Structural Design of Composite Blades for Wind and Hydrokinetic Turbines

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Outline

• Previous Work
  – coupled aero-structural optimization (*HARP_Opt* code)
  – simple structural model

• Newly Developed Structural Analysis Tool (*CoBlade*)
  – methodology & applications

• Structural Optimization
  – problem formulation
  – design of composite blade for tidal turbine

• Recommended Future Work
Previous Work: HARP Opt

Horizontal Axis Rotor Performance Optimization
- given: turbine & environmental specifications
- optimizes: blade shape, rotor speed & blade pitch control
- satisfying: maximum Annual Energy Production (AEP)

performance constraints (power, cavitation, etc.)
Previous Work: *HARP_Opt*

Simple Structural Model

- Thin-shelled cantilever beam
- One material w/ isotropic properties
- Bending strain is only constraint
- Shell thickness is only design variable

\[ \varepsilon = \frac{Mc}{EI} < \varepsilon_{\text{max allowable}} \]
Previous Work: \textit{HARP\_Opt}

Coupled Aerodynamic-Structural Optimization

- maximize energy production & minimize blade mass
- genetic algorithm identifies set of Pareto-efficient designs
Moving Forward: Structural Design

Develop a tool capable of modeling realistic composite blades

Image: www.Gurit.com
Overview of CoBlade software

Structural Analysis and Design of Composite Blades

• realistic modeling of composite blades
  – arbitrary topology & material properties

• 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

• structural analysis tool
  – arbitrary applied loads & body forces
  – recovery of 2D lamina-level strains & stresses
  – blade deflection & modal analysis
  – linear buckling analysis

• optimization of composite layup

Image: replica of Sandia SNL100-00 wind turbine blade using CoBlade
Methodology

Classical Lamination Theory + Euler-Bernoulli beam model + shear flow

Classical Lamination Theory (CLT)
- describes mechanical response of laminated plates

\[
A_{ij} = \sum_{k=1}^{N} (C_{ij})_k (z_k - z_{k-1}) \quad \text{extensional stiffness}
\]

\[
D_{ij} = \frac{1}{3} \sum_{k=1}^{N} (C_{ij})_k (z_k^3 - z_{k-1}^3) \quad \text{bending stiffness}
\]

\[
B_{ij} = \frac{1}{2} \sum_{k=1}^{N} (C_{ij})_k (z_k^2 - z_{k-1}^2) \quad \text{coupling stiffness}
\]

Image: G.S. Bir. “PreComp User’ Guide”
**Methodology**

**Composite Euler-Bernoulli Beam and shear flow approach**

- describes global mechanical behavior of composite beam

\[
\sigma_{zz} = E_{ref} \left[ \frac{V_z}{S^*} - \left( \frac{M_y H_x^* + M_x H_{xy}^*}{H_x^* H_y^* - H_{xy}^*} \right) x + \left( \frac{M_x H_y^* + M_y H_{xy}^*}{H_x^* H_y^* - H_{xy}^*} \right) y \right]
\]

\[
\frac{df_0}{ds}(s) = -t \frac{\partial \sigma_{zz}}{\partial z}, \quad \tau_{zs}(s) = \frac{f}{t}
\]

**Convert Beam Stresses into Equivalent Plate Loads**

- recover 2D strains & stress at lamina level

\[
\begin{bmatrix}
N_x \\
N_y \\
N_{xy} \\
M_x \\
M_y \\
M_{xy}
\end{bmatrix} = \begin{bmatrix}
A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\
A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\
A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\
B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\
B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\
B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66}
\end{bmatrix}\begin{bmatrix}
\varepsilon_{x0} \\
\varepsilon_{y0} \\
\gamma_{xy0} \\
\kappa_x \\
\kappa_y \\
\kappa_{xy}
\end{bmatrix}
\]
Methodology

Linear Buckling Analysis

- pinned boundary conditions (conservative)
- contributions from panel stiffness, curvature, thickness, & width

Modal Analysis

- **BModes**: Rotating Beam Coupled Modes (NREL code)

Optimization: Composite Layup

Material Legend:
- blade-root
- blade-shell
- spar-unis
- spar-core
- LEP-core
- TEP-core
- web-shell
- web-core

