UNIVERSITY of WASHINGTON

HARP_Opt: An Optimization Code for System Design of Axial Flow Turbines

Marine and Hydrokinetic Instrumentation, Measurement, & Computer Modeling Workshop

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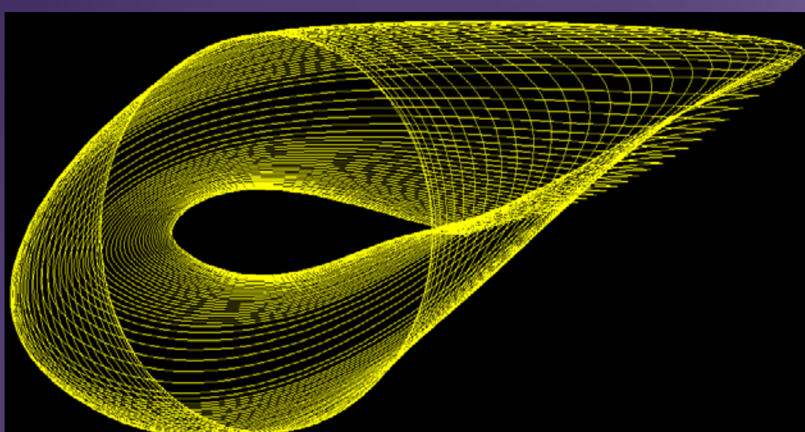


Objective

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* (*H*orizontal *A*xis *R*otor *P*erformance *Opt*imization)**

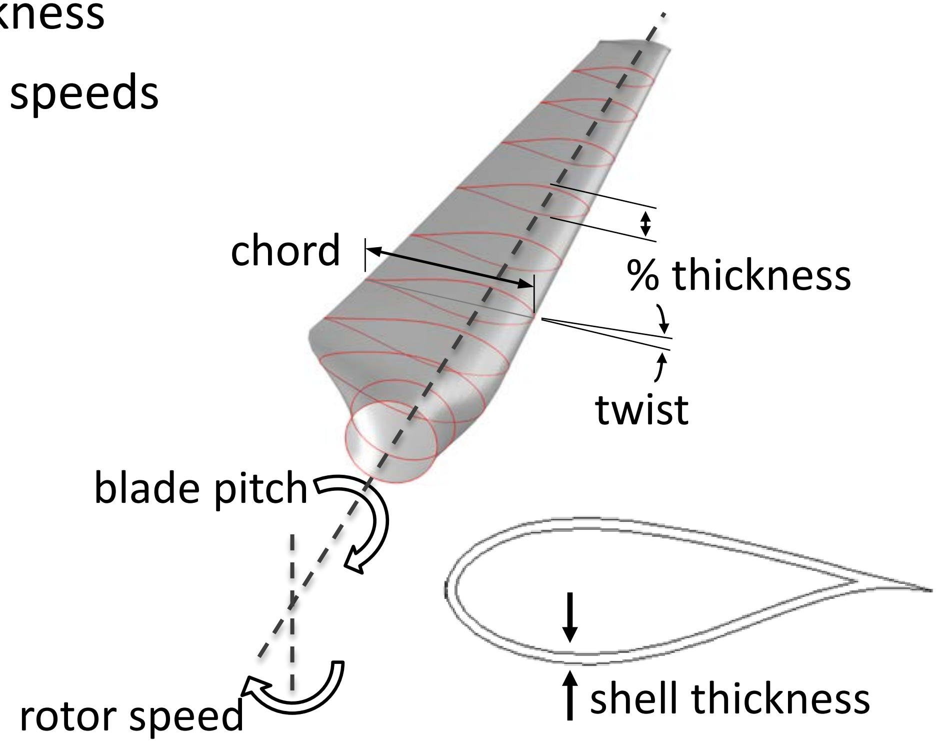
An optimization code for the design of horizontal-axis wind and hydrokinetic turbines

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

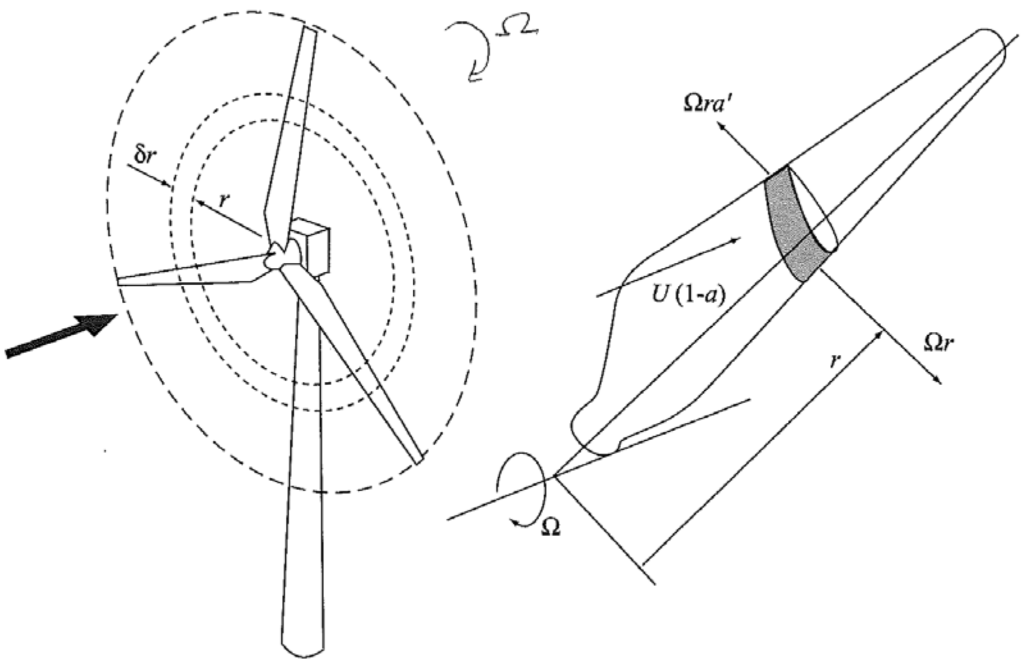
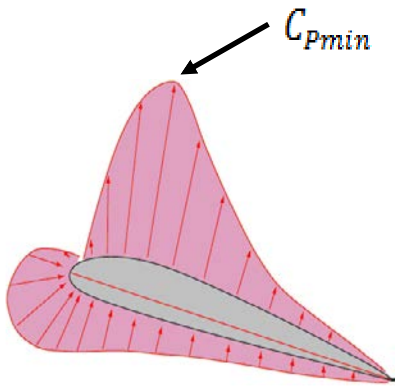


Image: Wind Energy Handbook



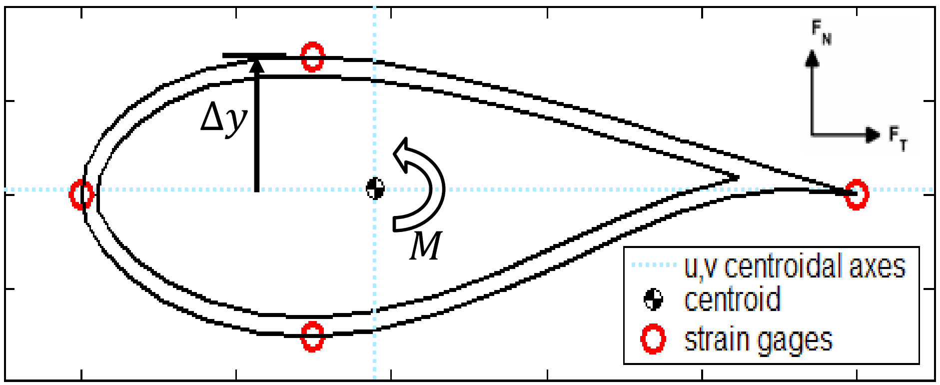
inception criteria:

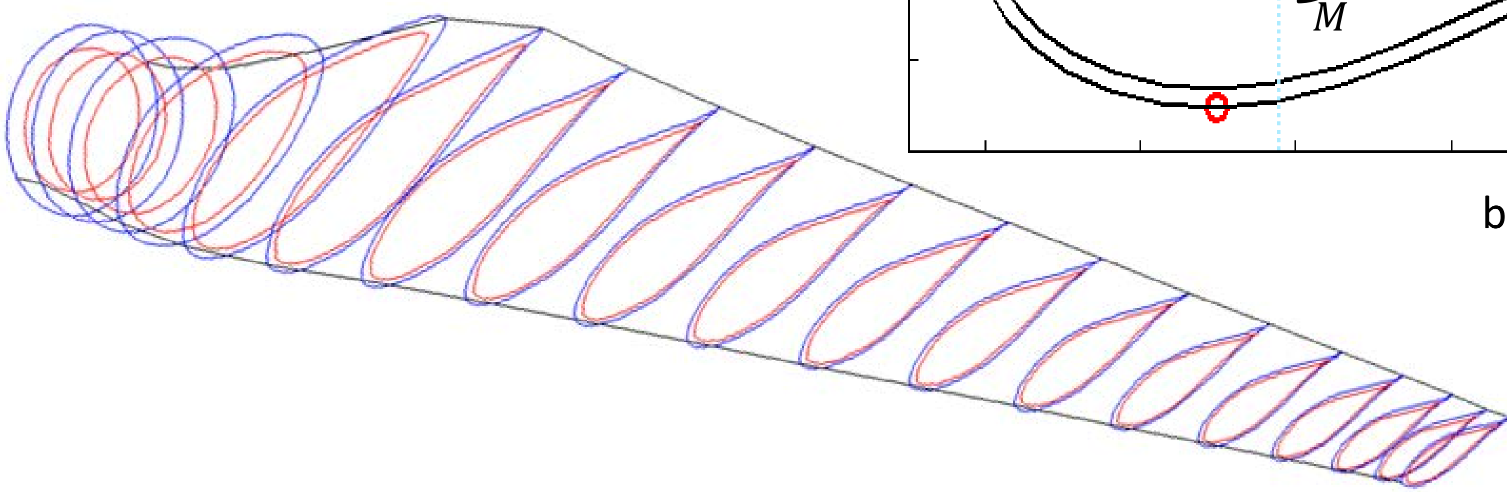
$$\sigma + C_{Pmin} \geq 0$$

$$\sigma = \frac{P_{atm} + \rho g h - (SF)P_{vapor}}{{}^{1}/{}_{2}\,\rho V_{loc}^{2}}$$

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





bending strain:

$$\varepsilon = (SF)\frac{M\Delta y}{EI}$$

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)

