation</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>Easier Deployment, Less blade stress, Less vibration</td>
</tr>
<tr>
<td>Solidity Ratio</td>
<td>Higher tip speed ratio</td>
</tr>
<tr>
<td>Number of Blades</td>
<td>Fewer parts, Less blade wake interference</td>
</tr>
</tbody>
</table>

**Notes:**
- Better starting torque allows for increased pitch and reduced aspect ratio.
- Higher efficiency leads to improved $C_p$ and manufacturability.
- Improved $C_p$ allows for higher pitch.
- Helical pitch reduces static torque variation.
- Aspect ratio impacts deployment and blade stress.
- Solidity ratio affects tip speed ratio.
- Number of blades influences parts and blade wake interference.
Outline

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

Baseline Configuration

3-Bladed Turbine
- D = 20 cm
- H = 20 cm
- Aspect Ratio = 43.7
- Pitch Angle = 30%
- Solidity = 3.0

4-Bladed Turbine
- D = 17.2 cm
- H = 23.4 cm
- Aspect Ratio = 1.36
- Pitch Angle = 60°
- Solidity = 3.0

4-Bladed Turbine
- D = 20 cm
- H = 20 cm
-Aspect Ratio = 43.7
- Pitch Angle = 30%
- Solidity = 3.0

Low Solidity Turbine
- D = 20 cm
- H = 20 cm
- Aspect Ratio = 43.7
- Pitch Angle = 15%
- Solidity = 3.0
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

- Reaction Torque Cell
- Particle Brake
- Optical Encoder
- Flex Coupling
- Locking Plate
- Bearing
Turbine Operation
Load Performance Results

- Baseline Configuration

\[ C_Q = \frac{T}{\frac{1}{4} \rho D^2 H u_0^2} \]

\[ C_P = \frac{T \omega}{\frac{1}{2} \rho D H u_0^3} \quad \lambda = \frac{\omega R}{u_0} \]
Lift and Drag for different $\alpha$

Region of Turbine Operation at 0.4 m/s

Region of Turbine Operation at 0.8 m/s

Increasing $\lambda$ decreases average $\alpha$

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

(a)

(b)

Torque Coefficient, $C_Q$

Power Coefficient, $C_P$

flume speed: 0.80 m/s
Strut Design Comparison

2 mm Spoke  4.8 mm Spoke  Circular Plate

Torque Coefficient ($C_Q$) vs. $\lambda$

Power Coefficient ($C_P$) vs. $\lambda$
Shaft Diameter Comparison

No Shaft 6.4 mm Shaft 12.7 mm Shaft

Torque Coefficient ($C_t$)

Power Coefficient ($C_p$)
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

Torque Coefficient ($C_Q$) vs. $\lambda$

Power Coefficient ($C_P$) vs. $\lambda$
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 $C_p$
Outline

- Micropower System Overview
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- Experimental Testing
- Modeling
- Conclusions and Future Work
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 $u_{REL}$
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 $\sigma_{C-R}$ than previously modeled
Flow Curvature

- Change in $\alpha$ from leading edge to trailing edge
- Important for high chord-to-radius ratio 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 \( \alpha \) at \( \frac{3}{4} \)-chord
    - \( C_D \) calculated at \( \alpha \) at \( \frac{1}{2} \)-chord
    - Biases \( \alpha \) 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**

![Lift Chart]

**Drag**

![Drag Chart]

Source: NASA, 2009
Implementation of Secondary Effects

Experimental Data at 0.8 m/s
Implementation of Secondary Effects

Experimental Data at 0.8 m/s

Model Prediction with no Secondary Effects
Implementation of Secondary Effects

- Experimental Data at 0.8 m/s
- Dynamic Stall added
- Model Prediction with no Secondary Effects
Implementation of Secondary Effects

Experimental Data at 0.8 m/s

Dynamic Stall added

Dynamic Stall & Pitch Rate Effects added

Model Prediction with no Secondary Effects
Implementation of Secondary Effects

- Dynamic Stall, Pitch Rate & Flow Curvature Effects added
- Dynamic Stall & Pitch Rate Effects added
- Dynamic Stall added
- Model Prediction with no Secondary Effects
Model Prediction of Inflow Variation
Extrapolation to 1.5 m/s

\[ C_{PERROR} = \max\left( \frac{C_P}{N-4}; N \right) - \min\left( \frac{C_P}{N-4}; N \right) \]
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

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)

\[ \alpha_{3/4} \approx 10^\circ \]

\[ \alpha_{1/2} \approx 6^\circ \]
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

