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

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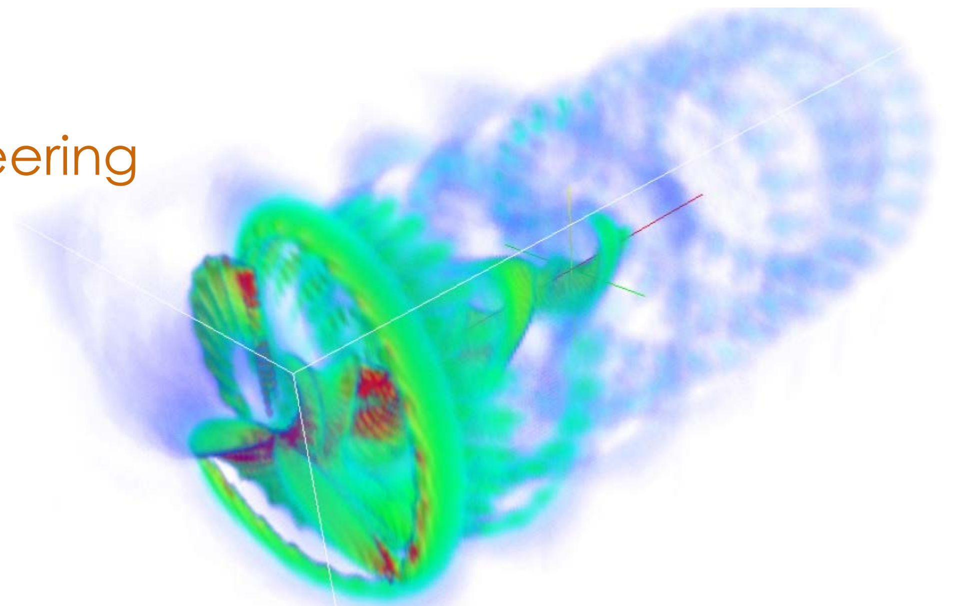


SSDL Sustainable Systems Design Laboratory

University of Victoria | Institute for Integrated Energy Systems

Outline

- Motivation
- Aerodynamic models
- Structural models
- MDO framework
- Initial results
- Future directions

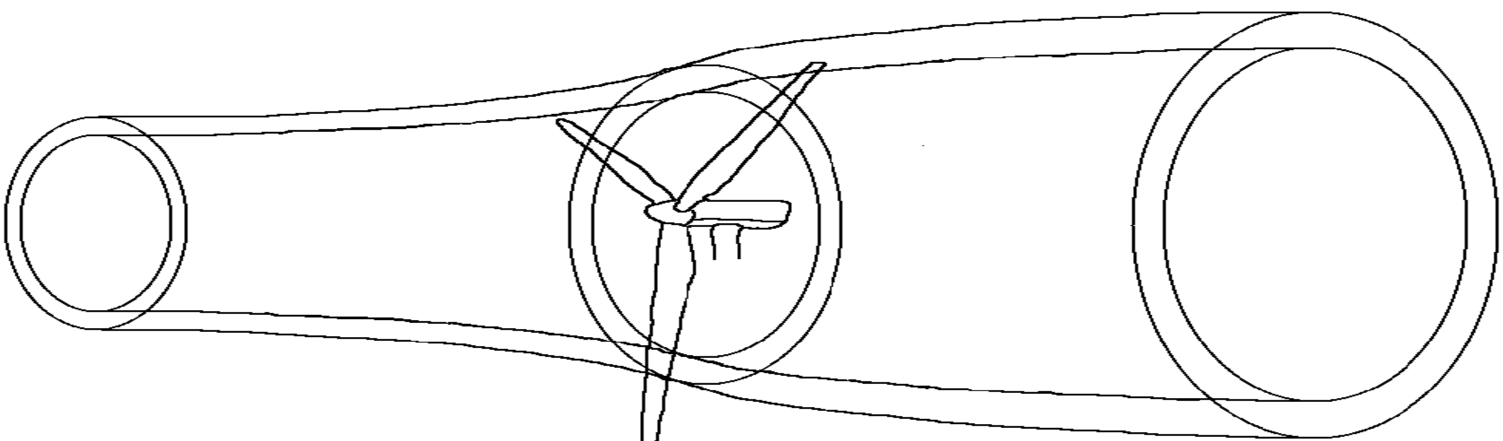
Larger and advanced machine concepts require better tools & optimization

- 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

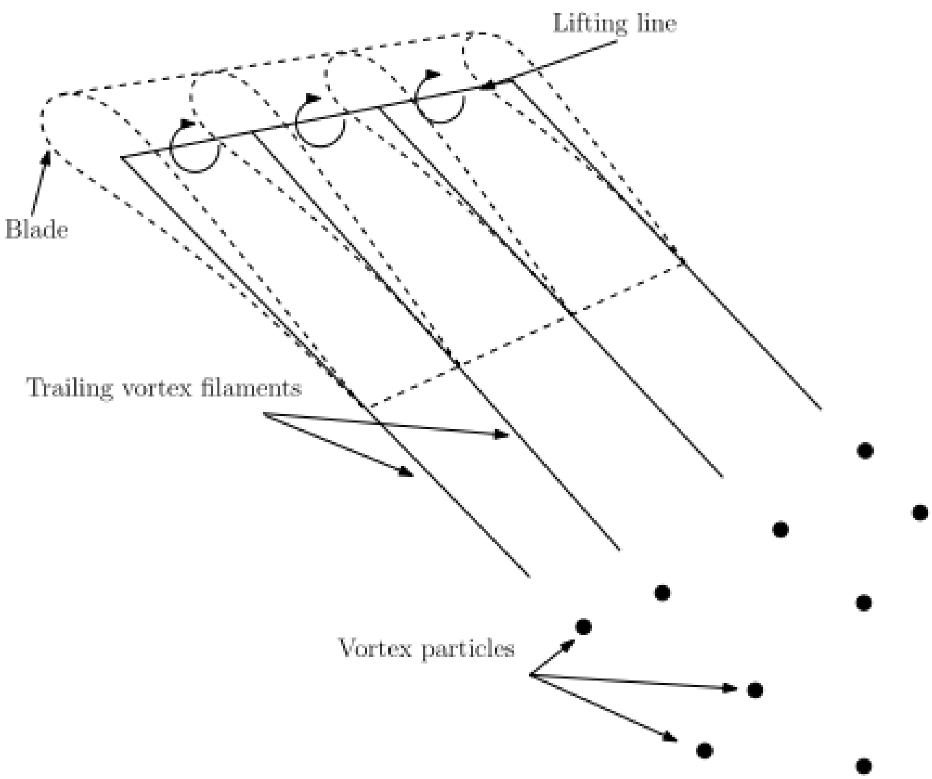
Blade Element Momentum(BEM) theory is the standard tool

- 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 mulitpole expansion
  - Solvers: evolve solution
- Coding features
  - Inheritance, templating, OpenMP