Maximize: $$\boldsymbol{AEP} * \prod_n p_n$$

p_{power}

$p_{cavitation}$

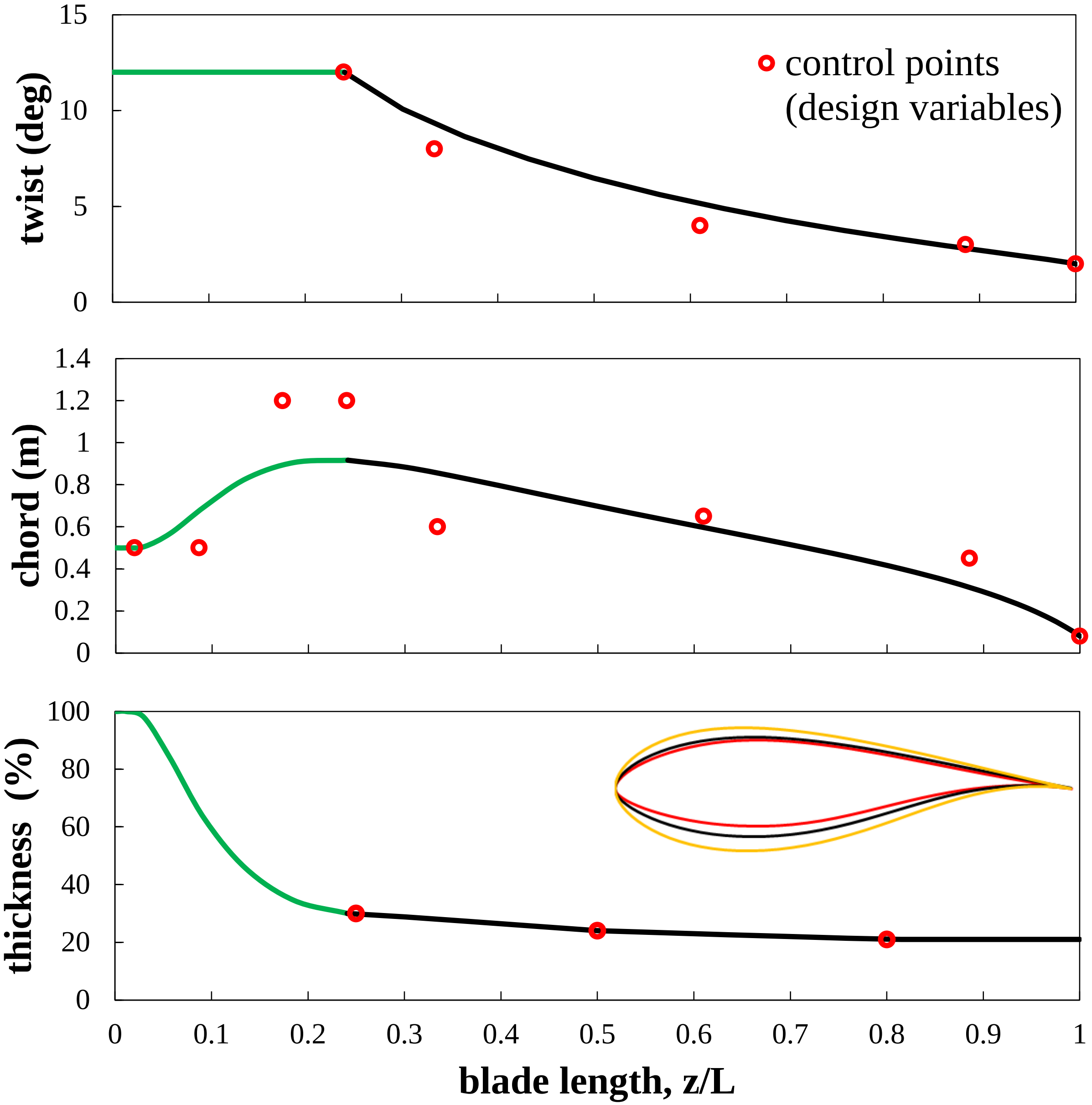
p_{torque}

Minimize: $$\boldsymbol{blade\ mass} * \prod_n p_n$$

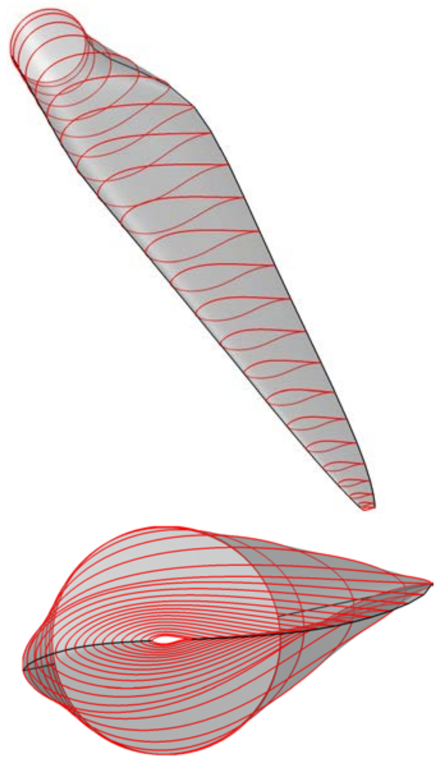
$p_{thickness}$

Penalty factors are proportional to the violation of constraints

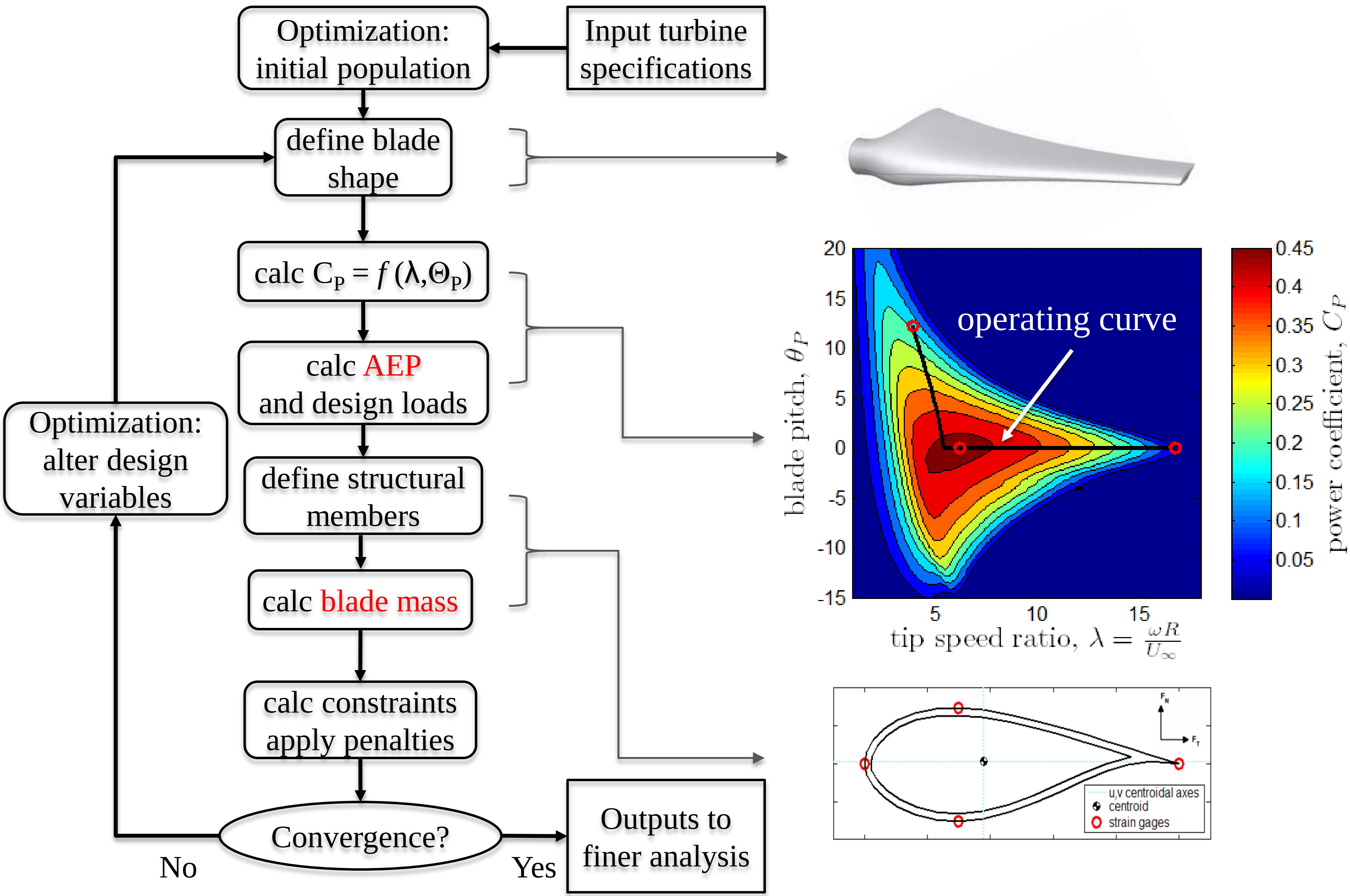
Technical Approach: Blade Geometry



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



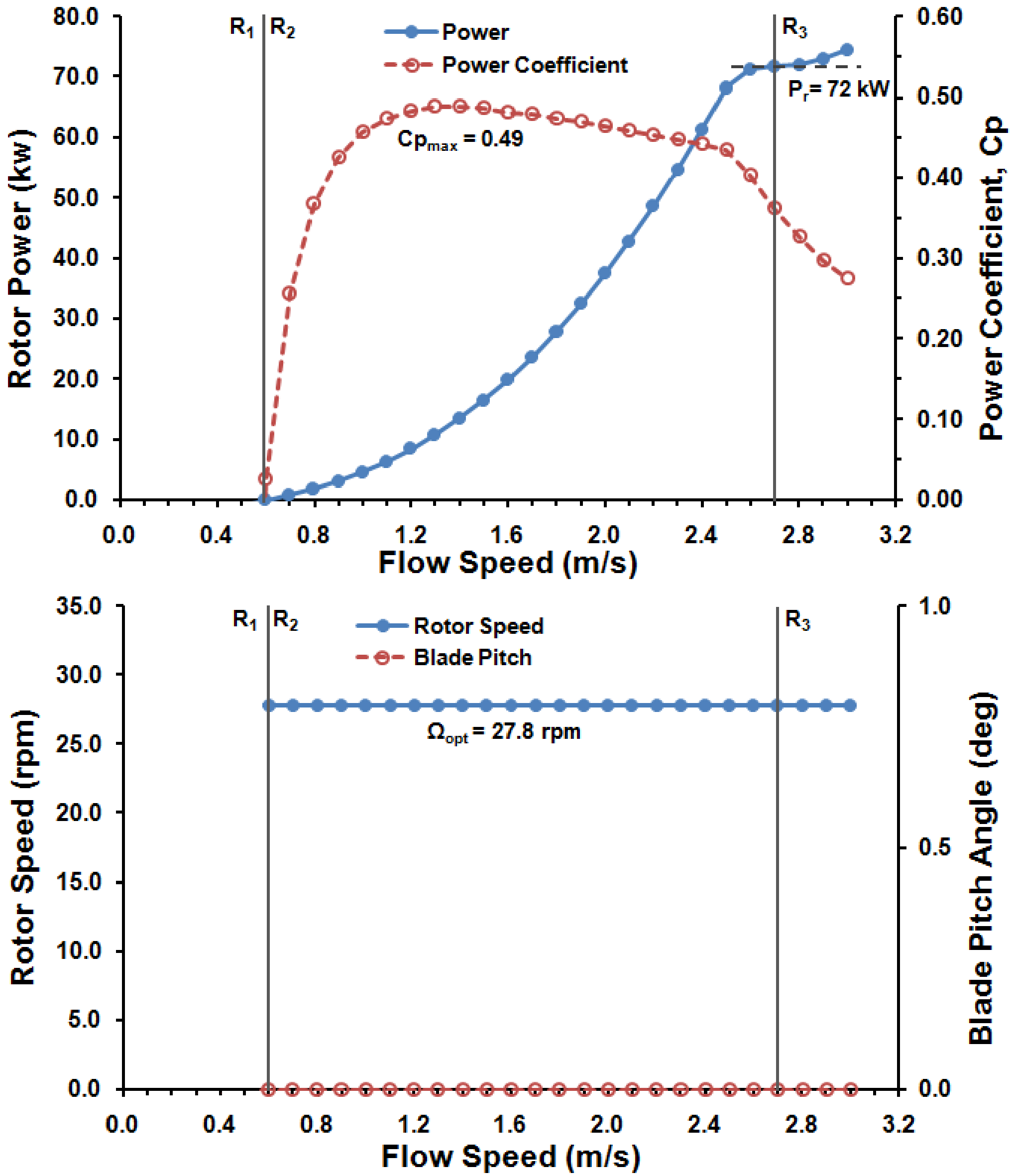
Technical Approach: Design Algorithm