- Dr. Brian Polagye
- Dr. Alberto Aliseda
- Dr. Brian Fabien
- Dr. Roy Martin
- Dr. Philip Malte
- Bill Kuykendall
- Kevin Soderlund, Eamon McQuaide
- Dr. Jim Thomson & APL
- Capstone Design Team: Nick Stelzenmuller, Bronwyn Hughes, Josh Anderson, Celest Johnson, Brett Taylor, Leo Sutanto
- NNMREC Organization
- Sandia National Labs
- Marie
Questions?
Backup Slides
System Performance

- **Battery Energy (W-hr)**
  - Average Load Power: 15 W
  - Average Delivered Power: 15.7 W

- **Tidal Speed (m/s)**

Time (days)
System Performance

- Turbine-generator matching

\[ \omega_{GEN} = G \omega_{TURB} \]
\[ T_{GEN} = \frac{\eta}{G} T_{TURB} \]

- Desired generator characteristics
  - Low speed operation
    - 60–80 rpm for direct drive
  - High efficiency
  - Flat efficiency curve
  - Fits within Sea Spider size constraints
  - Low starting torque, low cogging
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Sealed Lead-Acid</th>
<th>NiMH</th>
<th>NiCd</th>
<th>Lithium-Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Density (Wh/L)</td>
<td>Low 50-90</td>
<td>High 430</td>
<td>Low 15-100</td>
<td>High 570</td>
</tr>
<tr>
<td>Cycle Life (cycles)</td>
<td>Low 200-500</td>
<td>Medium 300-1000</td>
<td>High 1500</td>
<td>High 1000+</td>
</tr>
<tr>
<td>Memory Effect</td>
<td>Low No effect</td>
<td>Medium Less than NiCd</td>
<td>High Periodic discharge required</td>
<td>Low No effect</td>
</tr>
<tr>
<td>Charging Time</td>
<td>High 8-16 hours</td>
<td>Medium 2-4 hours</td>
<td>Low about 1 hour</td>
<td>Medium 1-4 hours</td>
</tr>
<tr>
<td>Cost ($/kWh)</td>
<td>Low $8.50</td>
<td>Medium $18.50</td>
<td>Low-Medium $11.00</td>
<td>High $24</td>
</tr>
<tr>
<td>Toxicity</td>
<td>Very high</td>
<td>Low</td>
<td>Very high</td>
<td>Low</td>
</tr>
<tr>
<td>Transportation Limitations</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Comments</td>
<td>Slow charging time; low energy density</td>
<td>Generates heat during high rate charge or discharge; tolerant of overcharge or overdischarge</td>
<td>Rugged; lowest cost per cycle; some limitations on use due to toxicity</td>
<td>Transportation limitations; requires complex circuit to operate safely; limited availability for high-power applications</td>
</tr>
</tbody>
</table>

Data Source:
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**
  
  \[
  C_L = \frac{F_L}{\frac{1}{2} \rho u_{REL}^2 A_p} = \frac{F_L}{\frac{1}{2} \rho u_{REL}^2 c h}
  \]
  
  \[
  C_D = \frac{F_D}{\frac{1}{2} \rho u_{REL}^2 A_p} = \frac{F_D}{\frac{1}{2} \rho u_{REL}^2 c h}
  \]

- **Normal - Tangential Force**
  
  \[
  C_T = \frac{F_T}{\frac{1}{2} \rho u_{REL}^2 A_p} = \frac{F_T}{\frac{1}{2} \rho u_{REL}^2 c h}
  \]
  
  \[
  C_N = \frac{F_N}{\frac{1}{2} \rho u_{REL}^2 A_p} = \frac{F_N}{\frac{1}{2} \rho u_{REL}^2 c h}
  \]
Helical Turbine Parameters

- Blade Profile

![Diagram showing blade profile and performance curves for different turbine models.](image-url)
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

\[ \omega = \frac{BH}{\pi D \tan \delta} \]

100% Wrap

50% Wrap
# Test Matrix

<table>
<thead>
<tr>
<th>Turbine Design</th>
<th>Strut Design</th>
<th>Flume Velocity (m/s)</th>
<th>Performance test</th>
<th>Static Torque</th>
<th>Dynamic Torque</th>
<th>Startup - Shutdown</th>
<th>Tilted Turbine</th>
<th>Wake Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Blade, from 4-bladed turbine</td>
<td>Circular Plates</td>
<td>6.4</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>4-bladed turbine</td>
<td>4.8 mm, 4-leg spokes</td>
<td>6.4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>2.0 mm, 4-leg spokes</td>
<td>6.4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>No shaft</td>
<td>6.4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Circular Plates</td>
<td>6.4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>--</td>
</tr>
<tr>
<td>3-bladed turbine</td>
<td>4.8 mm, 3-leg spokes</td>
<td>6.4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>--</td>
</tr>
<tr>
<td>Low Solidity Turbine</td>
<td>4.8 mm, 3-leg spokes</td>
<td>6.4</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>--</td>
</tr>
</tbody>
</table>

