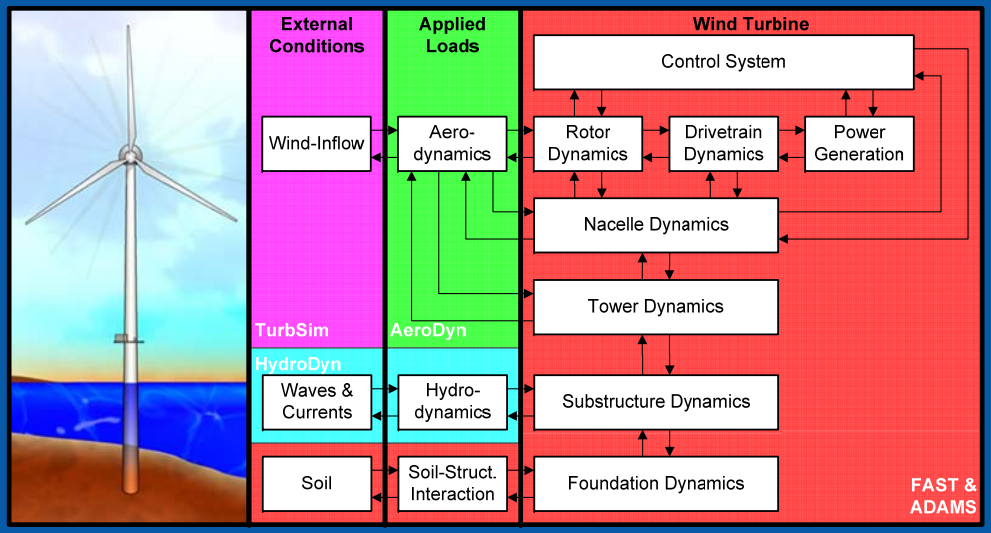
National Renewable Energy Laboratory
Innovation for Our Energy Future

Overview of Design Codes



TurbSim & Design Codes Workshop

September 22 – 25, 2008

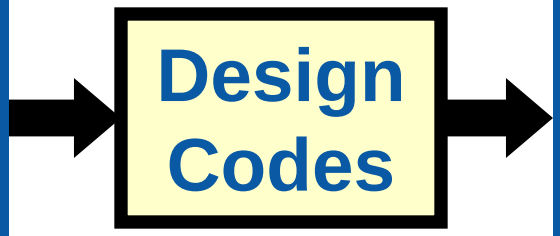
Jason Jonkman

Introduction & Background

Efficient Technology Transfer

Knowledge Areas

Wind & Waves
Aerodynamics
Aeroacoustics
Hydrodynamics
Structural Dynamics
Control Systems
Power Generation
Design Standards
Experimentation



Application Areas

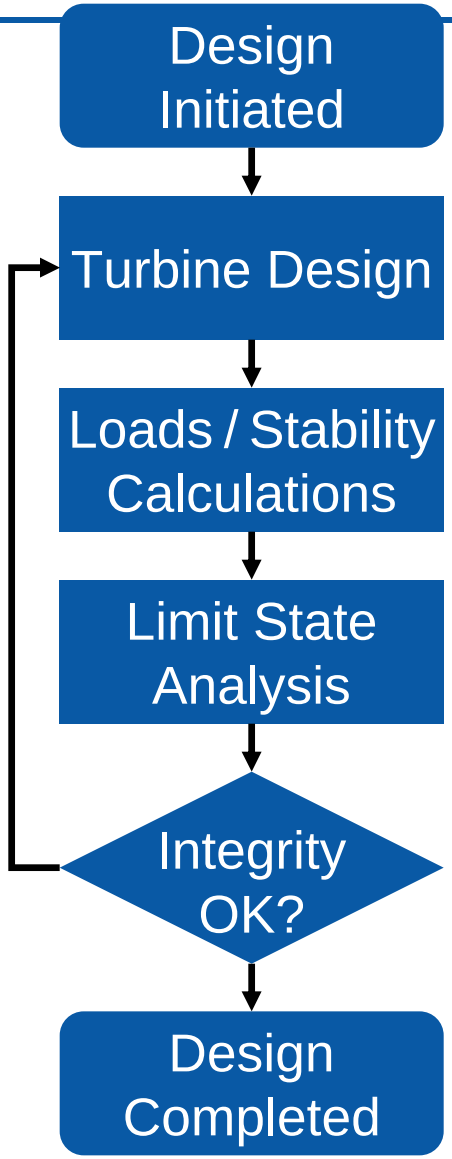
Conceptual Design
Rotor Performance
Control System Design
Loads Analysis
Stability Analysis
Design Certification
Design Reliability
Analyst Training
Testing Support