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

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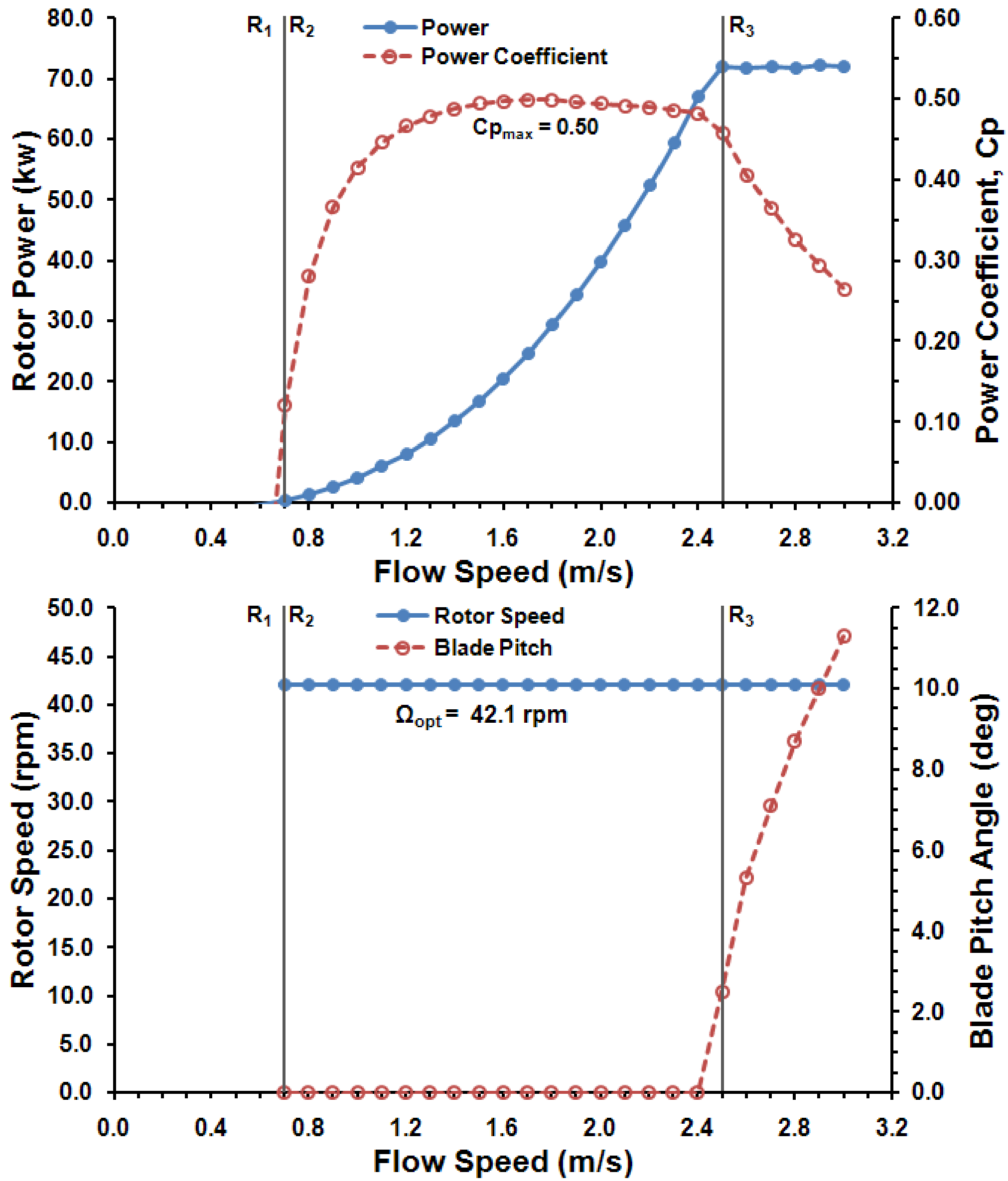
- **Fixed-Speed Variable-Pitch**
- Variable-Speed Variable-Pitch
- Variable-Speed Fixed-Pitch



Applications: Example #1

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

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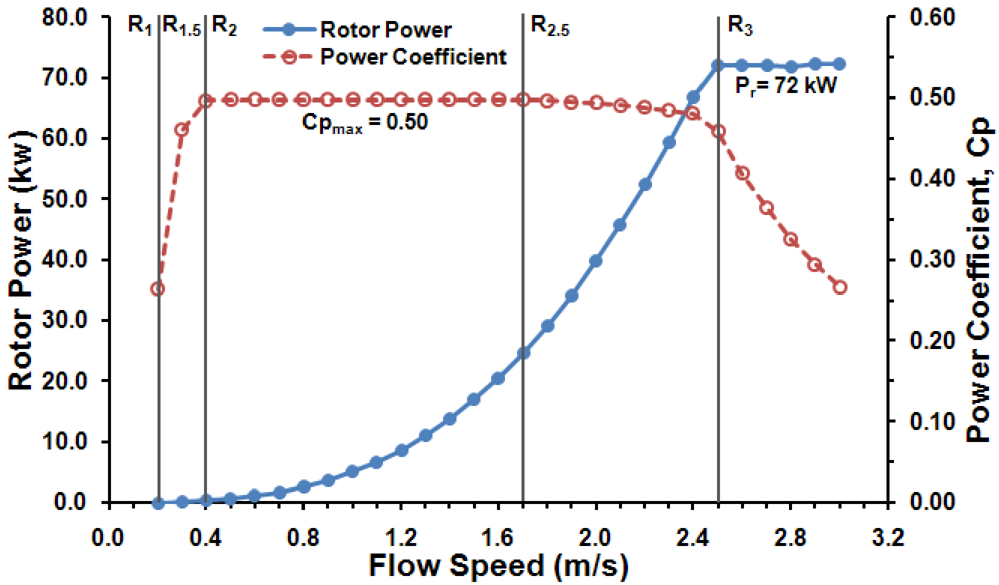
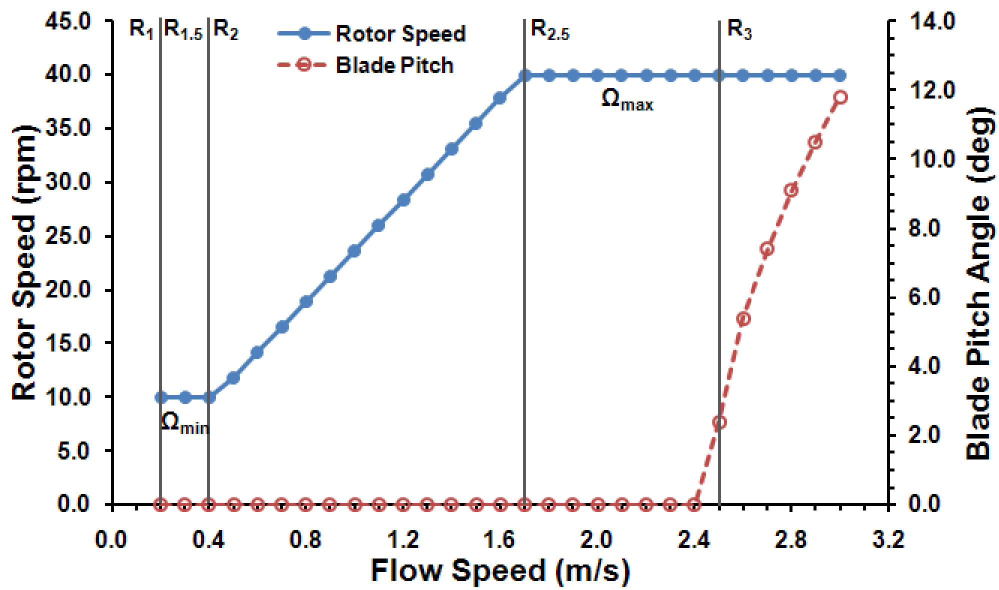
- Fixed-Speed Variable-Pitch
- **Variable-Speed Variable-Pitch**
- Variable-Speed Fixed-Pitch