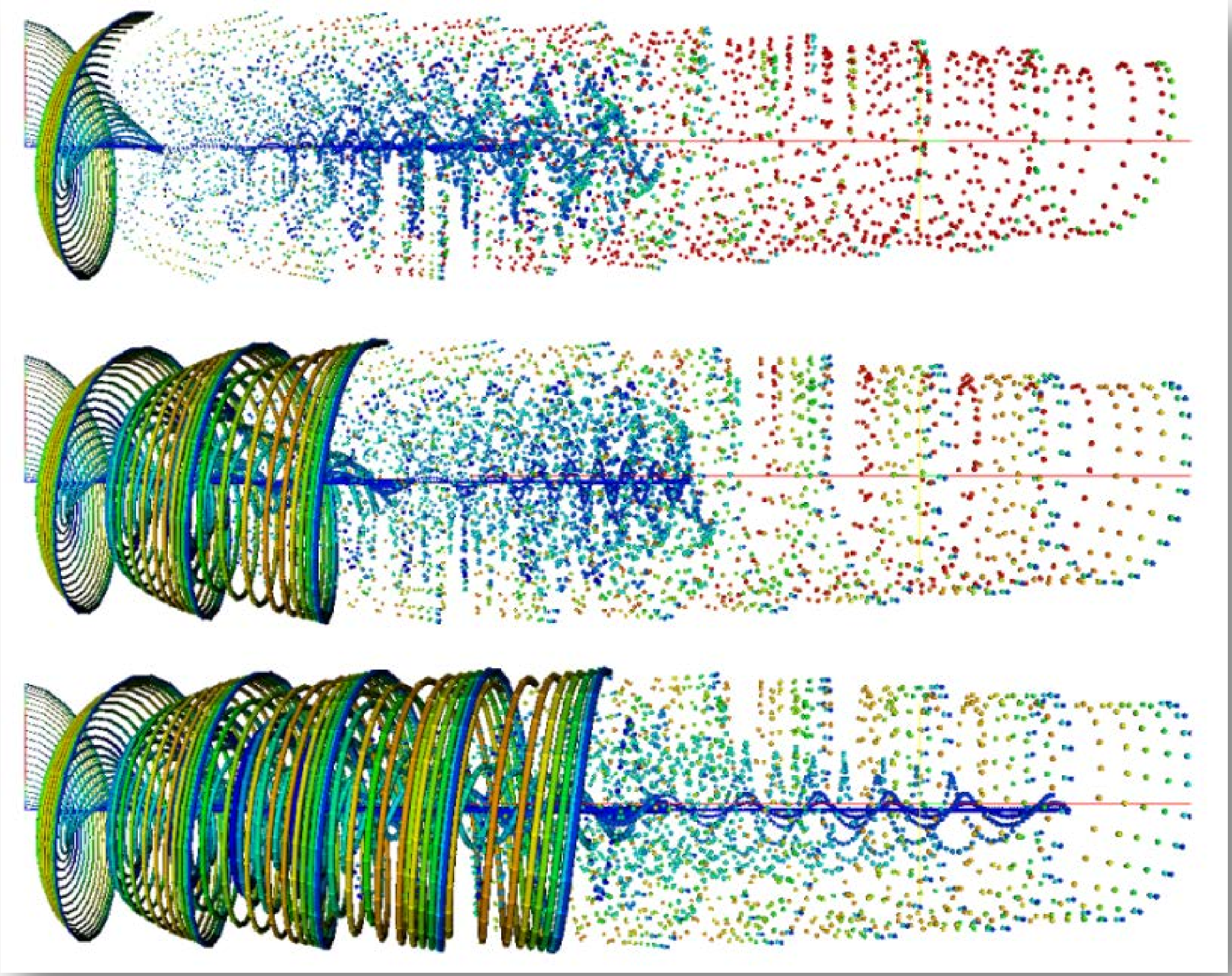
On-blade (inner) Prandtl-Weissinger lifting line model

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

$$\Gamma = \int_A \omega \cdot d\mathbf{A} = \frac{\nu Re C_l}{2}$$

- 3d corrections
  - Centrifugal pumping
  - Sweep

Wake models are arbitrary combinations of particles, filaments or sheets



Not your standard potential flow method!

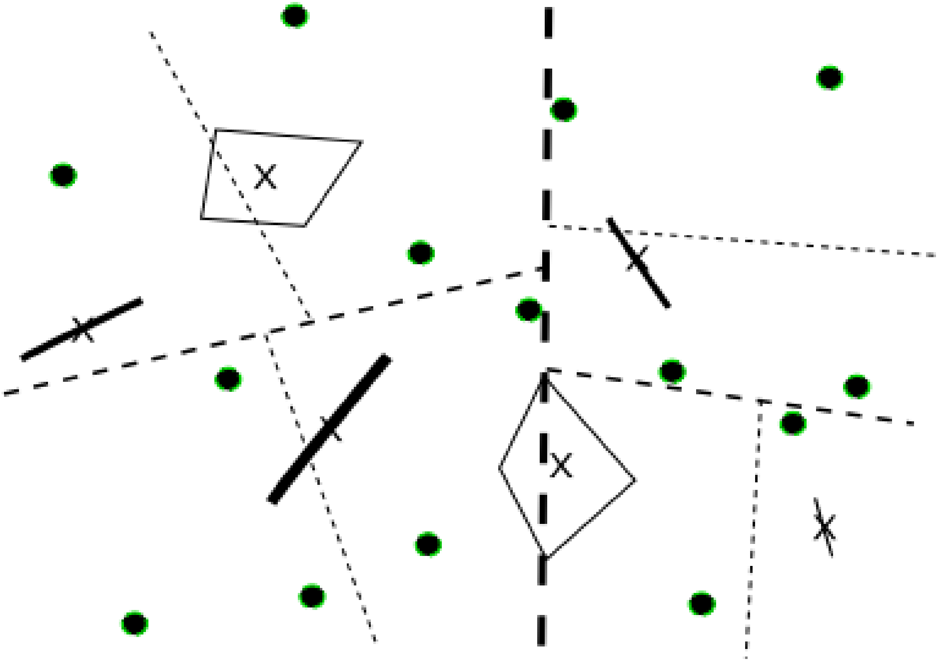
- Actually a vortex element based solution to the vorticity-velocity equations
  - –Helmoltz decomposition into scalar & vector potentials
  - –Viscosity present in core models
  - –Gaussian diffusion
    - Exact solution for a point vortex

$$\sigma_{t+\Delta t} = \sqrt{\sigma_t^2 + 2\nu\Delta t}$$

- 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 2nd order explicit solver

- Methods can look 2nd order from advection

$$\mathbf{x}_{t+\Delta t} = \mathbf{x}_t + \Delta t \mathbf{u}_{x(t)} + \frac{1}{2}(\Delta t)^2(\mathbf{x}_t \cdot \nabla \mathbf{x}_t) + O(\Delta t)^3$$

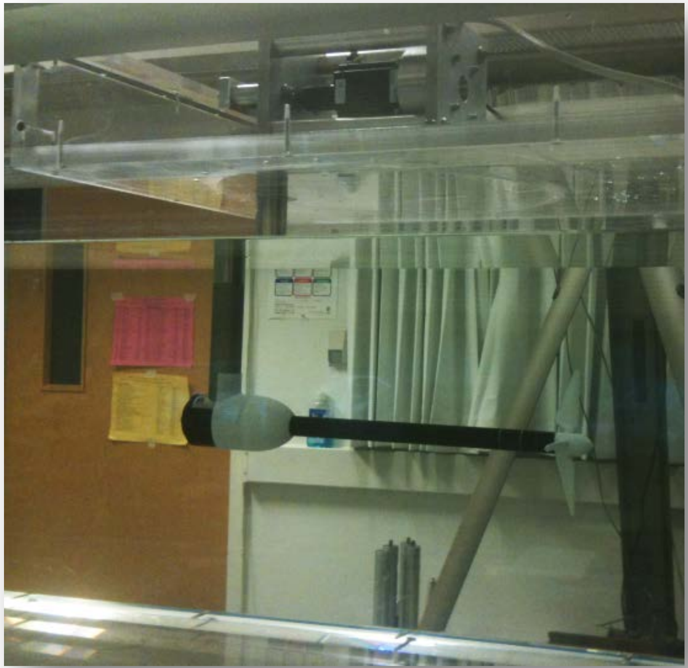
- But they are not!
  - Typically advect then diffuse for viscous splitting

$$\omega_n = (A(\Delta t)D(\Delta t))^n \omega_0$$

  - Can prove from Fourier expansions that this is only first order accurate
  - Need a 2nd 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

