Progress Towards a Mid-fidelity Wind Turbine MDO Capability for Advanced Aeroelastic Rotors

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Outline

• Motivation
• Aerodynamic models
• Structural models
• MDO framework
• Initial results
• Future directions
Larger and advanced machine concepts require better tools & optimization

• Composite layups
  – Bend-twist coupling
  – Large non-linear deflections

• Non-straight blades
  – Sweep & out-of-plane curvature
  – Tailoring of vorticity location

• Need to consider system
  – Unsteady performance
  – Multidisciplinary optimization
    • Continuous range of operating points
    • Efficient gradient calculations
Aerodynamic models
Blade Element Momentum (BEM) theory is the standard tool

- Momentum balance between far upstream and downstream
  - Bernoulli theory used to get blade conditions
- Explored various correction models
  - Centrifugal pumping
  - Hub loss model
  - Turbulent wake models
  - Vortex-tube based coning and expanding wake models
Lagrangian vortex model required for full generality

• Cost vs fidelity
  – Grid-based CFD: hrs-days
  – BEM not general: sec

• Vortex methods
  – Min-10’s of mins
  – Adaptively grid where wake vorticity exists
  – Many flavours!
  – Many element types
    • Particles, lines, sheets
  – Fixed & free wake
LibAero is our in-house C++ based code

• **Modularity**
  – Object oriented approach for testing of various sub models

• **Key classes**
  – Grid: geometry information & connectivity
  – Influence elements: anything that induces a velocity
    • Free-stream
    • Particles, filaments, wakes
    • Fast multi-pole expansion
  – Solvers: evolve solution

• **Coding features**
  – Inheritance, templating, OpenMP
On-blade (inner) Prandtl-Weissinger lifting line model

• Non-linear 2d airfoil lookup
  – Indexed by airfoil thickness, Re, AOA
  – Relate $C_l$ to bound circulation

\[ \Gamma = \int_A \omega \cdot dA = \frac{\nu Re C_l}{2} \]

• 3d corrections
  – Centrifugal pumping
  – Sweep
Wake models are arbitrary combinations of particles, filaments or sheets.
Not your standard potential flow method!

- Actually a vortex element based solution to the vorticity-velocity equations
  - Helmholtz decomposition into scalar & vector potentials
  - Viscosity present in core models
  - Gaussian diffusion
    - Exact solution for a point vortex
      \[
      \sigma_{t+\Delta t} = \sqrt{\sigma_t^2 + 2\nu\Delta t}
      \]

- Strength deformation term
  - Implicit in filament and sheet elements
  - Must be explicitly computed for particles
Speed is key, so fast multipole method (FMM) employed

• Use lumping to compute influence far away
• Reduce computational burden
  – $O(N^2)$ to $O(N)$
• Want balanced tree
  – Turbine wakes not represented well by standard octrees
  – Use binary tree
• FMM
  – Precompute far-away influences (multipoles)
We’ve implemented a true 2\textsuperscript{nd} order explicit solver

- Methods can look 2\textsuperscript{nd} order from advection
  \[ x_{t+\Delta t} = x_t + \Delta t u_x(t) + \frac{1}{2}(\Delta t)^2(x_t \cdot \nabla x_t) + O(\Delta t)^3 \]
- But they are not!
  - Typically advect then diffuse for viscous splitting
    \[ \omega_n = (A(\Delta t)D(\Delta t))^n \omega_0 \]
  - Can prove from Fourier expansions that this is only first order accurate
  - Need a 2\textsuperscript{nd} order accurate viscous splitting scheme
    \[ \omega_n = (A(\frac{\Delta t}{2})D(\Delta t)A(\frac{\Delta t}{2}))^n \omega_0 \]
Aerodynamic validation against Mexico and in-house rotor tests
Generally 2\textsuperscript{nd} order method better, especially at high $\lambda$

<table>
<thead>
<tr>
<th>Method</th>
<th>10 m/s</th>
<th>15 m/s</th>
<th>24 m/s</th>
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<tr>
<td>MEXICO</td>
<td>0.299</td>
<td>0.437</td>
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<tr>
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<td>0.386</td>
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<td>First Order Method N=45</td>
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<td>0.237</td>
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<tr>
<td>Second Order Method N=15</td>
<td>0.335</td>
<td>0.464</td>
<td>0.235</td>
</tr>
<tr>
<td>Second Order Method N=30</td>
<td>0.328</td>
<td>0.458</td>
<td>0.239</td>
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<tr>
<td>Second Order Method N=45</td>
<td>0.319</td>
<td>0.452</td>
<td>0.242</td>
</tr>
</tbody>
</table>
Numerical issues greatly improved

• Can converge at high $\lambda$ where explicit diverged
• Only need one full Jacobian re-eval
Structural models
Again a tradeoff between fidelity and complexity