Wind energy knowledge is transferred to the wind industry through design codes

The advancement of wind technology is limited by design code capability

Introduction & Background

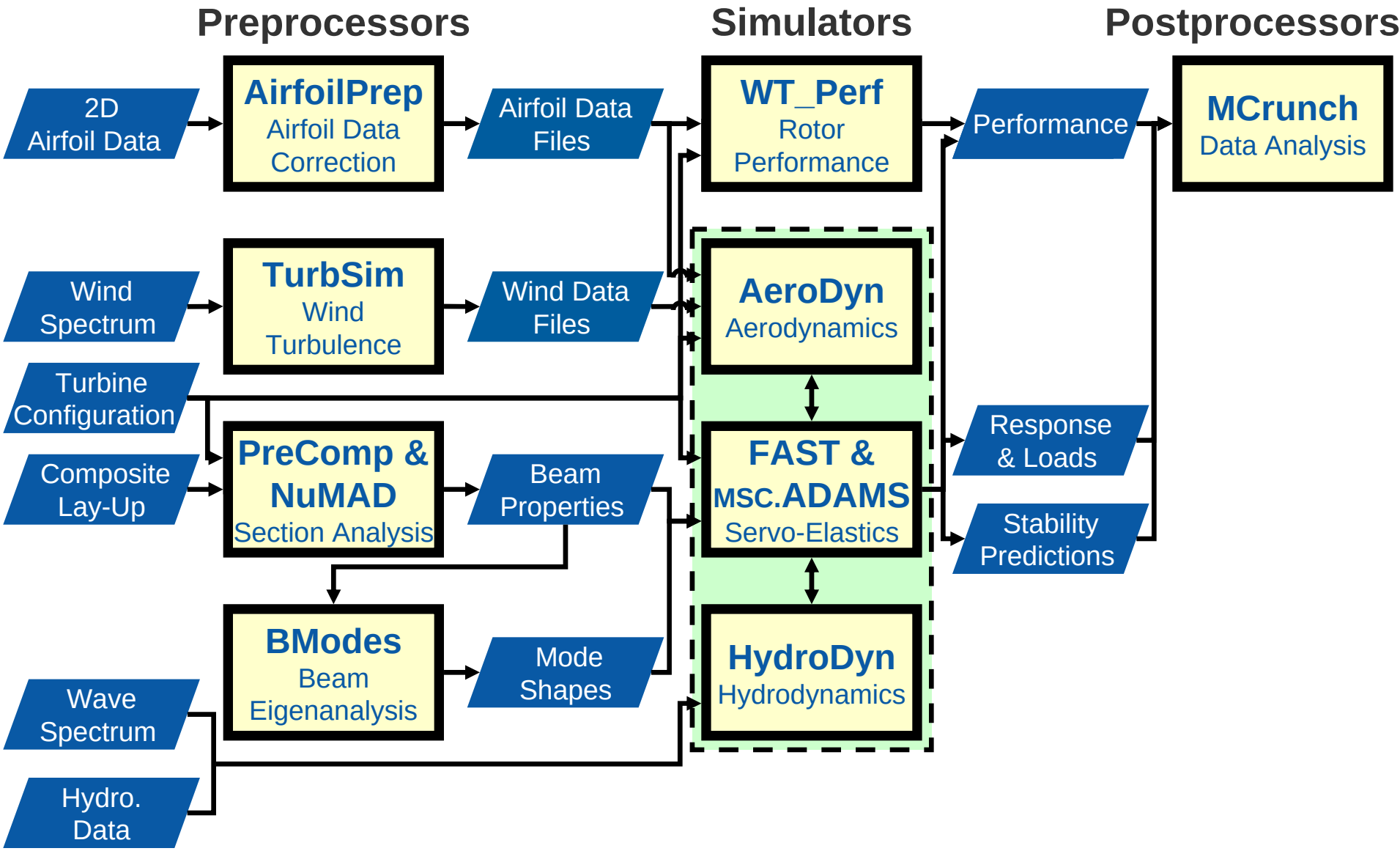
Wind Turbine Design Process



- Standards have codified the design & analysis process
- Coupled aero-hydro-servo-elastic models of the full system are used to calculate loads
- Loads are used within component models (e.g., FEA) to perform limit state analysis
- Structural integrity achieved when:
  Design Load ≤ Design Resistance
- Model inputs must be tuned with test data to ensure accurate response calculations