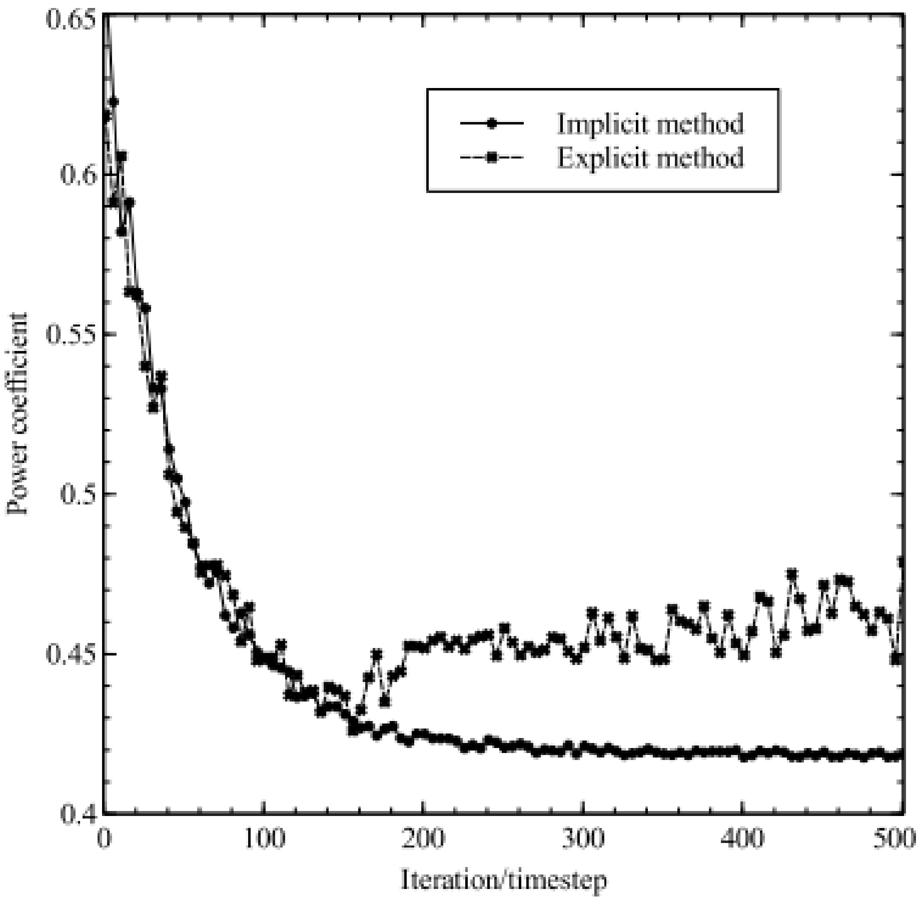


Generally 2nd order method better, especially at high λ

	10 m/s	15 m/s	24 m/s
MEXICO	0.299	0.437	0.227
First Order Method N=15	0.386	0.478	0.211
First Order Method N=30	0.343	0.466	0.234
First Order Method N=45	0.338	0.462	0.237
Second Order Method N=15	0.335	0.464	0.235
Second Order Method N=30	0.328	0.458	0.239
Second Order Method N=45	0.319	0.452	0.242

Numerical issues greatly improved

- Can converge at high λ 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 *a posteriori*

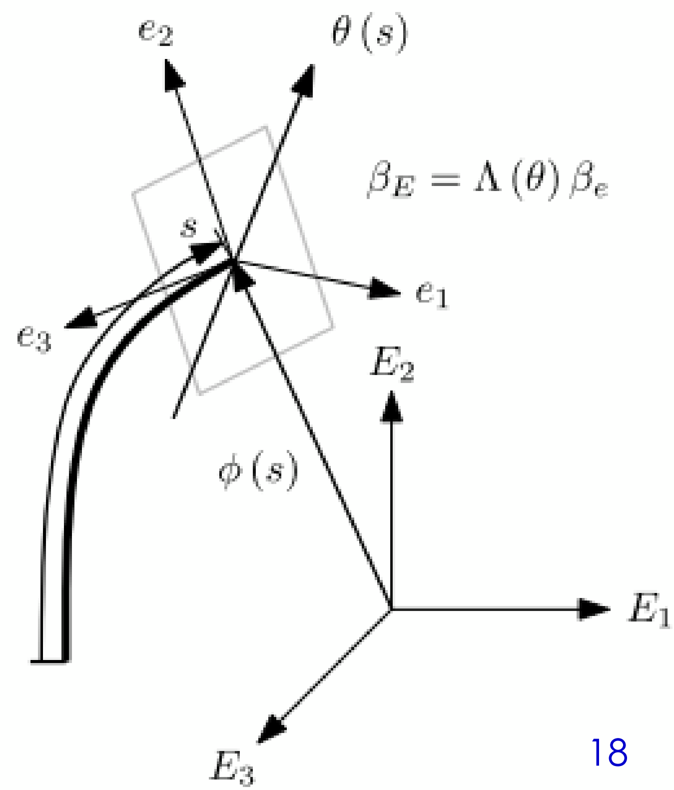
GEBT captures position ϕ and orientation Λ of cross-sections

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

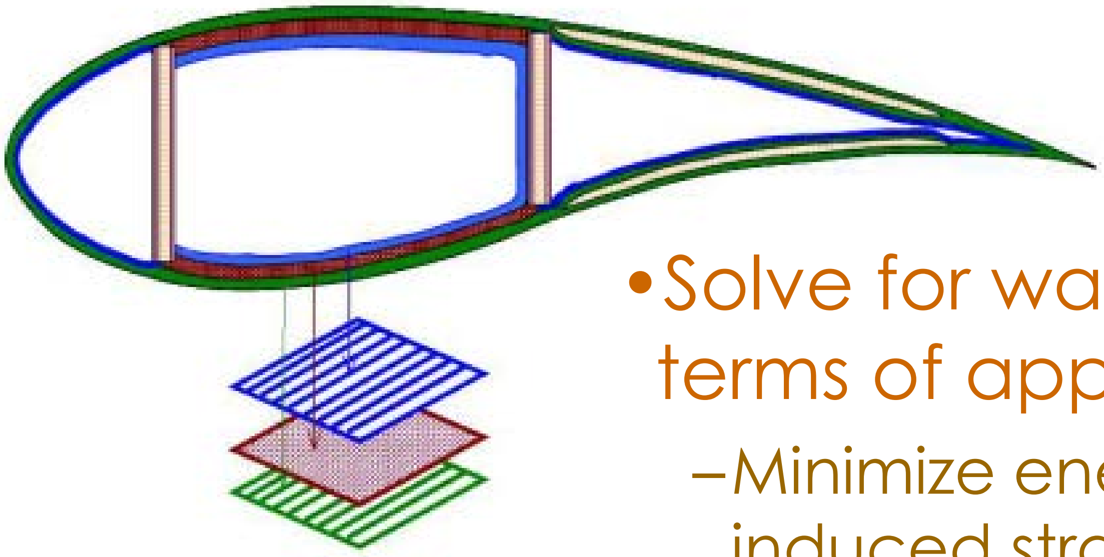
$$\mathbf{R} = \begin{bmatrix} \frac{d}{ds} & \mathbf{0}_3 \\ -\frac{d\phi}{ds}\times & \frac{d}{ds} \end{bmatrix} \begin{Bmatrix} \mathbf{n} \\ \mathbf{m} \end{Bmatrix} - \begin{Bmatrix} \bar{\mathbf{n}} \\ \bar{\mathbf{m}} \end{Bmatrix}$$