Material Properties:
- Failure Stresses:
  - $E_{11}$
  - $E_{22}$
  - $G_{12}$
  - $\nu_{12}$
  - $\sigma_{11,ft}$
  - $\sigma_{11,fc}$
  - $\sigma_{22,YT}$
  - $\sigma_{22,YC}$
  - $\tau_{12,y}$

Composite Layup
- all laminates balanced & symmetric
- high & low pressure surfaces symmetric
- identical shear web laminates
Optimization: Design Variables

Design Variables

- spar-cap width at inboard & outboard stations
- lamina thicknesses along blade length

![Graphs showing design variables across leading edge, trailing edge, and webs.](image-url)
Optimization: Objectives & Constraints

\[ \text{minimize: } f(\bar{x}) = \text{BladeMass} \times \prod_{n=1}^{N} \max\{1, p_n\}^{2} \]

\[
\begin{align*}
p_1 &= \frac{\sigma_{11,\text{max}}}{\sigma_{11,fT}} \\
p_2 &= \frac{\sigma_{11,\text{min}}}{\sigma_{11,fC}} \\
p_3 &= \frac{\sigma_{22,\text{max}}}{\sigma_{22,yT}} \\
p_4 &= \frac{\sigma_{22,\text{min}}}{\sigma_{22,yC}} \\
p_5 &= \frac{\tau_{12,\text{max}}}{\tau_{12,y}} \\
p_6 &= \left(\frac{\sigma}{\sigma_{\text{buckle}}}\right)^{\alpha} + \left(\frac{\tau}{\tau_{\text{buckle}}}\right)^{\beta} \\
p_7 &= \frac{\delta_{\text{tip}}}{\delta_{\text{allow}}} \\
p_8 &= \max\left\{\frac{\Delta \omega_{\text{separation}}}{|\omega_m - \omega_{\text{rotor}}|}\right\}, m = 1, \ldots, M_{\text{modes}}
\end{align*}
\]

subject to: \[ \overline{x}_{LB} \leq \bar{x} \leq \overline{x}_{UB} \]
\[ A \bar{x} \leq \bar{b} \]

penalty factors for maximum stress
penalty factors for buckling under compression & shear
penalty factor for tip deflection
penalty factor for separation of blade freqs. & rotor freq.
constraints ensure feasible geometry
Optimization: Example Design

Composite Blade Design for Tidal Turbine

- hydrodynamic design: Department of Energy Reference Tidal Current Turbine, ref. [1]
- design loads: extreme operating conditions in Puget Sound, WA., ref. [2]


CoBlade is fast: single evaluation: ~1 sec, total optimization: ~40 min

Blade mass is minimized, final iteration satisfies all constraints (no penalties)
Optimization: Results

normal stress, $\sigma_{zz}$ (MPa)

shear stress, $|\tau_{zs}|$ (MPa)

buckling criteria, $R$

Top Surface Lamina Stress Failure Criteria
Optimization: Results

![Graph showing optimization results with various stiffness and mass values along with mode frequencies.](image-url)
Conclusions

• Capable structural design tool, modeling of complex layups possible with CoBlade
• **NOT** a replacement for higher-fidelity FEM, but very effective for preliminary design work
• Limited validation studies
  – excellent agreement for analytically obtainable results
  – good agreement with ANSYS FEM model of tapered composite beam (collaboration w/ Penn. State)

Future Work

• Preliminary results seem reasonable, but require further validation
  – anisotropic layups
  – buckling
  – lamina-level strains/stresses
• Repeat coupled aero-structural optimization (**HARP_Opt**) with structural capabilities of **CoBlade**
• Include cross-coupled terms from CLT into beam equations
• Public release of **CoBlade** code & documentation
Thank you! Questions?

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The diagram illustrates the relationships between various reference axes and principal axes in a blade coordinate system. The section reference axes are shown as the chord line, which is aligned with the reference plane defined by the blade coordinate system's x-axis.

- **Centroidal principal axes**: Represented by the centroidal principal axes (CM, X_cm, Y_cm, Z_cm) and the chord line (R).
- **Inertial principal axes**: Indicated by the inertial principal axes (X, Y, Z) and the reference plane.
- **Elastic principal axes**: Depicted as elastic principal axes (X_sc, Y_sc, Z_sc).

The angles θ (aero, elastic, inertial, centroidal) show the orientation of these axes relative to the section reference axes. The diagram includes labels for TC and SC, which likely represent specific sections or configurations within the blade coordinate system.