Introduction & Background

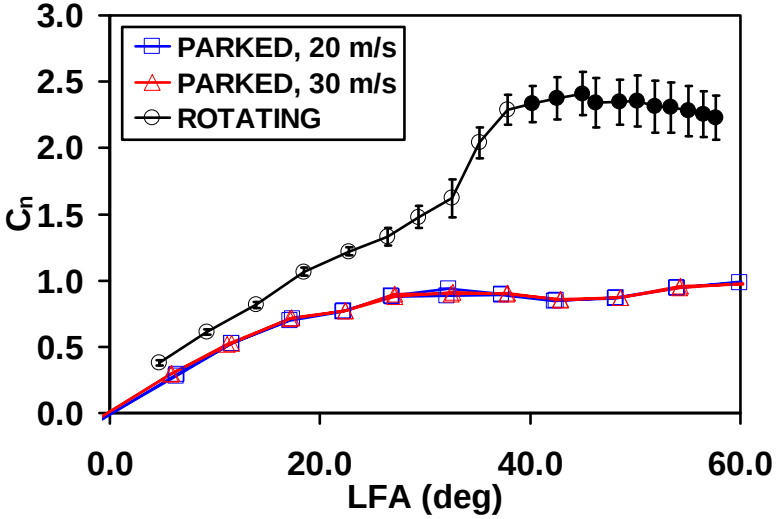
Key Codes in the Design Process



Design Codes

AirfoilPrep

- Generates airfoil data files from 2D data:
  - Adjusts 2D data for rotational augmentation (3D effects):
    - Selig/Du for lift (stall delay)
    - Eggers for drag
  - Extrapolates to high AoA:
    - Uses Viterna method or flat-plate theory for -180º < AoA < 180º data
  - Computes dynamic stall parameters
  - Blends aerodynamic coefficients

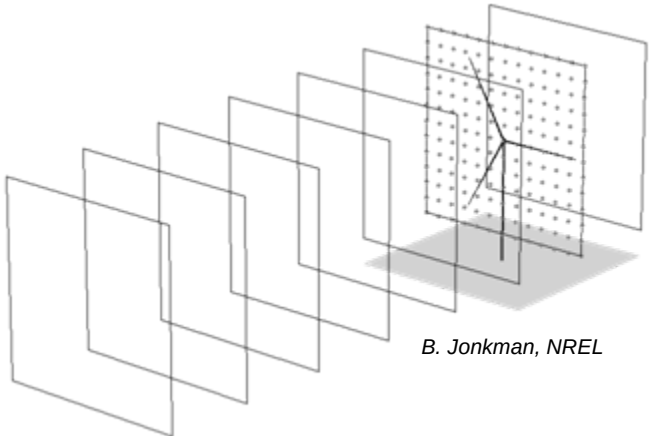


Data from NASA Ames Wind Tunnel: Unsteady Aerodynamics Experiment

- Current & planned work – Build functionality into **AeroDyn**
- Future opportunity – Include new stall delay models

Design Codes
TurbSim

- Computes full-field stochastic wind realizations:
  - Inputs are desired wind profile & turbulence characteristics
  - Includes IEC- & site-specific turbulence models
  - Option to generate coherent structures from LES & DNS output
- Current & planned work:
  - Improve coherence formulations (just released)
  - Apply code to determine impact of non-IEC turbulence on turbine response
- Future opportunities:
  - Optimize code to enable computation of larger grids
  - Include additional site-specific turbulence models
  - Add Mann model