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

$$\begin{Bmatrix} \mathbf{n} \\ \mathbf{m} \end{Bmatrix} = \begin{bmatrix} \Lambda & \mathbf{0}_3 \\ \mathbf{0}_3 & \Lambda \end{bmatrix} [\mathbf{C}] \begin{Bmatrix} \gamma \\ \kappa \end{Bmatrix}$$



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 2nd terms to get shear strain/stiffness)
- Transform to section stiffness matrices for GEBT

An adjoint gradient method has been derived for GEBT/VABS

State variables

Design variables

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

Residual of governing equations (must be satisfied)

Objective function

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

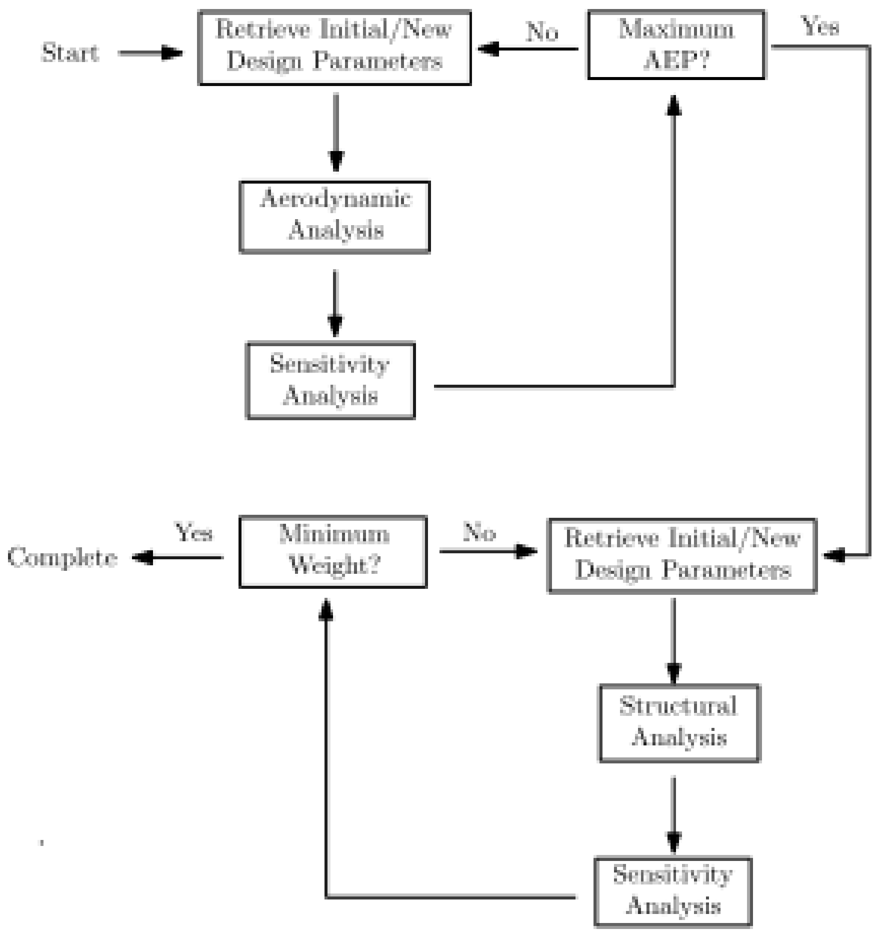
Direct, forward method
1 solve for each DV

Adjoint vector, solved for with non-linear adjoint equation

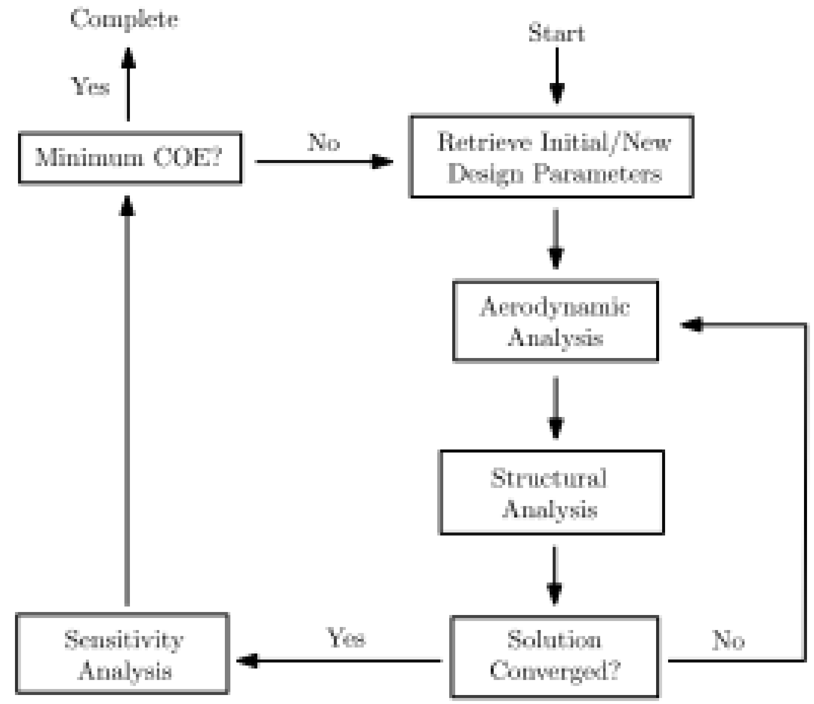
MDO framework

- 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 multidisplinary feasible (MDF) MDO framework is used