Applications: Example #1

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

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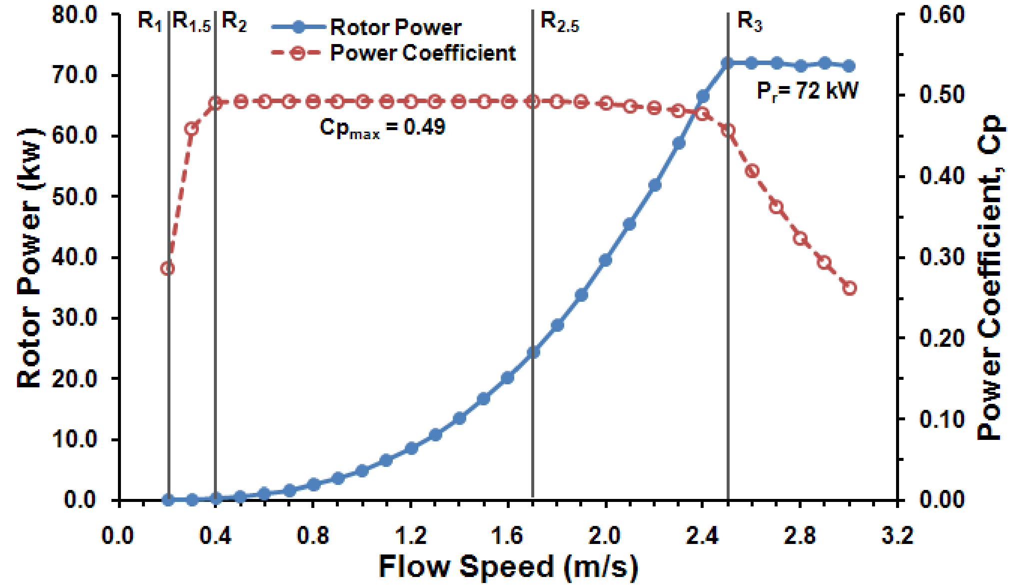
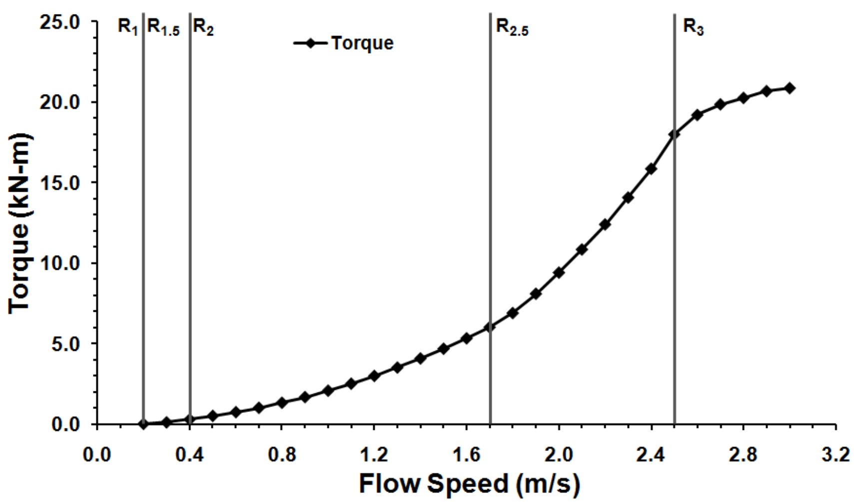
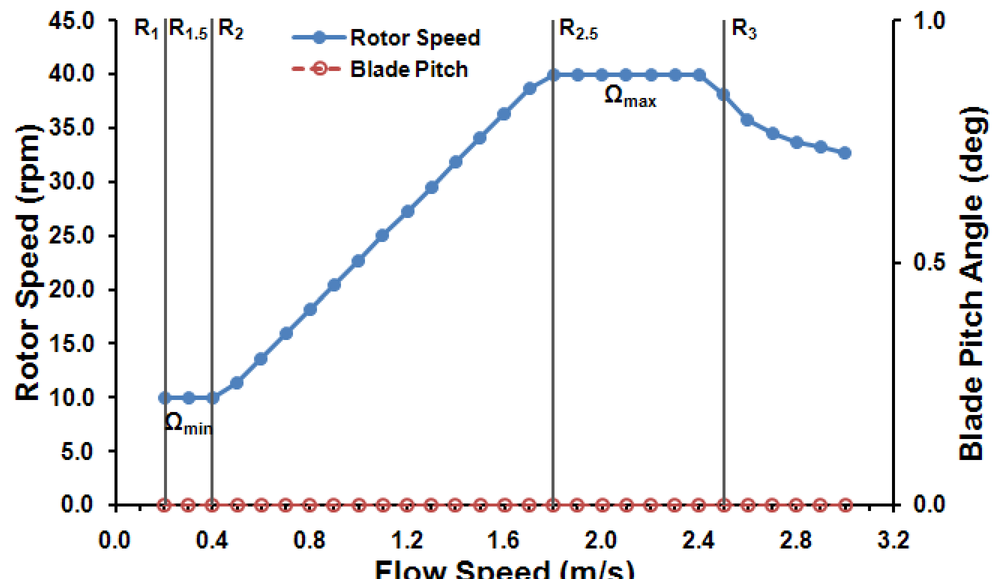






Applications: Example #1

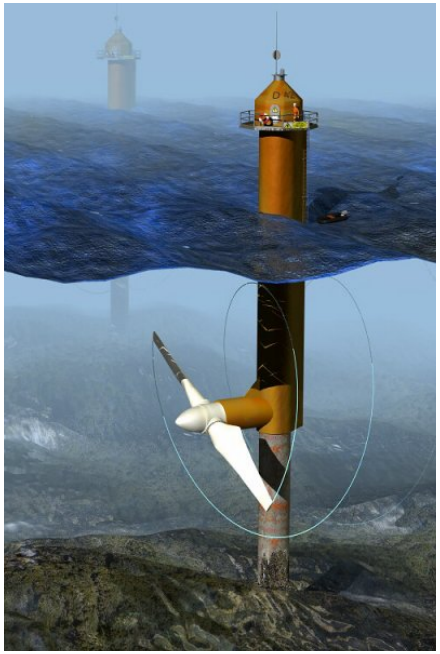
	Summary of Performance Data					
	V_{rated} (m/s)	Cp_{max} (-)	AEP (kW-hr/yr)	Max Flap (kN-m)	Max Torque (kN-m)	Max Thrust (kN)
FS-FP	2.7	0.49	148000	21.7	**25.6**	47.0
FS-VP	2.5	0.50	152000	21.4	16.4	46.0
VS-VP	2.5	0.50	**155000**	21.5	17.3	45.7
VS-FP	2.5	0.49	**154000**	22.0	**20.9**	45.8

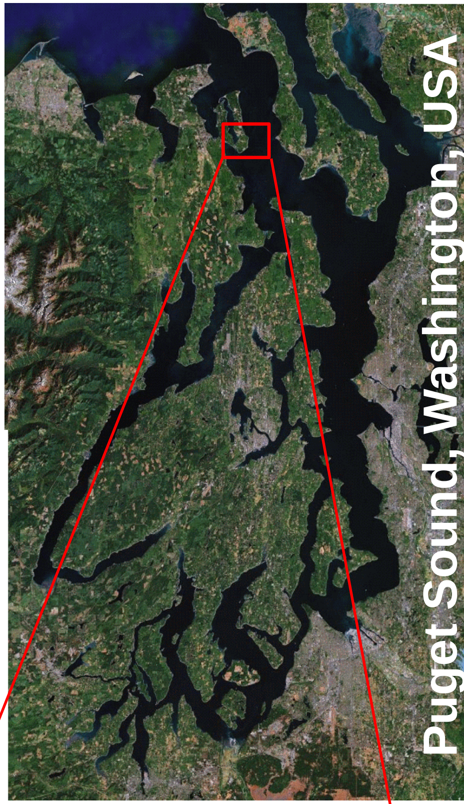
Applications: Example #2

Design Specs (Summary)	
Control =	VSVP (feather)
Rated Power =	250 kW
Diameter =	10 m
Flow Regime	Marrowstone Island, C5
E =	27.6 GPa
ρ =	1800 kg/m^3
Max Strain =	3000 microstrain
Sf_{cav}, SF_{loads} =	1.2
Hydrofoils =	Circular @ root FFA-W3-211 FFA-W3-241 FFA-W3-301

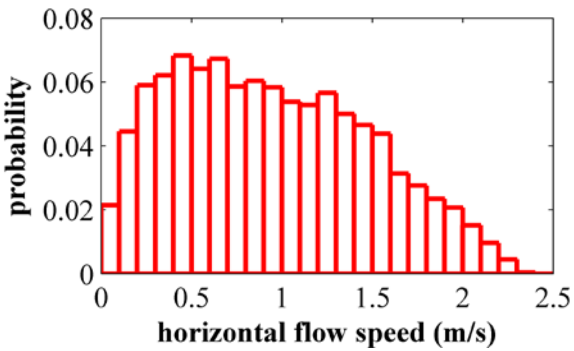
Representative values for composite fiberglass (GRFP) (E, ρ, Max Strain)