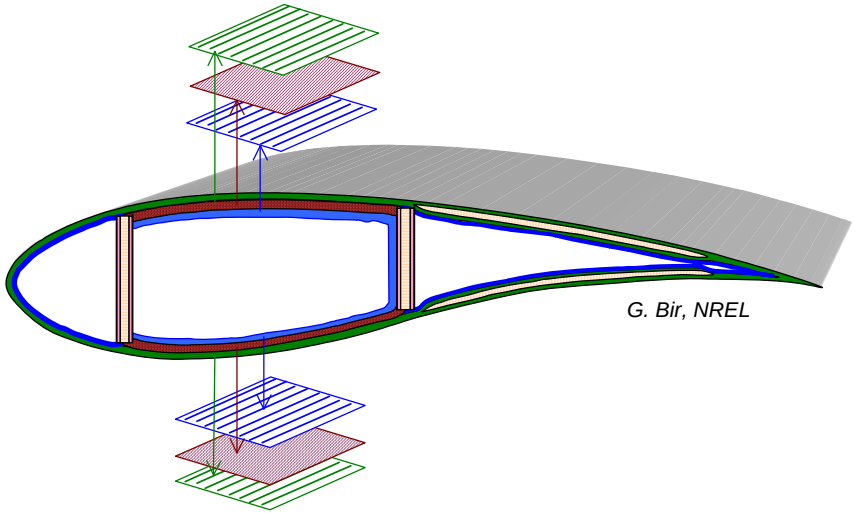
Full-Field Turbulence Grids

Design Codes

PreComp

- Computes coupled section properties of composite blades for beam-type models:
  - Inputs are the airfoil shape & internal lay-up of composite laminas
  - Uses a combined laminate theory (modified) with shear flow approach
- Current & planned work:
  - Add stress analysis
  - Validation
- Future opportunities:
  - Allow for built-in curvature & sweep
  - Add inverse design algorithm

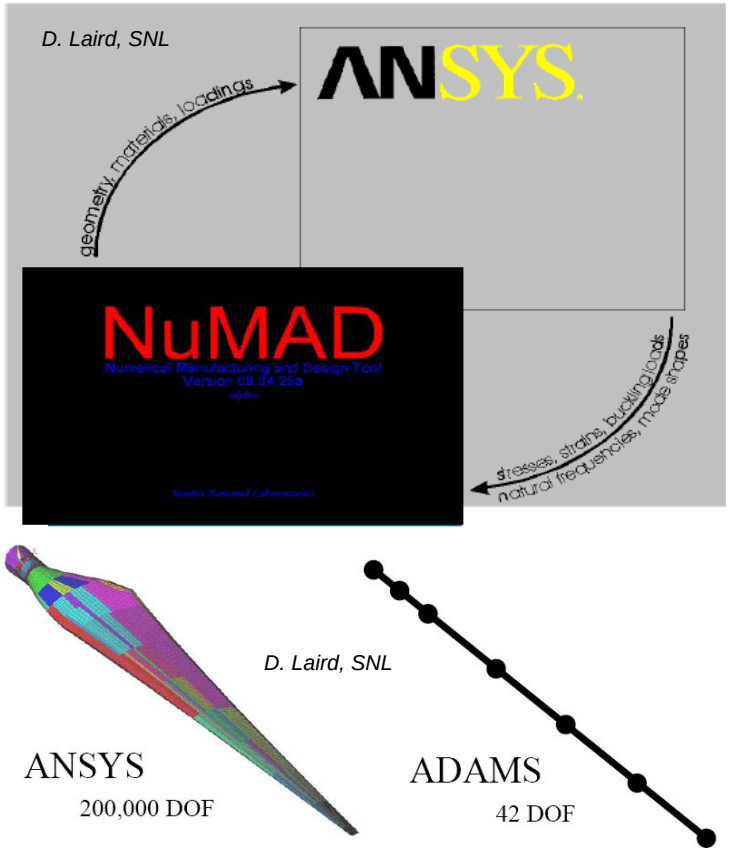
$$\begin{Bmatrix} F_X \\ M_Y \\ M_Z \\ T_X \end{Bmatrix} = \begin{bmatrix} \overline{EA} & S_{af} & S_{al} & S_{at} \\ S_{af} & \overline{EI}_{flap} & S_{fl} & S_{ft} \\ S_{al} & S_{fl} & \overline{EI}_{lag} & S_{lt} \\ S_{at} & S_{ft} & S_{lr} & \overline{GJ} \end{bmatrix} \begin{Bmatrix} u_e' \\ w'' \\ v'' \\ \theta' \end{Bmatrix}$$