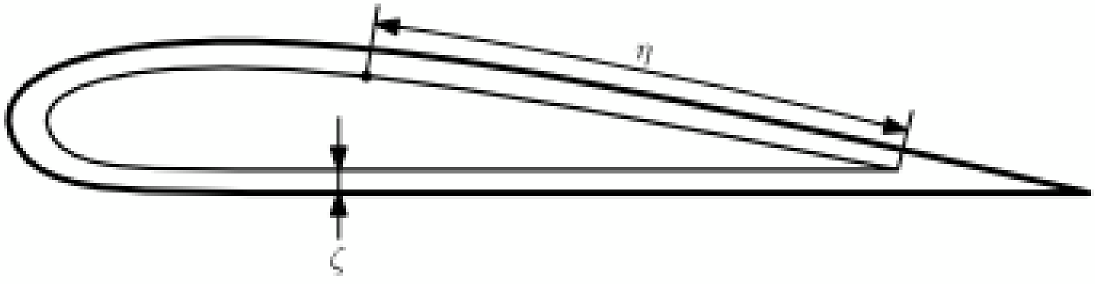
(a) Single-Discipline Feasible



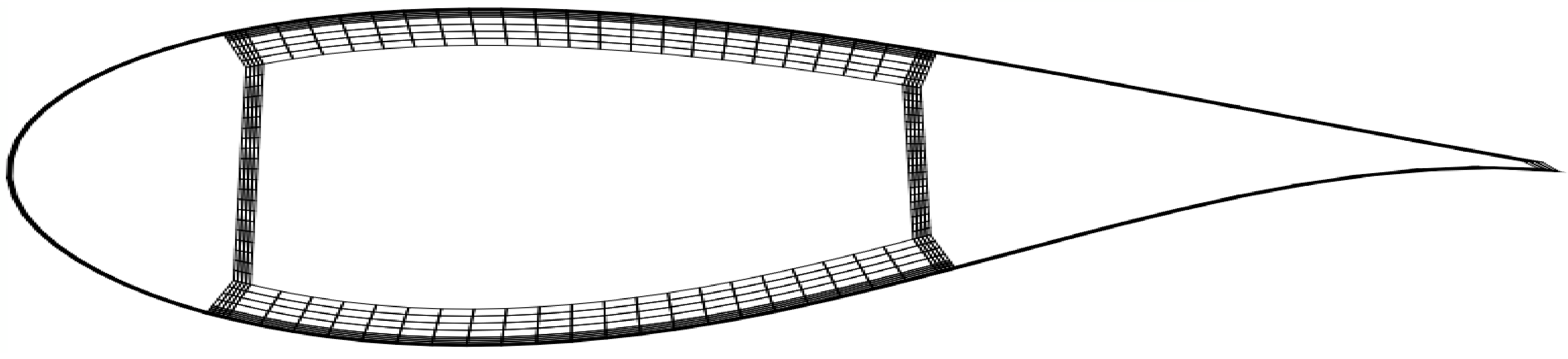
(b) Multi-Discipline Feasible

Structural definition based on slabs to reflect real layups (not splines)