• Full brick or shell FEM
  – Needed for local details and buckling analysis
  – Mostly overkill for aeroelastic simulations

• Separate beam and cross-sectional analysis
  – Geometrically exact beam theory (GEBT)
    • Greatly reduce number of DOFs
    • Fully non-linear axial, bending, torsional deflections
  – Variational asymptotic beam section (VABS) analysis
    • Arbitrary cross-section layup
    • Yields full coupling matrix
    • Can recover stresses \textit{a posteriori}
GEBT captures position $\phi$ and orientation $\Lambda$ of cross-sections

- Euler-Bernoulli theory has section orientation assumptions
- The GEBT governing residual equation is

$$R = \left[ -\frac{d}{ds} \times \frac{d\phi}{ds} \right] \left\{ \begin{array}{c} n \\ m \end{array} \right\} - \left\{ \begin{array}{c} \tilde{n} \\ \tilde{m} \end{array} \right\}$$

where $\tilde{n}$ and $\tilde{m}$ are external forces and moments and the internal forces/moments are

$$\left\{ \begin{array}{c} n \\ m \end{array} \right\} = \left[ \begin{array}{cc} \Lambda & 0_3 \\ 0_3 & \Lambda \end{array} \right] [C] \left\{ \begin{array}{c} \gamma \\ \kappa \end{array} \right\}$$
VABS theory has been well validated

- Solve for warping solution in terms of applied beam strains
  - Minimize energy of internally induced strains
  - Neglect asymptotically small terms (need up to 2\textsuperscript{nd} terms to get shear strain/stiffness)

- Transform to section stiffness matrices for GEBT
An adjoint gradient method has been derived for GEBT/VABS

\[ \mathbf{R}(x, y) = 0 \]

State variables \( \frac{dJ}{dy} \) Design variables

Objective function

\[
\frac{dJ}{dy} = \frac{\partial J}{\partial y} + \int \left\{ \frac{\partial J}{\partial x} \right\}^T \left\{ \frac{dx}{dy} \right\} d\mathcal{D} \\
= \frac{\partial J}{\partial y} + \int \left\{ \frac{\partial J}{\partial R} \right\}^T \left[ \frac{\partial R}{\partial x} \right] \left\{ \frac{dx}{dy} \right\} d\mathcal{D} \\
= \frac{\partial J}{\partial y} + \int \left\{ \frac{\partial J}{\partial R} \right\}^T \left\{ \frac{\partial R}{\partial y} \right\} d\mathcal{D}
\]

Residual of governing equations (must be satisfied)

Direct, forward method 1 solve for each DV

Adjoint vector, solved for with non-linear adjoint equation
MDO framework

• Steady-state operating conditions
  – Chord/twist profile DVs
  – Sectional layup DVs
  – Maximize power/material volume

• SQP algorithm
  – FD gradients of block Gauss-Seidel coupled solve
A multidisciplinary feasible (MDF) MDO framework is used.
Structural definition based on slabs to reflect real layups (not splines)

- Sectional coordinate scheme

- Natural structure grids for VABS
Each slab defines a laminate layup

- $l_{i1}$
- $l_{i0}$
- $l_{i2}$
- $l_{i3}$
- $l_{i4}$
- $l_{i5}$

$\pm 45^\circ$ Crack Prevention

Material A

Material B

Fiber Angle
The slab width profile is controlled by splines (manufacturing possible)
VABS section computations at natural transition points along the blade
Explicit aerodynamic gradients have proved a challenge

Able to optimize from $C_p$ 0.458 to 0.541 for Mexico rotor baseline with appropriate step size, free wake aerodynamics only
Structures-only optimization for bend-twist coupling with fixed aerodynamic loads

• Sandia 100m uniaxial fibreglass blade baseline
• Traditional spline-based vs slab-based parameterization
  – 2 slab
  – 3 slab
Slab-based designs are lighter
Initial coupled MDO test optimization with Sandia 100m baseline design

- Used a fixed wake to aid convergence
Relaxed wake coupled optimization with adapted step sizes for each DV
Future directions

• Continue to improve aero model
  – Try implicit method in MDO framework

• Incorporate unsteadiness
  – Controller, performance, IEC fatigue, etc
  – Reduced order models

• Composite properties from base constituents

• MDO
  – Coupled adjoint
  – Full wind-speed range
  – Other system components: generator, tower, etc
  – Alternative decomposed MDO frameworks
Thanks for listening!

• And thanks to all those hard-working students
  – Current: Mike McWilliam, Stephen Lawton, Manuel Fluck, Ghulam Mustafa, Iman Khorsand, Matt Hall
  – Past: Shane Cline, Patricio Lillo

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