FFA hydrofoils resistant to cavitation and soiling



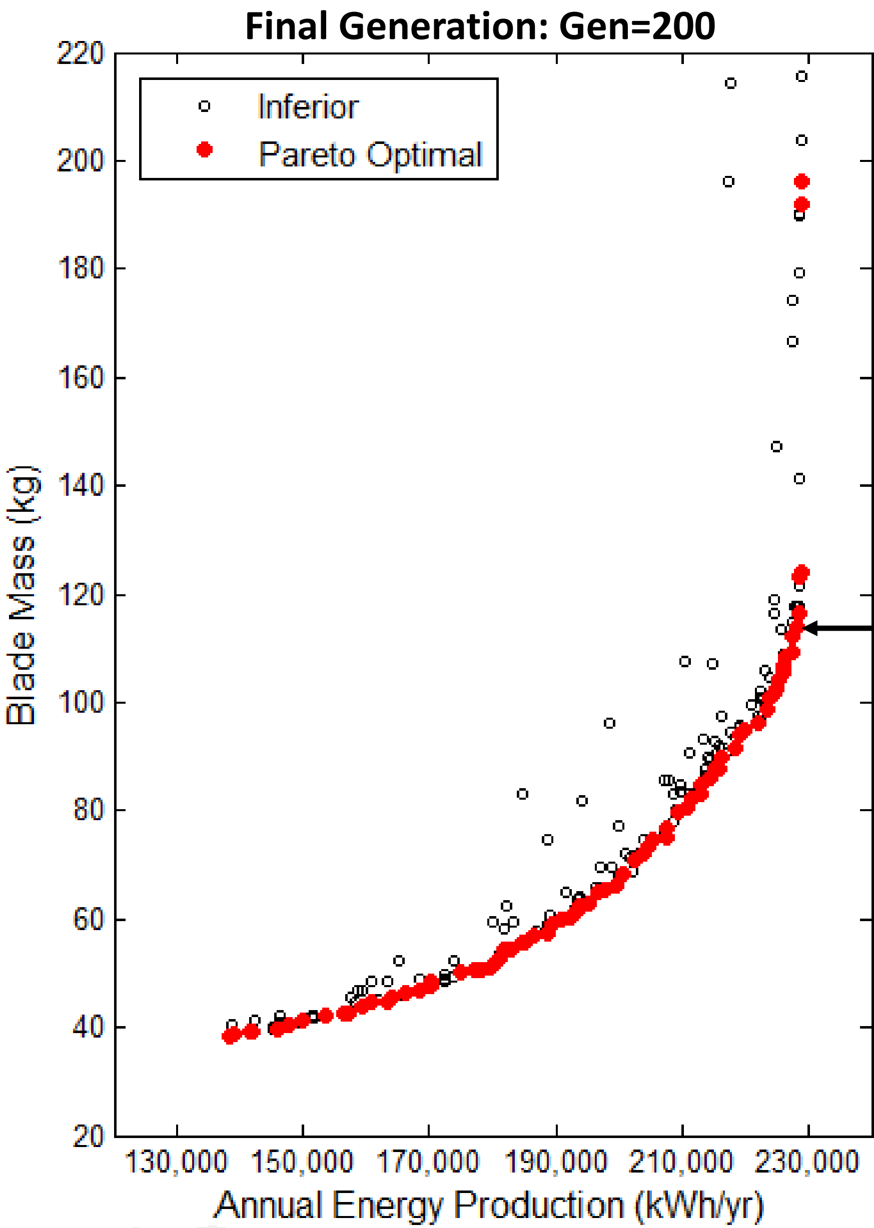


Marrowstone Island (site C5)*

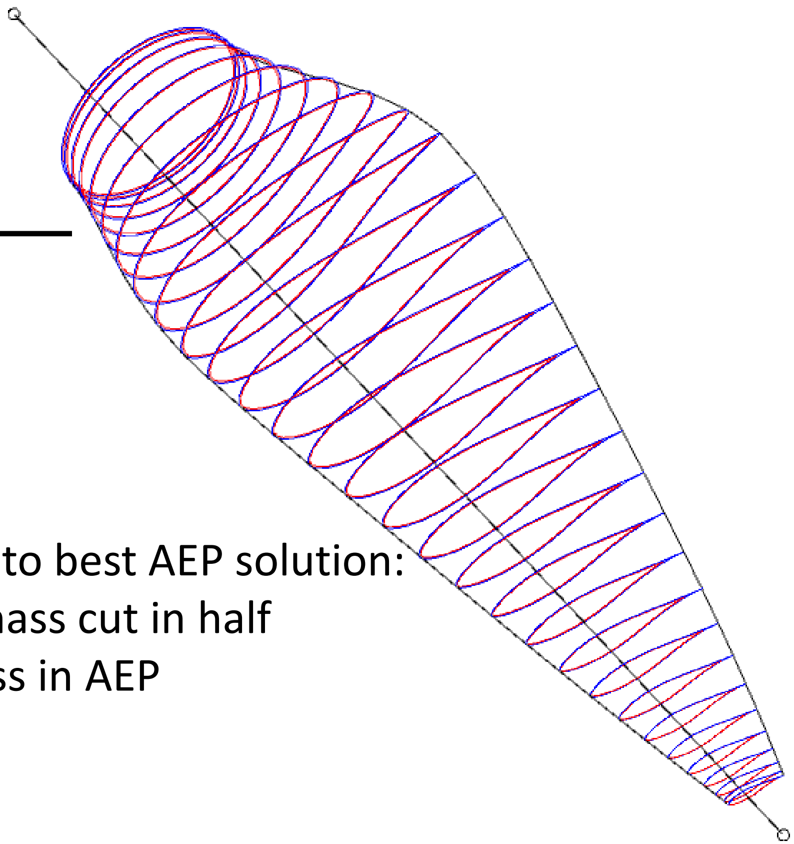


*Gooch, S., et al. "Site Characterization for Tidal Power," *Oceans*, 2009.