G. Bir, NREL

Design Codes
NuMAD

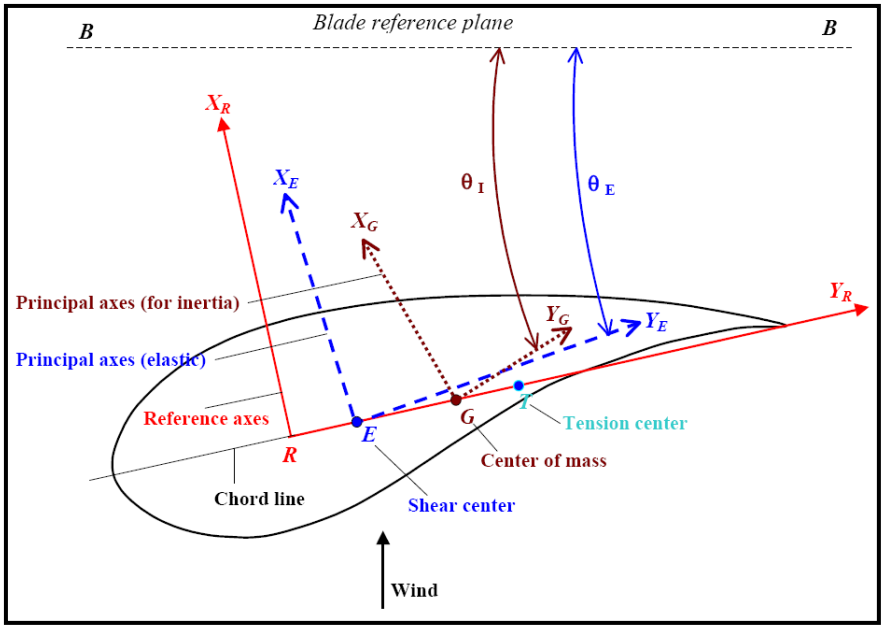
- A GUI pre- & post-processor for ANSYS®-based FEA analysis:
  - Tailored to wind turbine blades
  - Enables one to easily create a 3D FEA model & perform structural analysis
  - Beam property extraction feature to produce section properties for beam-type models
- Current & planned work:
  - Add airfoil-independent skin material & shear web placement
  - Add capability to model flatback airfoils
  - Introduce meshing control
  - Introduce multiple element formulations
- Future opportunities:
  - Allow for built-in curvature & sweep



Design Codes

BModes

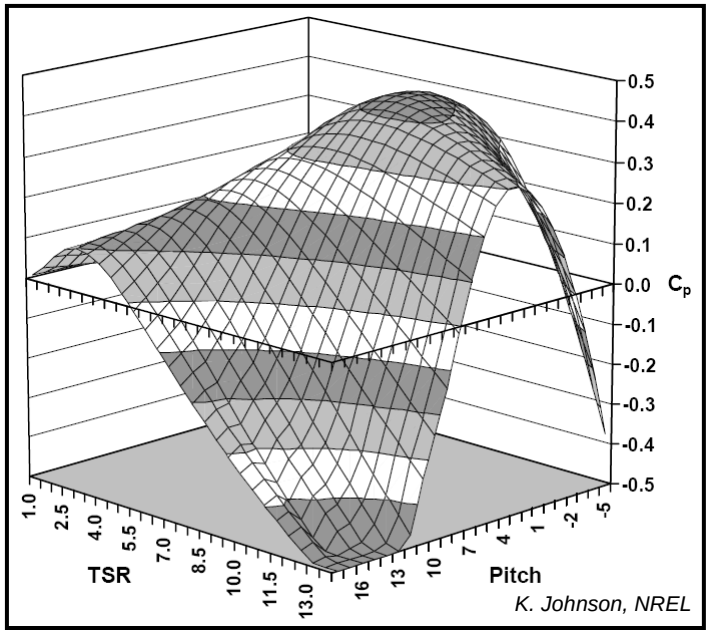
- Computes coupled mode shapes & frequencies of blades & towers:
  - Considers axial-flap-lag-torsion coupling
  - Inputs are the boundary conditions & distributed isotropic beam properties
  - Based on a 15-DOF FE developed to handle rotation-related terms
- Current & planned work:
  - Add modeling of towers with guy wires, flexible foundations, & floating bases
  - Import modes directly to **FAST**
  - Verification & validation
- Future opportunities:
  - Allow for anisotropic material (from **PreComp** or **NuMAD**)
  - Allow for hinged blade root
  - Allow for built-in curvature & sweep
  - Build into **FAST** for runtime calculation of modes



