
Marine and Hydrokinetic Instrumentation, Measurement, & Computer Modeling Workshop
Broomfield, CO
July 9-10, 2012

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Objective

Develop a design tool for wind & hydrokinetic turbines rotors, combining
• aerodynamic models
• structural models
• multi-objective optimization

Applications

• Sizing of new machines
• Modifications to existing designs

Motivation

• Difficult problem considering many variables & constraints
• Optimization leads to improved designs beyond our intuition
• Accelerate design process
**Intro: HARP_Opt code**

**HARP_Opt (Horizontal Axis Rotor Performance Optimization)**

An optimization code for the design of horizontal-axis wind and hydrokinetic turbines

**Objectives:**
- maximize annual energy production (AEP)
- minimize blade mass

**Given:**
- turbine & environmental specifications

**Variables:**
- blade shape, rotor speed & blade pitch control
- structural material thickness

**Constraints:**
- power, cavitation, rotor speeds
- max allowable strain
Technical Approach: Hydrodynamics

• Blade Element Momentum Theory
  – WT_Perf (NREL code), simpler than CFD but computationally fast
  – Steady performance, uniform or sheared inflow
  – Hub/tip losses, turbulent wake state, corrections for 3D stall-delay
  – Cavitation inception model

\[ \sigma + C_{P_{min}} \geq 0 \]

\[ \sigma = \frac{P_{atm} + \rho gh - (SF)P_{vapor}}{1/2 \rho V_{loc}^2} \]
Technical Approach: Structural Mechanics

- Euler-Bernoulli beam theory
  - Thin-shell cantilever beam, isotropic material properties
  - Design load resolved from max root moment over full range of operating conditions (with applied safety factor)
  - Consider max allowable bending strain only

\[ \varepsilon = (SF) \frac{M\Delta y}{EI} \]
Technical Approach: Optimization

Optimization Algorithm

- Multi-Objective Genetic Algorithm
  - Mimics biological evolution, i.e. “survival of the fittest”
  - Slow convergence, good for multi-optima problems, no gradient info required

Objectives and Fitness Function

- Penalty method (a constrained problem becomes unconstrained)

\[ \text{Maximize:} \quad AEP \times \prod_{n} p_n \]

\[ p_{\text{power}} \]
\[ p_{\text{cavitation}} \]
\[ p_{\text{torque}} \]
\[ p_{\text{thickness}} \]

\[ \text{Minimize:} \quad \text{blade mass} \times \prod_{n} p_n \]

Penalty factors are proportional to the violation of constraints
Technical Approach: Blade Geometry

- Bézier curves define twist and chord distributions
- % thickness denotes airfoil placement
- Great degree of freedom in possible blade shapes

![Graphs showing twist, chord, and thickness distributions along blade length.](image)
Technical Approach: Design Algorithm

Input turbine specifications

Optimization: initial population

define blade shape

calc \( C_p = f(\lambda, \Theta_P) \)

calc AEP and design loads

define structural members

calc blade mass

calc constraints

apply penalties

Convergence?

Yes

Outputs to finer analysis

No

Optimization: alter design variables

tip speed ratio, \( \lambda = \frac{\omega R}{U_\infty} \)

operating curve
Applications: Example #1
Design of 5m dia., 72 kW MHK turbine: investigate various control schemes

- Fixed-Speed Fixed-Pitch
- Fixed-Speed Variable-Pitch
- Variable-Speed Variable-Pitch
- Variable-Speed Fixed-Pitch
Applications: Example #1
Design of 5m dia., 72 kW MHK turbine: investigate various control schemes

- Fixed-Speed Fixed-Pitch
- **Fixed-Speed Variable-Pitch**
- Variable-Speed Variable-Pitch
- Variable-Speed Fixed-Pitch
Applications: Example #1
Design of 5m dia., 72 kW MHK turbine: investigate various control schemes

- Fixed-Speed Fixed-Pitch
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Applications: Example #1

Design of 5m dia., 72 kW MHK turbine: investigate various control schemes

- Fixed-Speed Fixed-Pitch
- Fixed-Speed Variable-Pitch
- Variable-Speed Variable-Pitch
- Variable-Speed Fixed-Pitch
## Summary of Performance Data

<table>
<thead>
<tr>
<th></th>
<th>(V_{\text{rated}}) (m/s)</th>
<th>(C_{\text{p,max}}) (-)</th>
<th>AEP (kW-hr/yr)</th>
<th>Max Flap (kN-m)</th>
<th>Max Torque (kN-m)</th>
<th>Max Thrust (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS-FP</td>
<td>2.7</td>
<td>0.49</td>
<td>148000</td>
<td>21.7</td>
<td>25.6</td>
<td>47.0</td>
</tr>
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<td>FS-VP</td>
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<td>0.50</td>
<td>152000</td>
<td>21.4</td>
<td>16.4</td>
<td>46.0</td>
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<td>VS-VP</td>
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<td>0.50</td>
<td>155000</td>
<td>21.5</td>
<td>17.3</td>
<td>45.7</td>
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<tr>
<td>VS-FP</td>
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<td>0.49</td>
<td>154000</td>
<td>22.0</td>
<td>20.9</td>
<td>45.8</td>
</tr>
</tbody>
</table>
**Applications: Example #2**