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

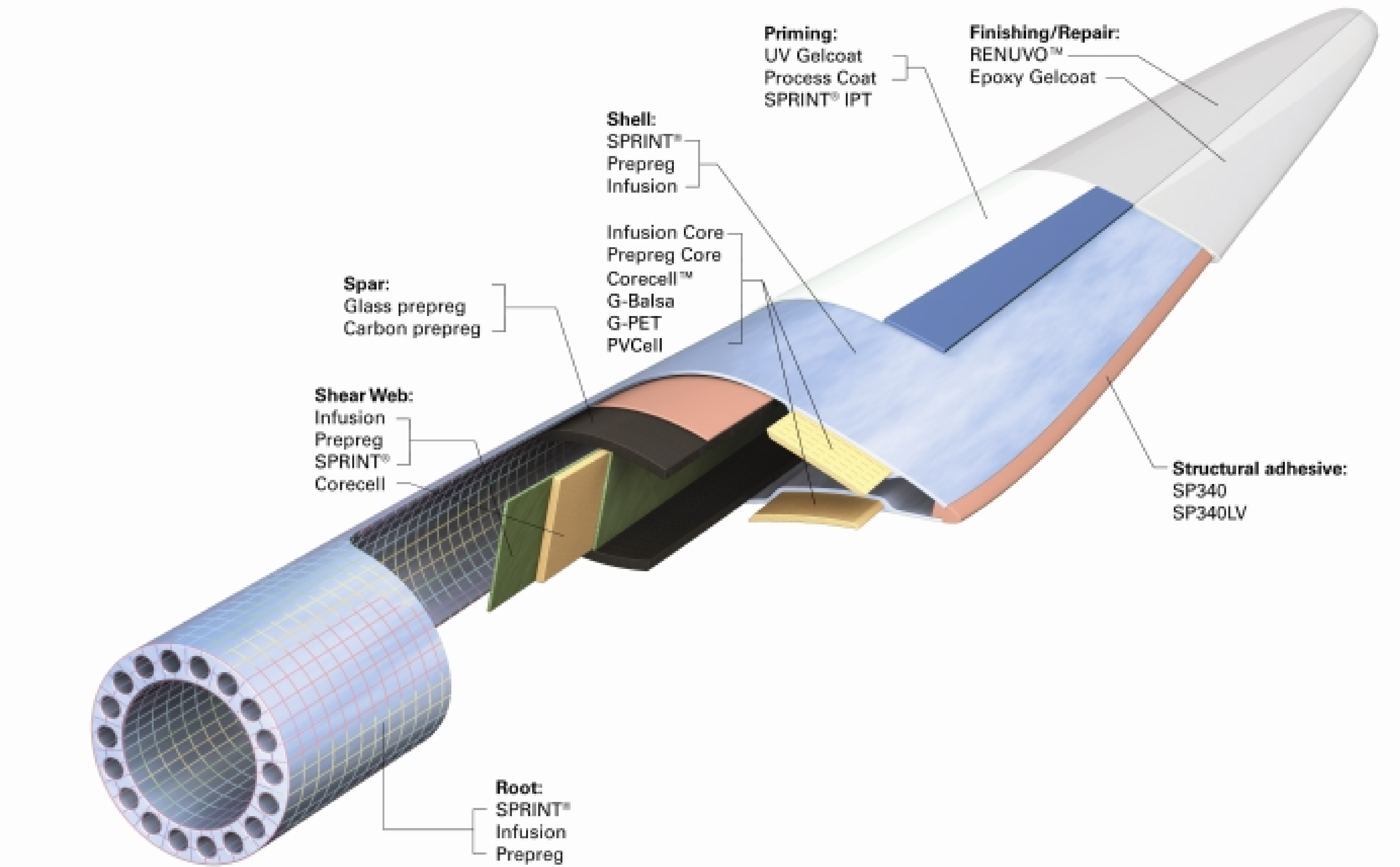


Image: *www.Gurit.com*

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

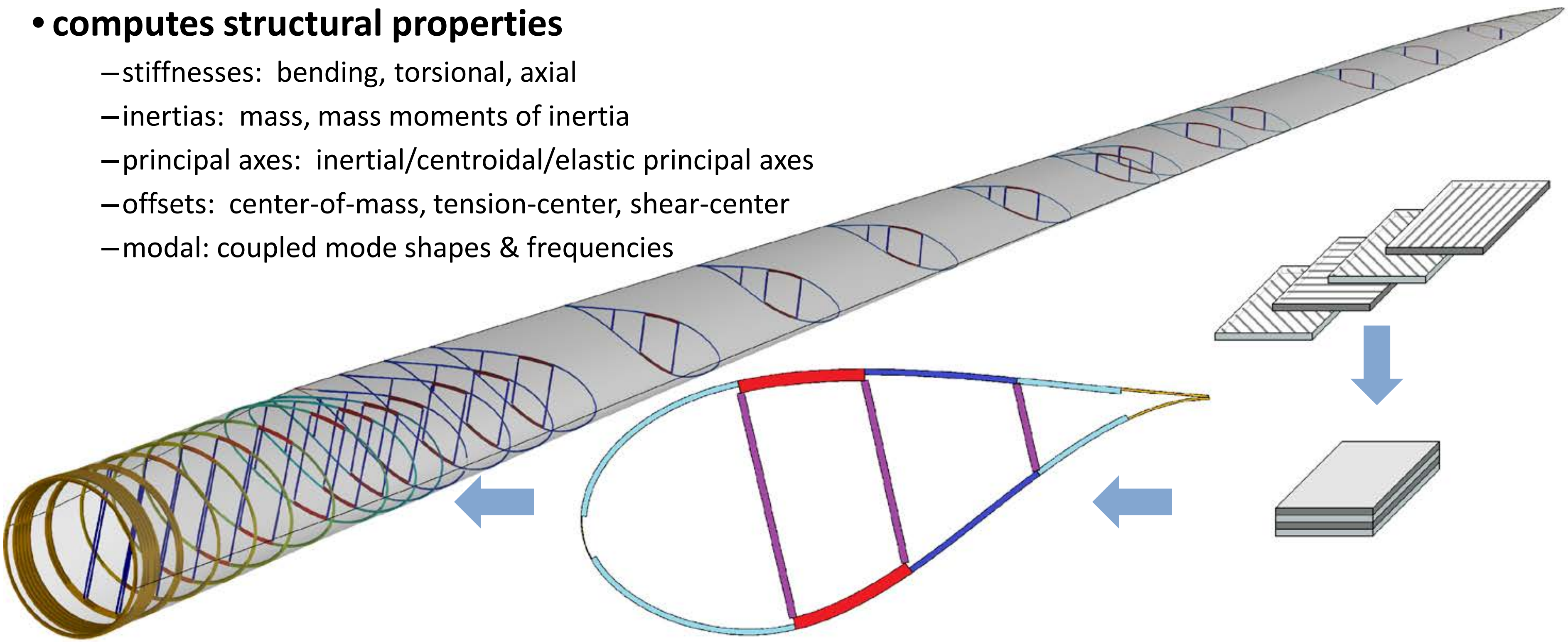


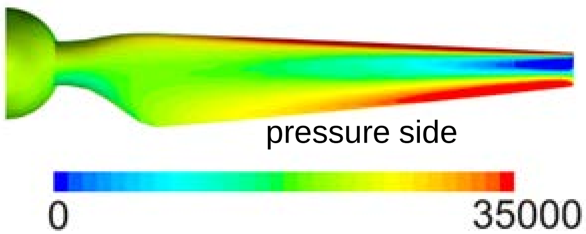
Image: replica of Sandia SNL100-00 wind turbine blade modeled with *CoBlade*

Future Direction: Advanced Structural Optimization

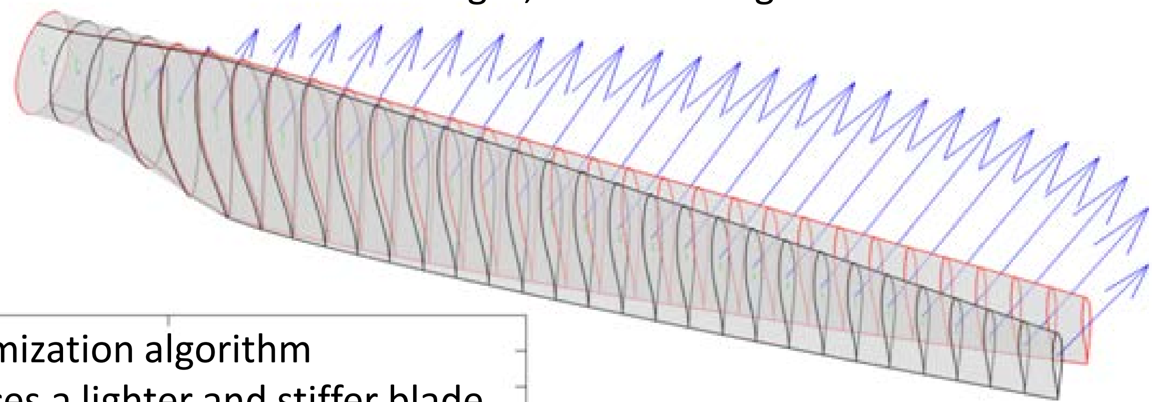
Optimization of Composite Blade for Tidal Turbine

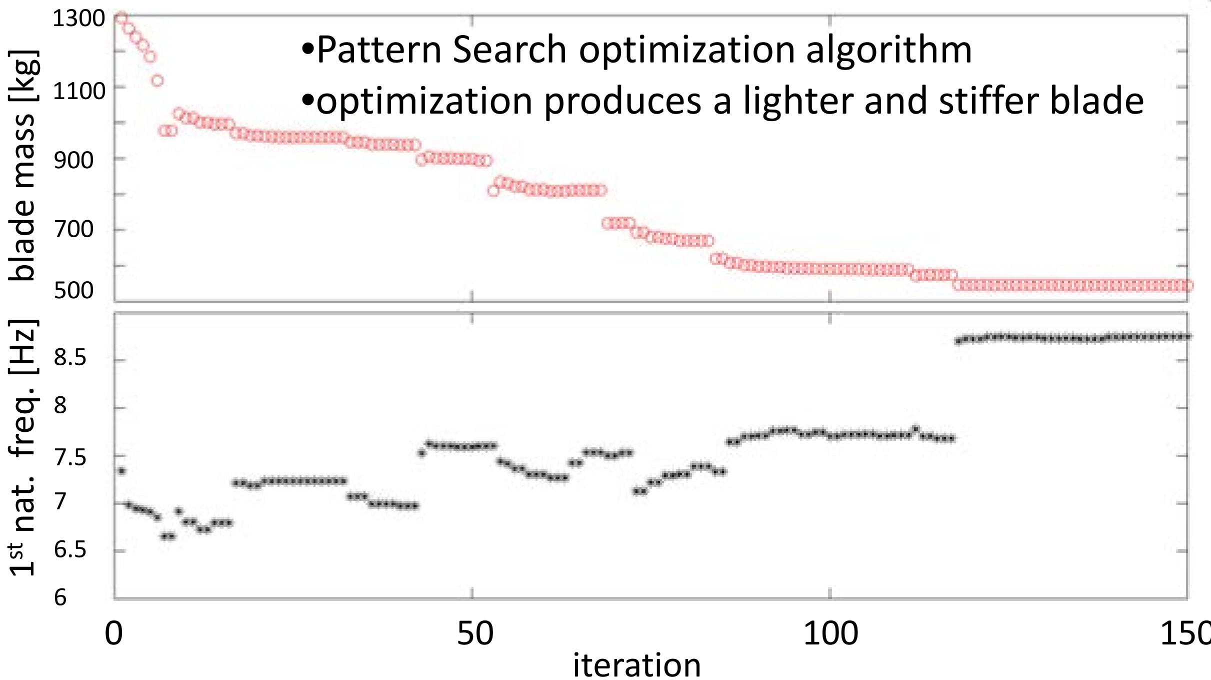
- NREL Ref. Model Tidal Turbine: 2-bladed, 550 kW, 20m dia. rotor
- design loads: CFD simulation of 2.85 m/s sudden gust (operating condition)

pressure loads [Pa] (M. Lawson 2011)

