Probabilistic Wind Turbine System Models in Three Courses: Composite Materials, Aerodynamics, Grid Integration

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University of Victoria | Institute for Integrated Energy Systems

SSDL Sustainable Systems Design Laboratory

Outline

Why Probabilistic Models?

Composite Structures

Turbulent Aero(structural) dynamics

(Smart) Grid Integration

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Wind energy systems inherently involve variability

- Wind input
  - High f turbulence
  - Fat tail distributions (extremes)
  - Seasonal/annual mean wind speed variation
  - Decadal-scale variations
- Wave loading offshore
- Blade erosion & soiling
- Large-scale (manual) manufacturing
  - Limit & fatigue strengths
  - Stiffness variations
- Mechanical & electrical component reliability
- Aero-structural response to these inputs
  - Controller actions
  - Fatigue & extreme loads
  - Power output

System analysis models must handle this variability to be trusted and explore full design space

- But we already do this, don't we?
  - Monte Carlo analyses
    - IEC load sets + statistical extrapolation
    - Combined wind/wave conditions
    - Decomposed MDO frameworks
  - Quite expensive even for low fidelity BEM-type models
- My group's research goals:
  - **Medium fidelity** models viable for system optimization
  - **Intrinsically probabilistic** models to quantify/mitigate risk
  - **Design studies** on advanced concepts, airborne, offshore
  - Examine system **economics & grid integration**

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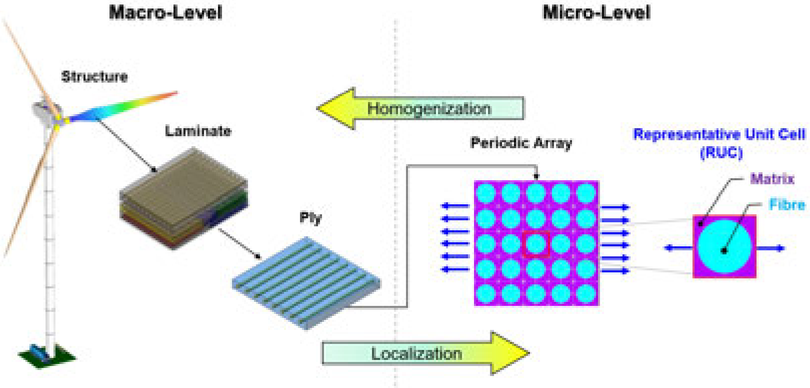
Micromechanics models use matrix & fibre properties avoiding coupon tests for alternative layups



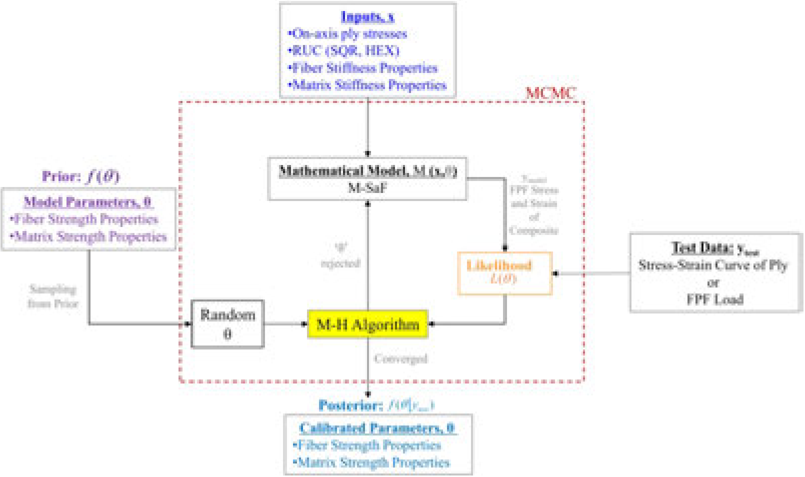
Relate micro $\underline{\sigma}^j$ and macro $\underline{\sigma}$ stresses: $\underline{\sigma}^j = [SAF]\underline{\sigma}$

Elements of SAF computed via FEM simulations

Failure criteria applied at points j based on material strengths

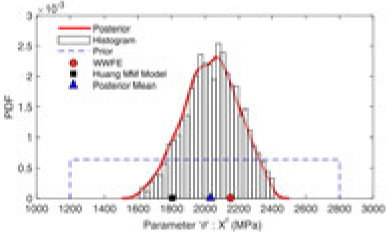
Markov Chain Monte Carlo (MCMC) methods used to evaluate Bayes's theorem estimates