Design Codes

WT_Perf

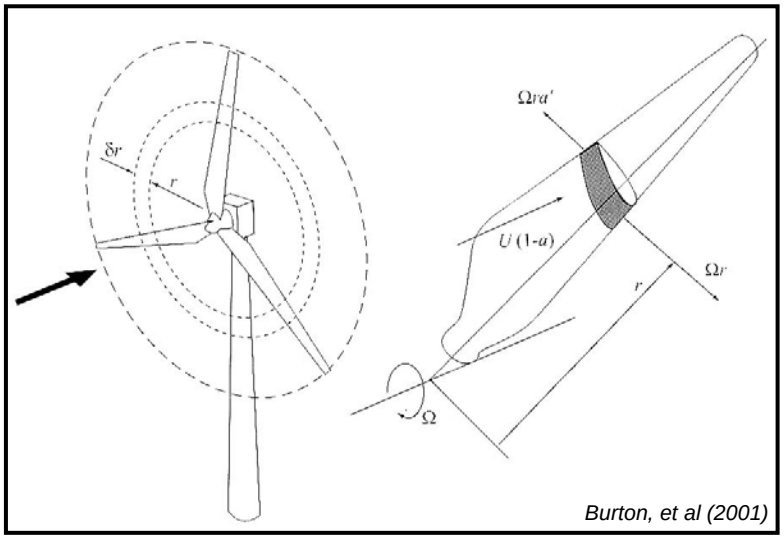
- Calculates steady-state rotor performance:
  - Inputs are rotor geometry, airfoil data, wind, pitch, & rotor speed
  - Uses BEM theory
- Current work – Improve solution algorithm
- Future opportunities:
  - Add algorithm for tuning airfoil data to match measured performance
  - Add blade optimization algorithm
  - Incorporate new aerodynamic models (e.g., vortex wake)



Power Coefficient for the CART2

Design Codes
AeroDyn

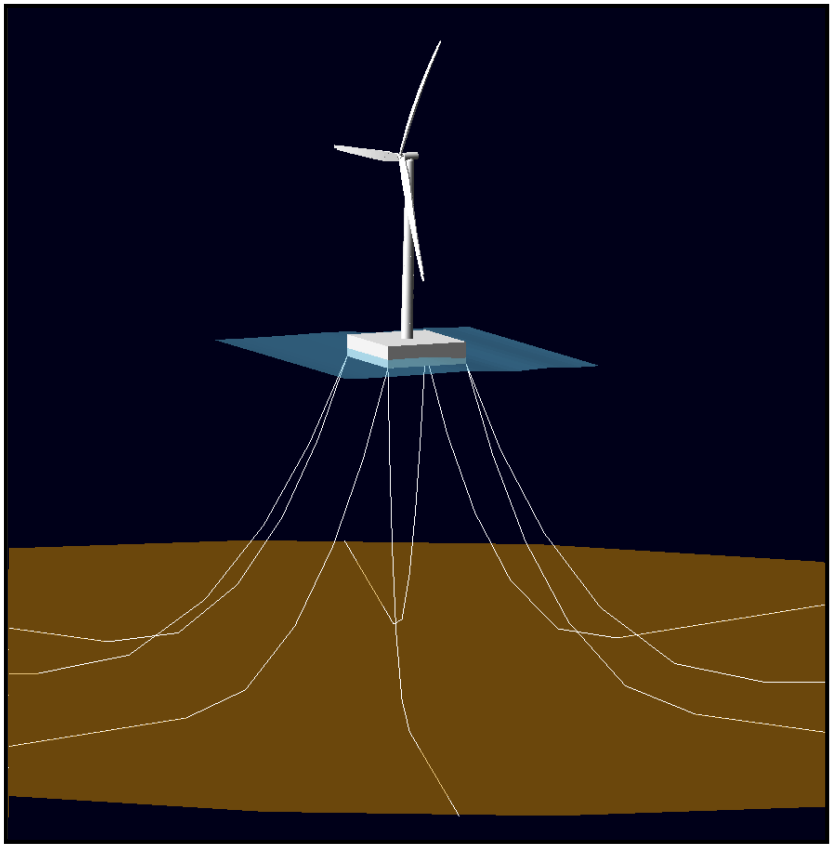
- Computes aerodynamics as part of the aero-elastic solution:
  - Equilibrium (BEM) & dynamic (GDW) wake
  - Beddoes-Leishman dynamic stall
  - Turbulent (**TurbSim**) & uniform wind inputs
  - Fully coupled to **FAST** & **ADAMS**
- Current & planned work:
  - Overhaul to improve functionality & usability
  - Hosted kick-off meeting with 50 attendees
  - Develop improved interface with co-simulation & modularization
  - Automate rotational augmentation correction (substitute for **AirfoilPrep**)
  - Add tower, nacelle, & hub influence & loading
- Future opportunities:
  - Incorporate new aerodynamic models (e.g., vortex wake)
  - Develop linearized models for stability analysis
  - Add aero-acoustic noise predictor (replacement for **FAST**'s noise module)
  - Implement new physics for hydro-kinetic turbines