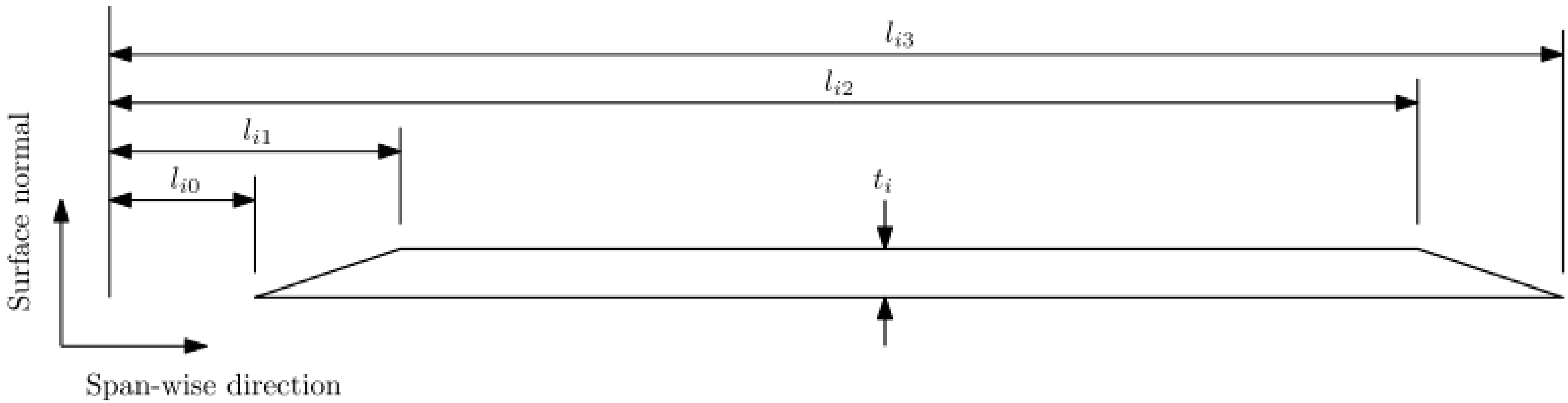
- Sectional coordinate scheme

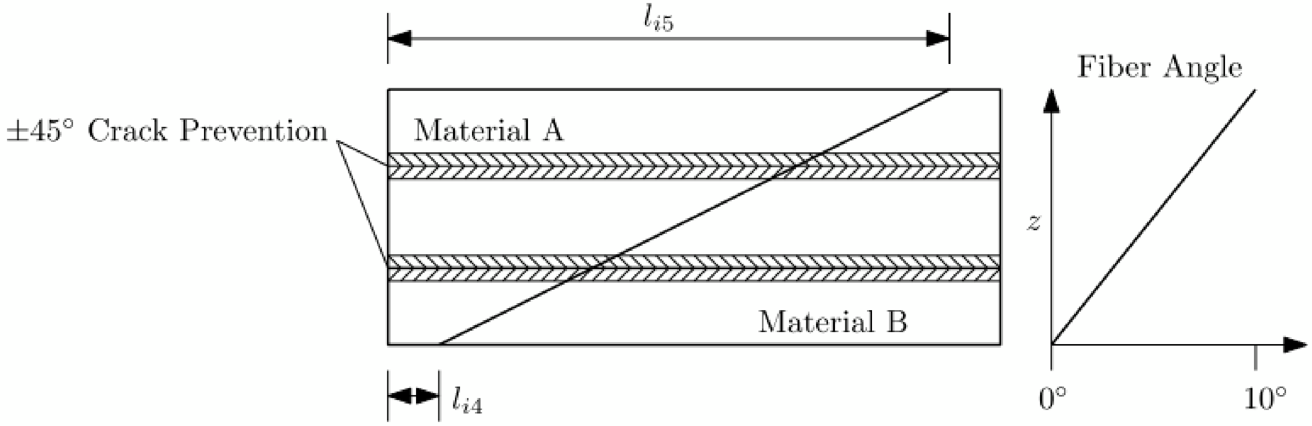


- Natural structure grids for VABS

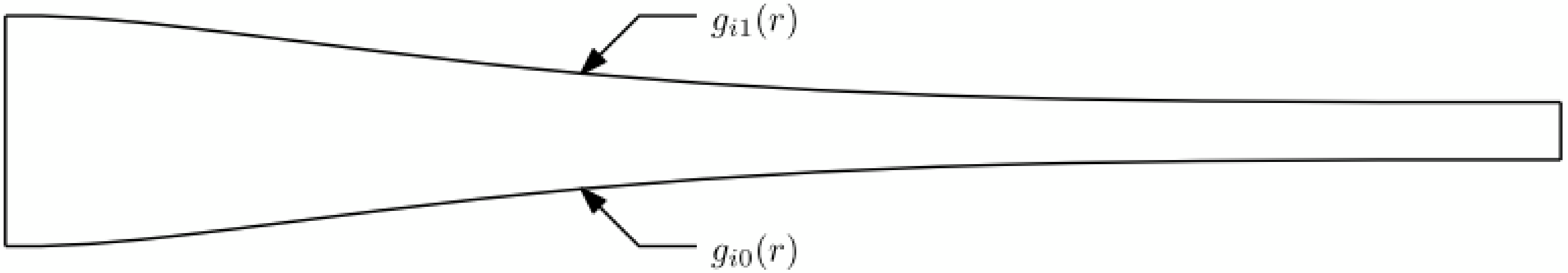


Each slab defines a laminate layup

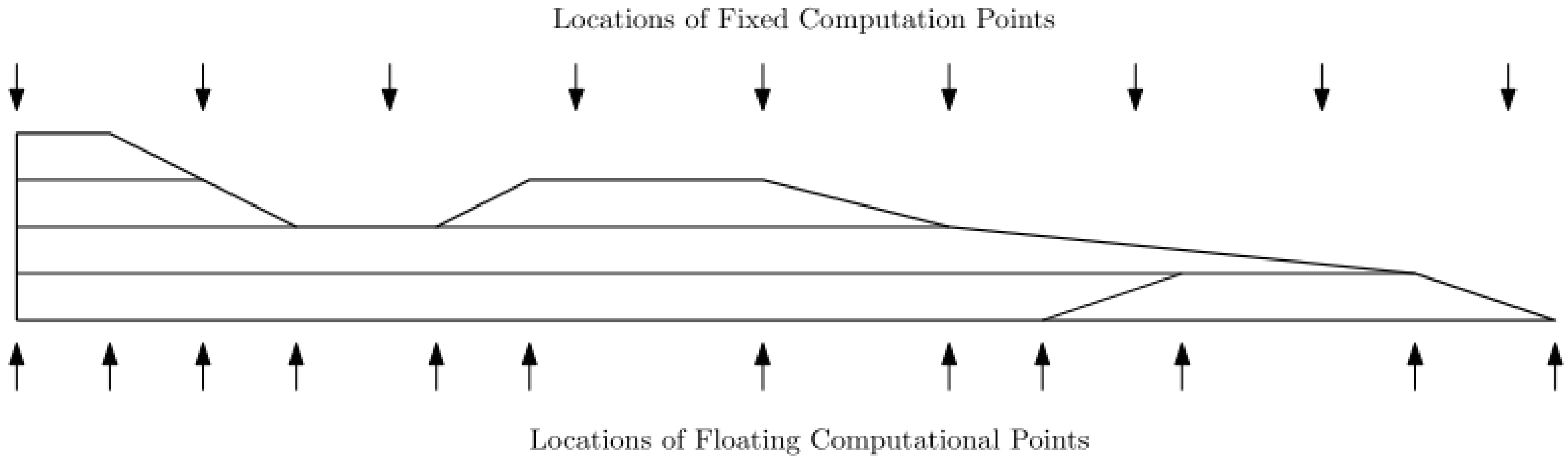




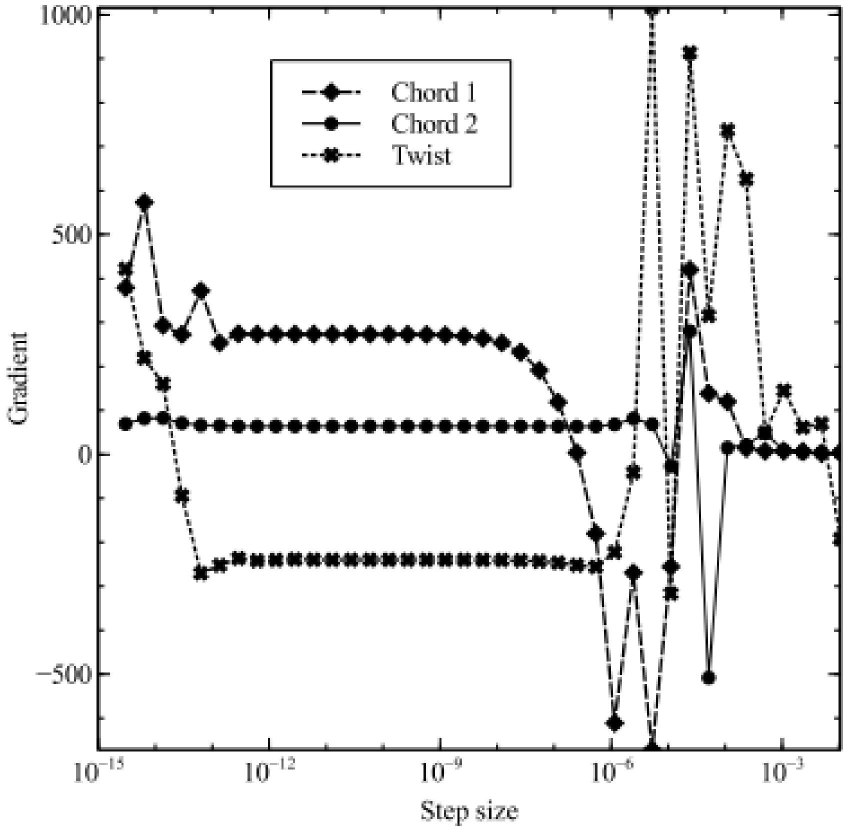
The slab width profile is controlled by splines (manufacturing possible)