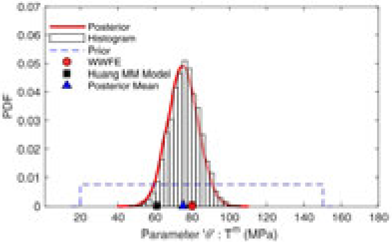
$$f(\Theta|y_{test}) = \frac{f(y_{test}|\Theta)f(\Theta)}{f(y_{test})} = \frac{L(\Theta)f(\Theta)}{f(y_{test})}$$



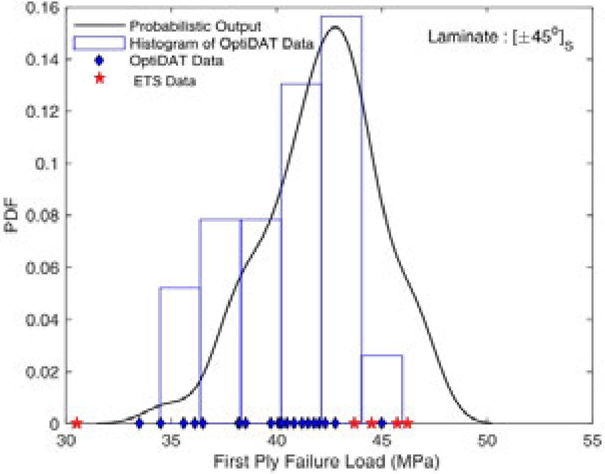
Statistical strengths calibrated using a limited set of experimental results

- Uniform prior (unbiased)
- Likelyhood function
  - Assume normal distribution of properties
- Histogram algorithm output
  - Kernel density estimator on MCMC results
- Fibre and matrix strengths
  - Compressive, tensile, shear
  - Ultimate and fatigue





Forward statistical analysis of candidate layups is then possible (ultimate & fatigue)



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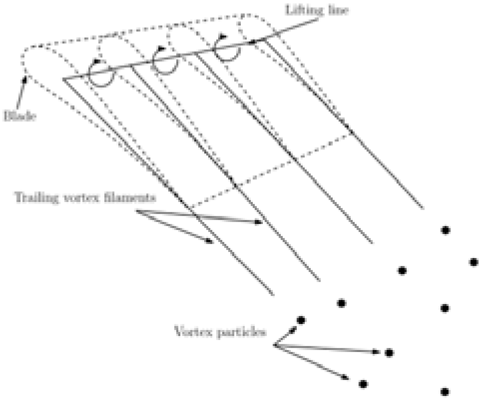
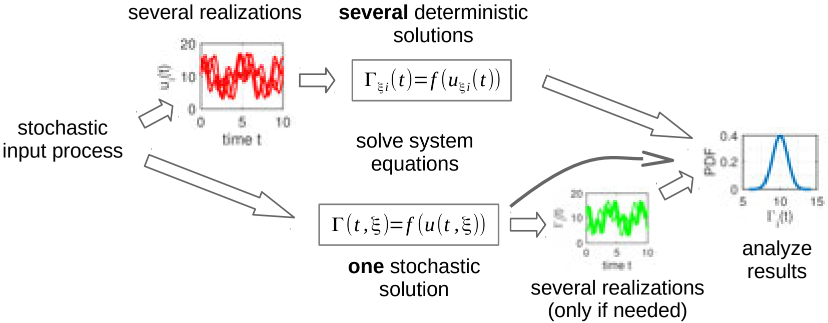
To explore new (multi-MW scale, floating) concepts, need to get beyond BEM

- Physics not captured by BEM
  - Non-linear motion & deflections
  - Swept/winglet blades
- Unsteady aerodynamics
- CFD still to costly for unsteady design
- Vortex-based methods appropriate
  - But costly for unsteady design
- Also want **gradients** for unsteady performance



Fundamentally, we want to replace many time-domain simulations with a single solution in the stochastic space



We have adopted intrusive chaos (polynomial) methods to analyze in the stochastic domain

Expand wind inflow model with random phase angles $\xi \in [-\pi, \pi]$ as:

$$u_\infty(t_n, \boldsymbol{\xi}) = \sum_{r=0}^{R-1} \hat{u}_r(t_n)\, \Psi_r(\boldsymbol{\xi})$$

** Lots of groundwork on describing correlated wind fields with minimum number of ξ phase angles

Expand circulate strength Γ (lift) as:

$$\Gamma(t_n, \boldsymbol{\xi}) = \sum_{r=0}^{R-1} \hat{g}_r(t_n)\, \Psi_r(\boldsymbol{\xi})$$

Functionals $\Psi_r(\boldsymbol{\xi})$ define polynomials (exponentials) of random variable ξ

- Choose form based on PDF of ξ
- Legendre polynomials for uniform distributions

Solution procedure is equivalent to one time-domain solve but obtain results for all possible ξ values