<table>
<thead>
<tr>
<th>Design Specs (Summary)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control</strong> =</td>
<td>VSVP (feather)</td>
</tr>
<tr>
<td><strong>Rated Power</strong> =</td>
<td>250 kW</td>
</tr>
<tr>
<td><strong>Diameter</strong> =</td>
<td>10 m</td>
</tr>
<tr>
<td><strong>Flow Regime</strong> =</td>
<td>Marrowstone Island, C5</td>
</tr>
<tr>
<td><strong>E</strong> =</td>
<td>27.6 GPa</td>
</tr>
<tr>
<td><strong>ρ</strong> =</td>
<td>1800 kg/m³</td>
</tr>
<tr>
<td><strong>Max Strain</strong> =</td>
<td>3000 microstrain</td>
</tr>
<tr>
<td><strong>Sf_{cav}, SF_{loads}</strong> =</td>
<td>1.2</td>
</tr>
</tbody>
</table>
| **Hydrofoils** =       | Circular @ root  
FFA-W3-211  
FFA-W3-241  
FFA-W3-301 |

- Representative values for composite fiberglass (GRFP)
- FFA hydrofoils resistant to cavitation and soiling

Applications: Example #2

- Structural objectives *compete* with hydrodynamic objectives
- Identify “Pareto frontier”: a set of equally optimal design (in a mathematic sense)
- Make *trade-offs within Pareto set*, rather than consider full parameter range

Compared to best AEP solution:
- blade mass cut in half
- < 1% loss in AEP
Moving Forward:

Develop a tool capable of modeling realistic composite blades

Image: www.Gurit.com
Future Direction: Advanced Structural Optimization

**CoBlade**: Software for Structural Analysis & Design of Composite Blades

- **realistic modeling of composite blades**
  - arbitrary topology & material properties

- **technical approach**
  - Euler-Bernoulli beam & shear flow theory
  - classical lamination theory
  - linear (eigenvalue) buckling
  - finite-element modal analysis

- **computes structural properties**
  - stiffnesses: bending, torsional, axial
  - inertias: mass, mass moments of inertia
  - principal axes: inertial/centroidal/elastic principal axes
  - offsets: center-of-mass, tension-center, shear-center
  - modal: coupled mode shapes & frequencies

- **optimization of composite layup**

*For a given (static) design load, minimize blade mass subject to constraints on:*

- max allowable lamina stresses
- blade tip deflection
- panel buckling stresses
- separation of blade & rotor nat. frequencies

Image: replica of Sandia SNL100-00 wind turbine blade modeled with CoBlade
Future Direction: Advanced Structural Optimization

Optimization of Composite Blade for Tidal Turbine

- NREL Ref. Model Tidal Turbine: 2-bladed, 550 kW, 20m dia. rotor
- design loads: CFD simulation of 2.85 m/s sudden gust (operating condition)

<table>
<thead>
<tr>
<th>pressure side</th>
<th>pressure loads [Pa] (M. Lawson 2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>35000</td>
</tr>
</tbody>
</table>

- Pattern Search optimization algorithm
- optimization produces a lighter and stiffer blade
Max Stress Failure Criteria (Compression) for Laminas Along Top (Suction) Surface:

Effective Beam Stresses:
- normal stress, $\sigma_{zz}$ (MPa)
- shear stress, $|\tau_{zs}|$ (MPa)
- buckling criteria, $R$

<table>
<thead>
<tr>
<th>$R$</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>blade-shell material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>root build-up material</td>
<td></td>
<td></td>
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<tr>
<td>spar-cap material</td>
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<tr>
<td>core material</td>
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</table>
Progress to-date:

- developed *preliminary design tool* for axial flow wind & hydrokinetic turbines, method is generalized to a *variety of turbine configurations* & sizes
- consideration of *multiple design criteria & constraints* leads to satisfactory design in all areas (hydrodynamics, structures, & controls)
- enabling improved performance & reduced design time

Areas for Refinement

Short-term (Sept. 2012 release)

- implement Pattern Search optimization algorithm (*much* faster & deterministic)
- improve MATLAB/Fortran interface, allowing for parallel HPC
- make HARP_Opt cross-platform, develop GUI and non-GUI versions for improved usability & interfacing

Longer-term

- consider fatigue as design criteria (hydro-elastic analysis, i.e. *FAST* code)
Thank you! Questions?

**WT_Perf**: Turbine Performance Simulator

**HARP_Opt**: Optimization Software for Turbine Design

**CoBlade**: Software for Analysis & Design of Composite Blades
no website yet—contact dsale@uw.edu for source & documentation
[depts.washington.edu/nnmrec/docs/20120213_SaleD_pres_StructuralDesign.pdf](http://depts.washington.edu/nnmrec/docs/20120213_SaleD_pres_StructuralDesign.pdf)

Acknowledgements
Special thanks to the crew at NWTC!

This work has also been made possible by
- U.S. Department of Energy, National Renewable Energy Laboratory
- University of Washington, Northwest National Marine Renewable Energy Center
- National Science Foundation, Graduate Research Fellowship under Grant No. DGE-0718124