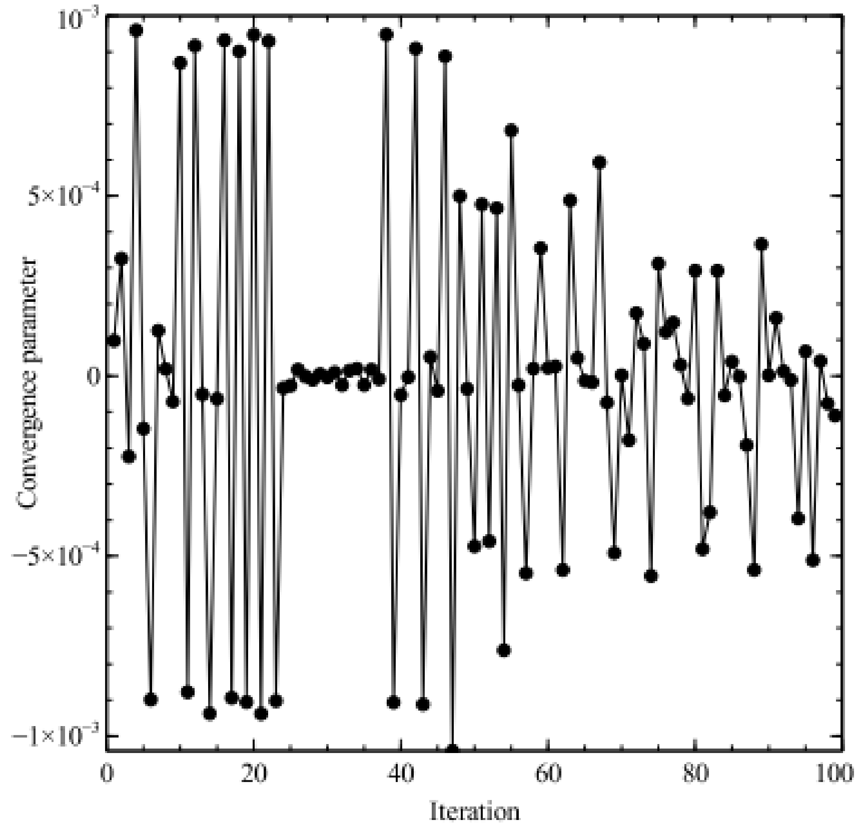


VABS section computations at natural transition points along the blade



Explicit aerodynamic gradients have proved a challenge

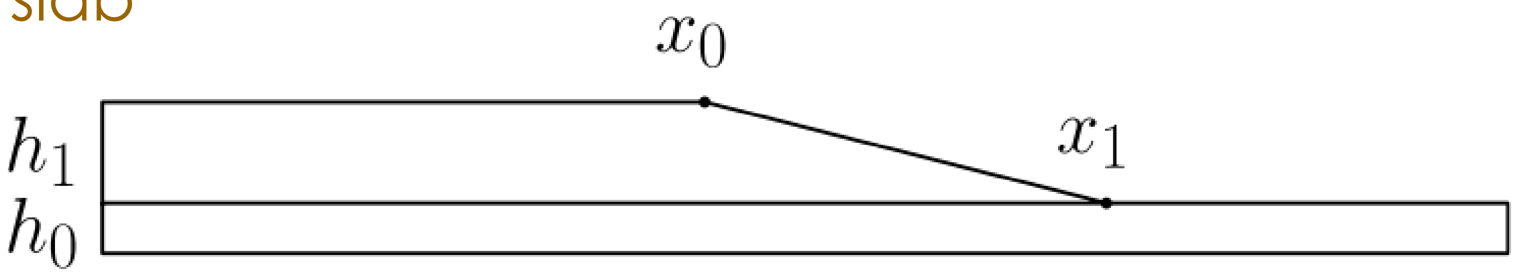




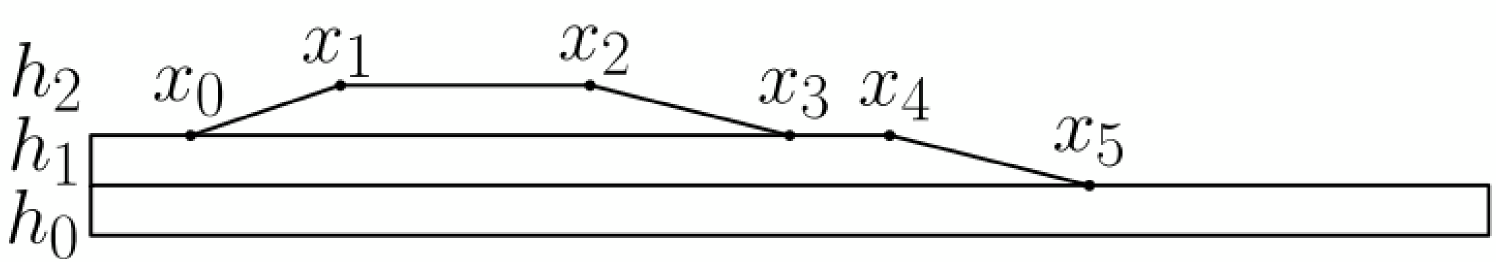
Able to optimize from *Cp* 0.458 to 0.541 for Mexico rotor baseline with appropriate step size, free wake aerodynamics only

Structures-only optimization for bend-twist coupling with fixed aerodynamic loads

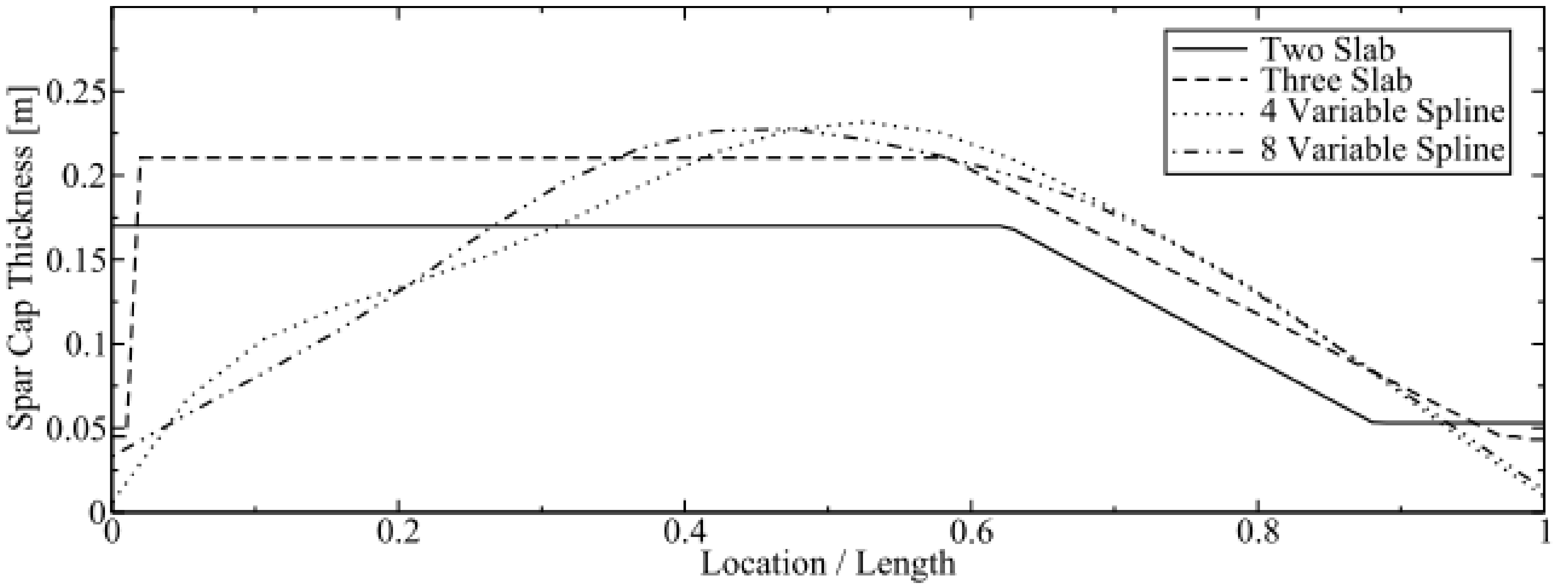
- Sandia 100m uniaxial fibreglass blade baseline
- Traditional spline-based vs slab-based parameterization
  - 2 slab