Use inner product $\langle \square, \Psi_r(\boldsymbol{\xi}) \rangle$ 'stochastic Galerkin' projection

- Orthogonality property of $\Psi_r(\boldsymbol{\xi})$ when chosen correctly
- Equations for coefficients in time fall out

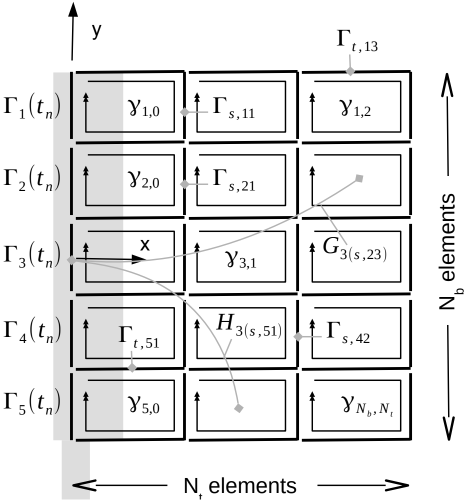
$$\hat{u}_r(t_n) \qquad \hat{g}_r(t_n)$$

- Note that these solutions are functions of time
  - Not a Fourier transform!
  - Can handle non-linear, time dependent effects

Output quantity calculations

- Time-domain for specific ξ realization
  - Validation with time dependent code
- Directly compute statistical moments from $\hat{g}_r(t_n)$
  - PDF reconstruction methods
- All possible wind input fields evaluated simultaneously

We've applied the stochastic Galerkin method to stationary blades/wings (lifting line)...



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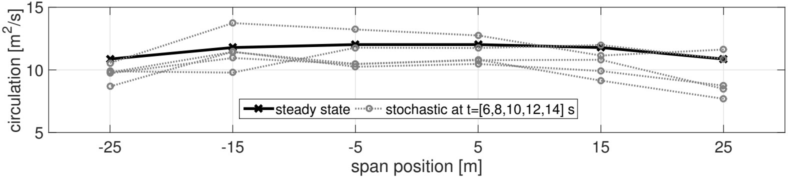
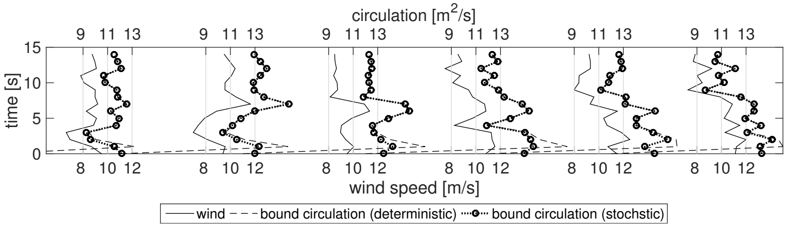
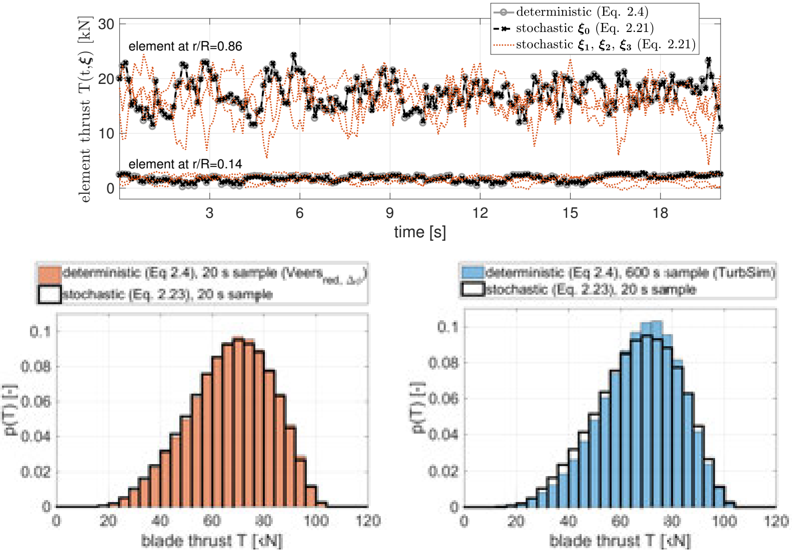