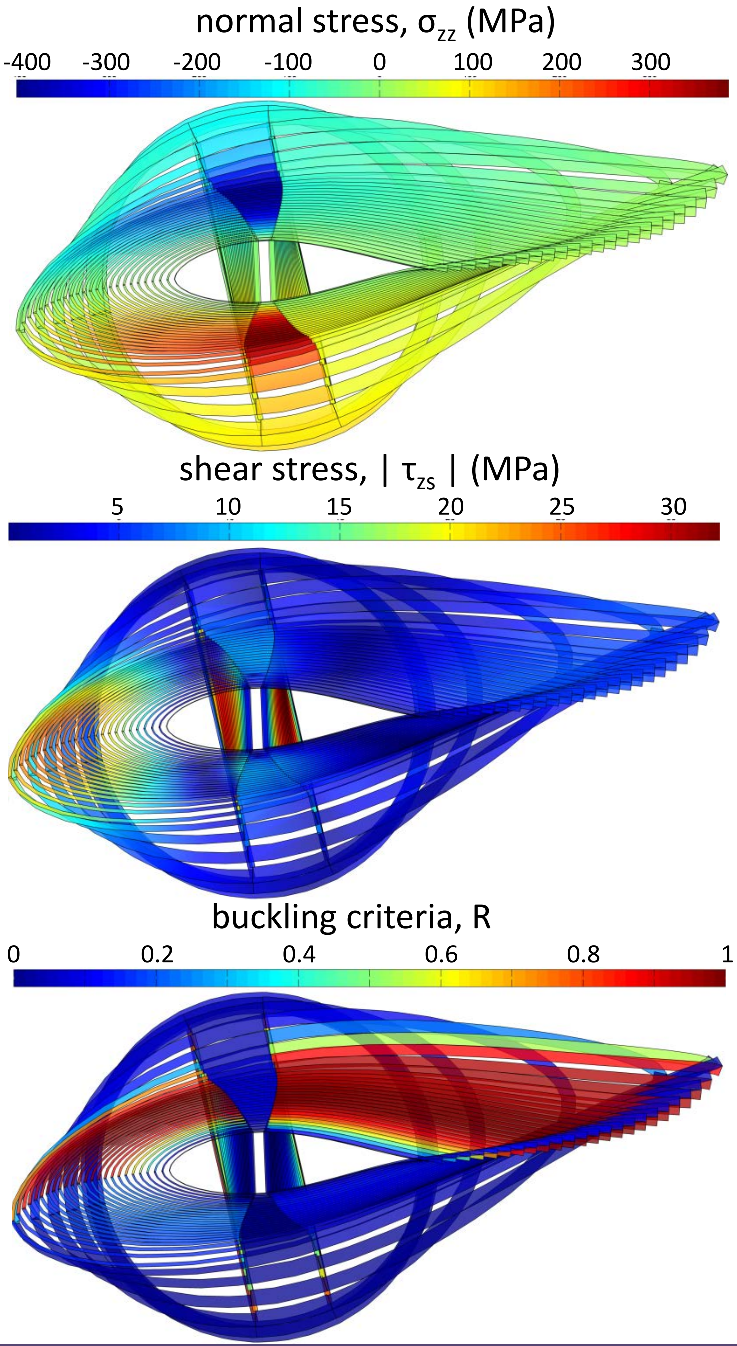


blade displacement & resultant hydrodynamic, net weight, and centrifugal loads

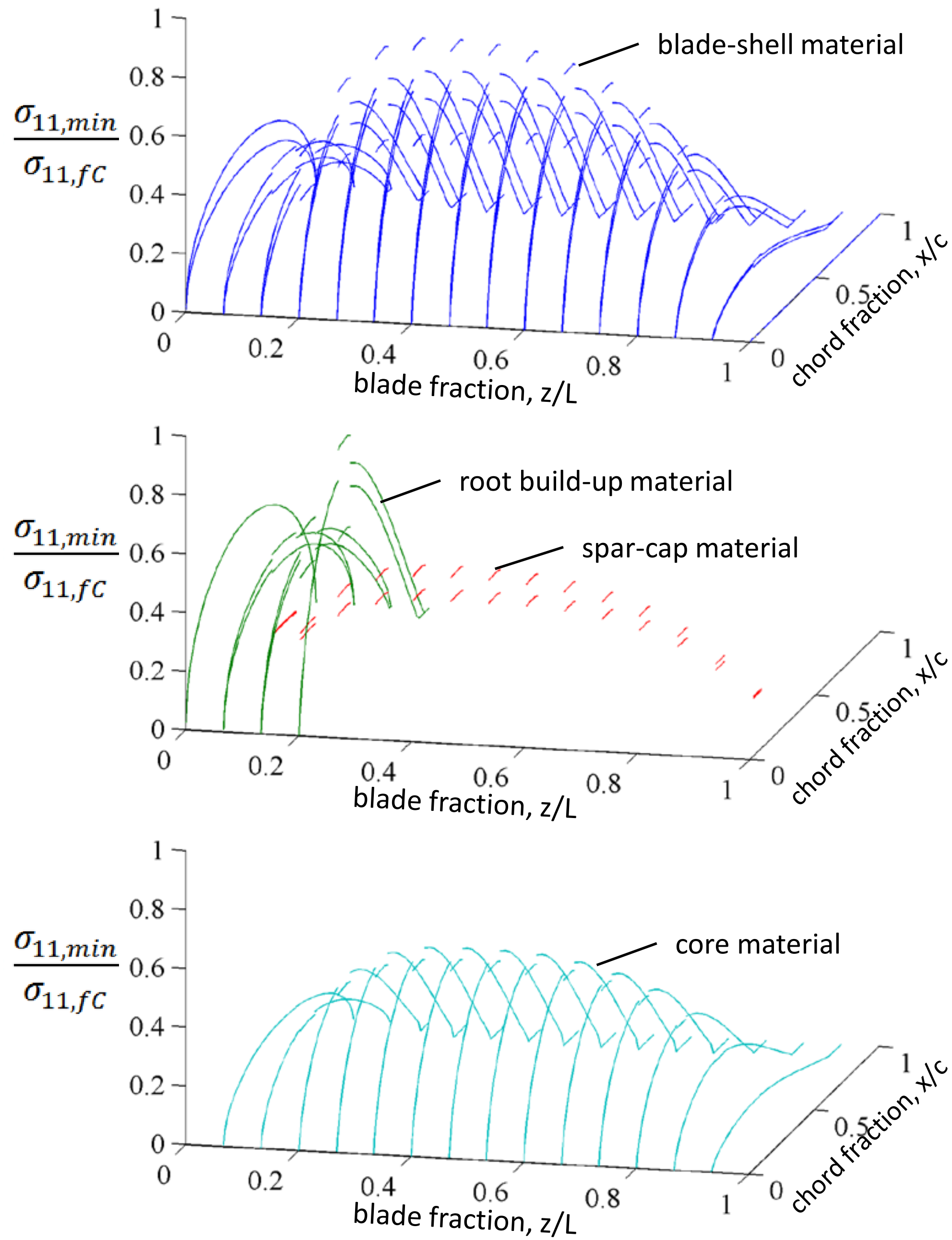




Effective Beam Stresses:



Max Stress Failure Criteria (Compression) for Laminas Along Top (Suction) Surface:



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

wind.nrel.gov/designcodes/simulators/WT_Perf/

HARP_Opt: Optimization Software for Turbine Design

wind.nrel.gov/designcodes/simulators/HARP_Opt/

CoBlade: Software for Analysis & Design of Composite Blades

no website yet—contact dsale@uw.edu for source & documentation

Sale & Aliseda (2012) "Structural Design of Composite Blades for Wind &Hydrokinetic Turbines"

depts.washington.edu/nnmrec/docs/20120213_SaleD_pres_StructuralDesign.pdf

Acknowledgements

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