  - 3 slab



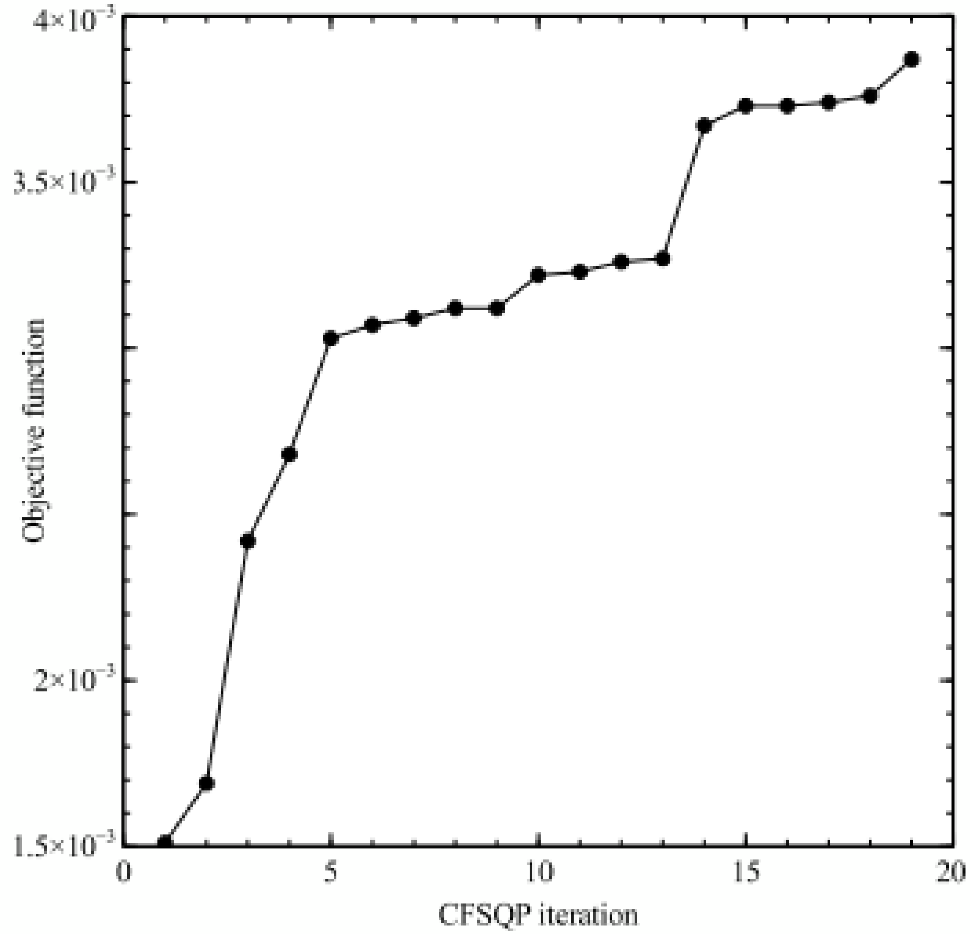
Slab-based designs are lighter



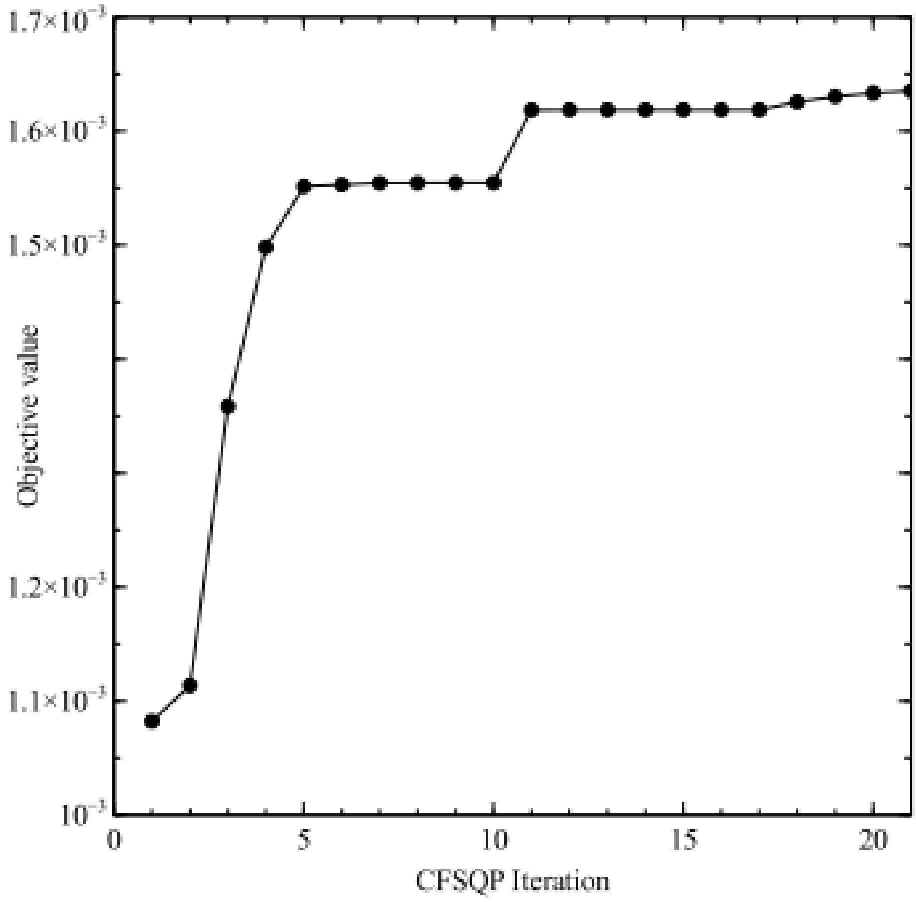
Parameterization	Volume $[m^3]$
4 Variable Spline	175.4
8 Variable Spline	175.1
Two Slab (4 Variables)	125.4
Three Slab (9 Variables)	144.3

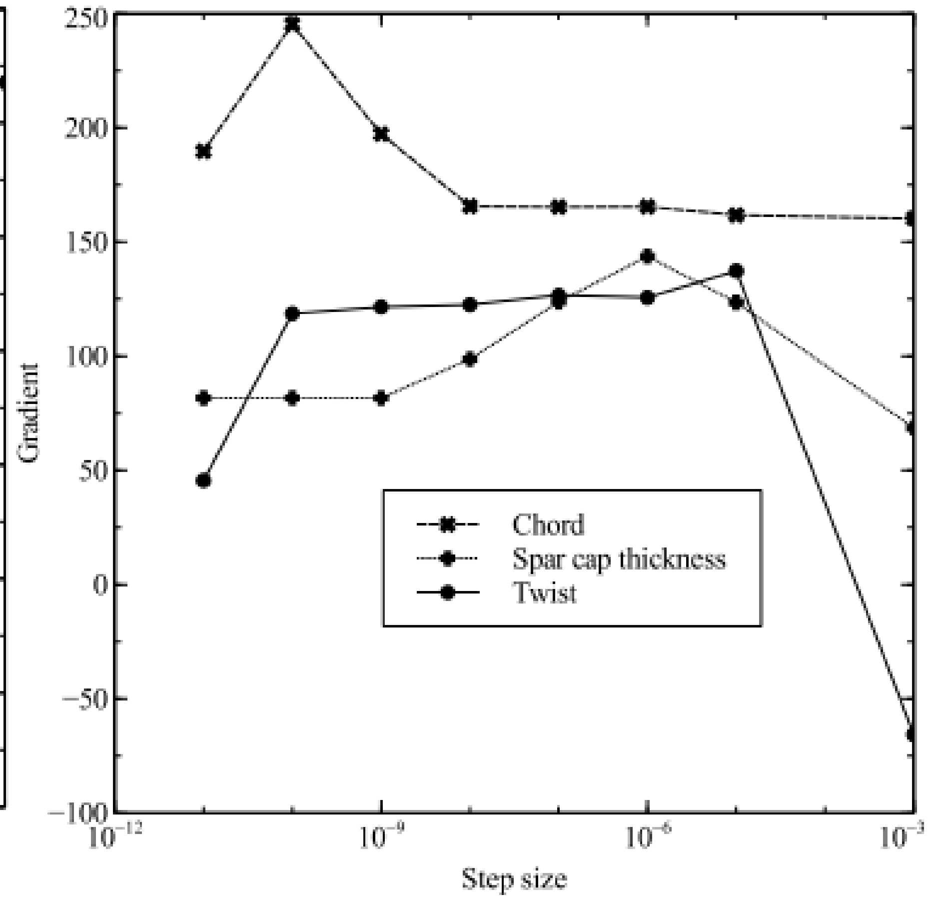
Initial coupled MDO test optimization with Sandia 100m baseline design

- 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
- E-mail: curranc@uvic.ca