… and simplified BEM compared to 100 deterministic sample wind inputs



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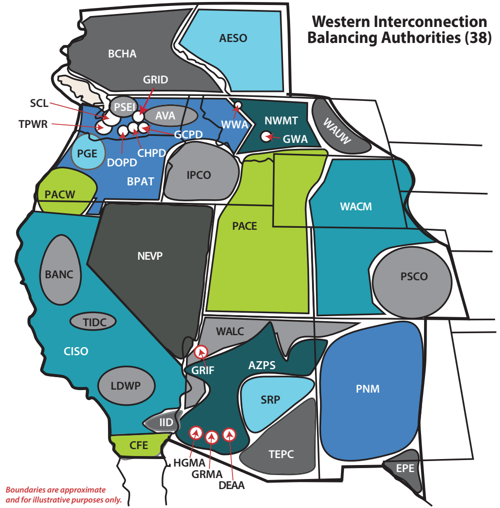
Wind energy's value depends on the grid-delivered product, hopefully greater than the costs to provide it

- Various components in levelized cost of energy
  - Base materials – capital costs
  - Aerostructural performance – power capture/loads
  - Variability in system costs captured with previous approaches
- But value is different than costs
  - Levelized avoided cost of energy (LACE)
    - LCOE estimates revenue *requirements*
    - LACE estimates revenues *available*
  - Firming services costs
- How to model variable grid system performance?

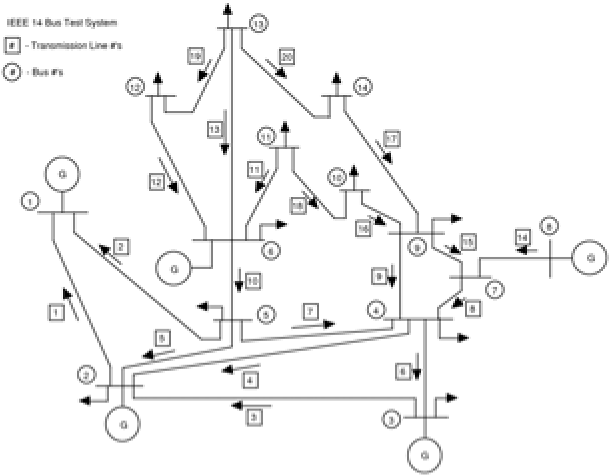
The interconnected grid is large and complicated, requiring efficient solutions methods



The power grid is modeled by a set of (non-)linear power flow equations

Distribution and transmission grid governing equations

$$[P_i, Q_i] = f(V_i, \delta_i) \qquad [P_{ik}, Q_{ik}] = f(V_i, V_k, \delta_{ik})$$



Cumulant-based analysis methods to handle stochastic generation and loads on each bus

Input definition

Real P_i and imaginary Q_i power injections represent generation and loads on each bus

- Compute moments μ_v of the distributions
- Convert moments to cumulants κ_v of those distributions

Analysis method

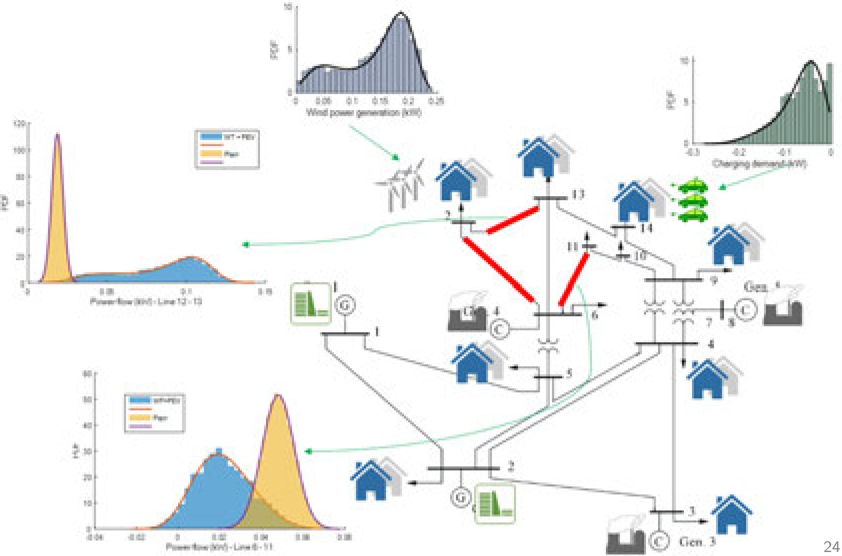
Basic cumulant arithmetic for $Y = AX$: $\kappa_{Y,v} = A^v \kappa_{X,v}$
We extended to cumulant tensors for **correlated** variables and polynomial functionals

- Linearize polar form of equations & truncate
- Rectangular form of power flow equation expansion
- $\Rightarrow$ exact quadratic equation!

Post-process results

$[V_i, \delta_i, P_{ik}, Q_{ik}]$ outputs impacting costs, etc.
Maximum-entropy PDF reconstruction from κ_v

IEEE 14 bus example with wind power generation and plug-in vehicle loads



Thanks for listening!

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