Burton, et al (2001)

Design Codes
HydroDyn

- Computes hydrodynamics as part of the hydro-elastic solution:
  - Morison's equation for monopiles
  - Linear radiation/diffraction theory for floating platforms
  - Regular or irregular linear waves
  - Fully coupled to **FAST** & **ADAMS**
- Current & planned work:
  - Add 2nd-order waves for monopiles (with UT-Austin)
  - Develop improved interface
- Future opportunities:
  - Add additional nonlinear effects
  - Extension to water-power buoys
  - Validation

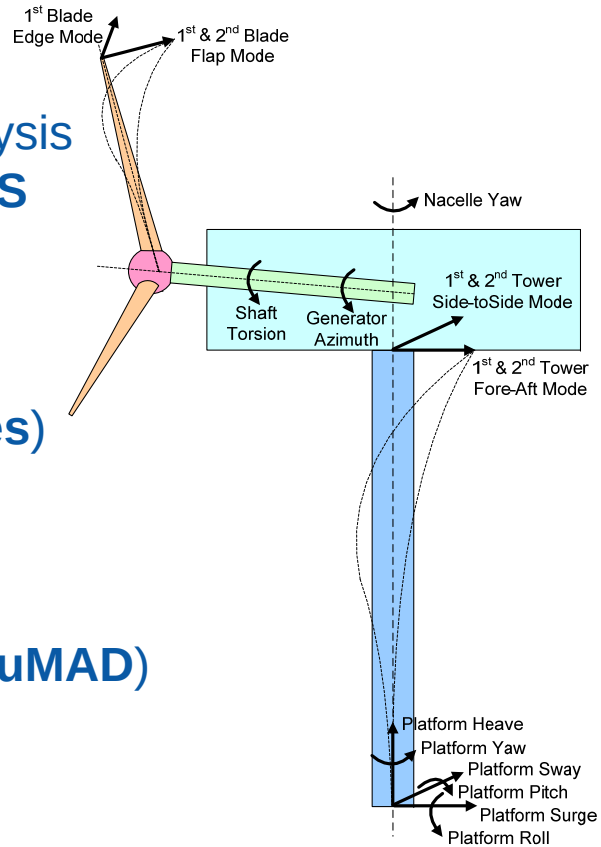


NREL 5-MW Turbine on ITI Energy Barge

Design Codes

FAST

- Computes structural-dynamic & control-system responses as part of the aero-hydro-servo-elastic solution:
  - Uses a combined modal & multi-body representation through 24 DOFs
  - Controls through subroutines, DLLs, or Simulink® with MATLAB®
  - Fully coupled to **AeroDyn** & **HydroDyn**
  - Nonlinear time-domain solution for loads analysis
  - Linearization with MBC for controls & stability analysis
  - Preprocessor for building turbine models in **ADAMS**
  - Evaluated by Germanischer Lloyd WindEnergie
- Planned work:
  - Interface to overhauled **AeroDyn**
  - Replace unc'pld with coupled modes (from **BModes**)
  - Increase number of mode DOFs
  - Add blade-pitch DOFs & actuator models
- Future opportunities:
  - Allow for anisotropic material (from **PreComp** or **NuMAD**)
  - Allow for built-in curvature & sweep
  - Build in **BModes** for runtime calculation of modes
  - Add animation capability