X: Test Completed
Test Calculations

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

Load Performance Test

Static Torque Test
Typical Test Results

Load Performance Test

Static Torque Test
Streamwise View

\( \theta = 0^\circ \)  
\( \theta = 20^\circ \)  
\( \theta = 40^\circ \)  
\( \theta = 70^\circ \)

Static torque near maximum

Static torque drops
Single Blade Static Torque
Single Blade Torque Superposition
Streamwise View

\[ \theta = 0^\circ \]
\[ \theta = 20^\circ \]
\[ \theta = 40^\circ \]
\[ \theta = 70^\circ \]

Static torque near maximum

Unobstructed (-T) blade

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

3-Bladed Turbine

4-Bladed Turbine

Static Torque Test Results

- 4-Blade Turbine
- 3-Blade Turbine

flume speed: 0.70 m/s

Static Torque Coefficient, C_qs

Angle, degrees

0 50 100 150 200 250 300 350

0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08
Tilted Turbine Test

<table>
<thead>
<tr>
<th>Strut Design</th>
<th>Tilt Angle (degrees)</th>
<th>Tilt Velocity</th>
<th>Predicted $C_p$ Loss from $\cos(\text{Tilt})$</th>
<th>Actual $C_p$ Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 mm, 4-Leg Spoke</td>
<td>0</td>
<td>0.720</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>0.719</td>
<td>-0.2%</td>
<td>-5.6%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.717</td>
<td>-0.7%</td>
<td>-8.8%</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.709</td>
<td>-2.8%</td>
<td>-23.0%</td>
</tr>
<tr>
<td>2 mm Circular Plate</td>
<td>0</td>
<td>0.720</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>0.719</td>
<td>-0.2%</td>
<td>-4.5%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.717</td>
<td>-0.8%</td>
<td>-4.4%</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.709</td>
<td>-3.3%</td>
<td>-8.9%</td>
</tr>
</tbody>
</table>
Wake Measurement Test

- Baseline Configuration
- Flume: 0.78 m/s
- Wake measurements along turbine centerline
Start-up Shutdown Test Profile

<table>
<thead>
<tr>
<th>Starting Angle</th>
<th>Load Torque (Nm)</th>
<th>Cut-In Speed (m/s)</th>
<th>Cut-Out Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.006</td>
<td>0.47</td>
<td>0.21</td>
</tr>
<tr>
<td>10</td>
<td>0.006</td>
<td>0.47</td>
<td>0.21</td>
</tr>
<tr>
<td>20</td>
<td>0.006</td>
<td>0.47</td>
<td>0.21</td>
</tr>
<tr>
<td>30</td>
<td>0.006</td>
<td>0.58</td>
<td>0.22</td>
</tr>
<tr>
<td>40</td>
<td>0.006</td>
<td>0.60</td>
<td>0.20</td>
</tr>
<tr>
<td>50</td>
<td>0.006</td>
<td>0.57</td>
<td>0.19</td>
</tr>
<tr>
<td>60</td>
<td>0.006</td>
<td>0.60</td>
<td>0.23</td>
</tr>
<tr>
<td>70</td>
<td>0.006</td>
<td>0.55</td>
<td>0.18</td>
</tr>
<tr>
<td>80</td>
<td>0.006</td>
<td>0.47</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>Average cut-in/cut-out speed at 0.006 Nm load torque:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>0.53</strong></td>
<td></td>
<td><strong>0.21</strong></td>
</tr>
</tbody>
</table>

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 $u_{REL}$
- Total change in circulation over time is zero (Kelvin’s theorem):
- Vortex-induced velocity at a point is found by Biot-Savart Law:
- Circulation strength is found from Kutta-Joukowski theorem:
- Predictor-corrector to solve system of equations
Boeing Vertol Dynamic Stall Model

\[
\alpha_{REF(L,D)} = \alpha - K_1 \gamma \sqrt{\frac{c \dot{\alpha}}{2u_{REL}}} \text{sign}(\dot{\alpha}).
\]

\[
C_L = \left( \frac{c_{LREF}}{\alpha_{REF} - \alpha_{ZL}} \right) \alpha
\]

\[
C_D = C_{DREF}
\]
Flow Curvature

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

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

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

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

- ‘Virtual camber’
Full-Scale Turbine Prediction

All Secondary Effects Active

\[ C_P \]

\[ \lambda \]

\[ C_P \text{ Error} \]

\[ \lambda \]
Full-Scale Turbine Prediction

Dynamic Stall only
Model Prediction of Strut Drag

- $u_o = 0.8 \text{ m/s}$