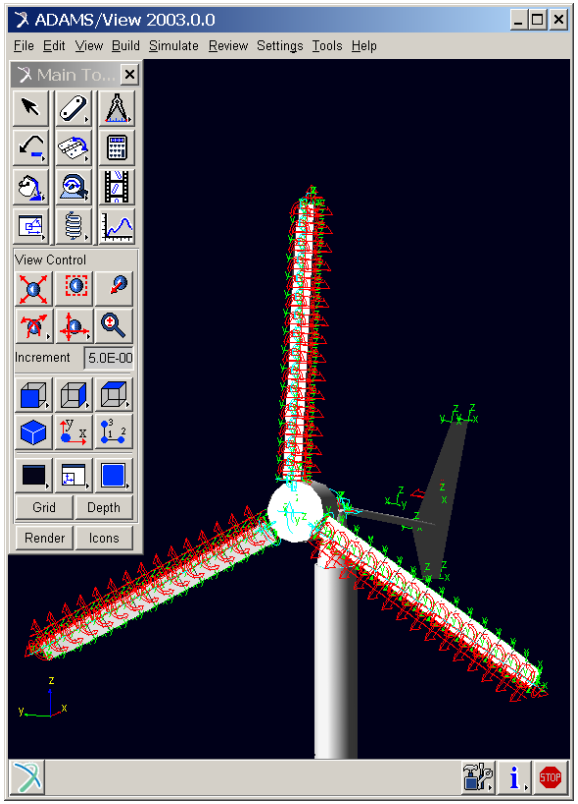


FAST DOFs for a 3-Bladed Turbine

Design Codes

MSC.ADAMS®

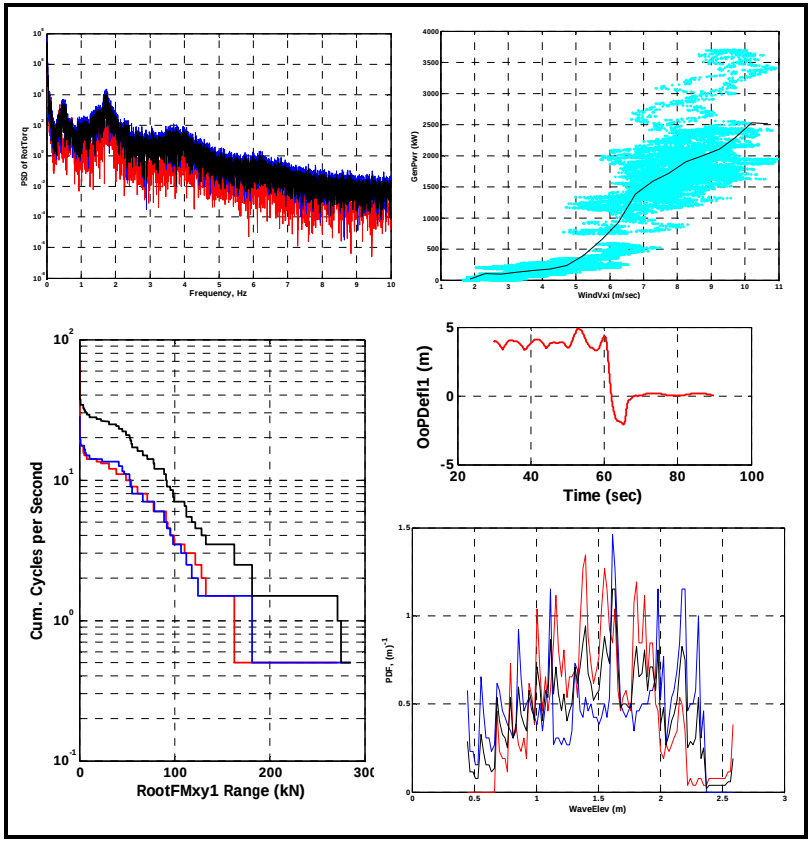
- Computes structural-dynamic & control-system responses as part of the aero-hydro-servo-elastic solution:
  - Commercial product from MSC Software
  - Uses a multi-body representation with virtually unlimited DOFs
  - Controls through subroutines or DLLs
  - Nonlinear time-domain solution for loads analysis
  - Linearization of nonrotating system
  - Fully coupled to **AeroDyn** & **HydroDyn**
  - Datasets can be created by **FAST**
  - Bypasses some limitations of **FAST**
  - Evaluated by Germanischer Lloyd WindEnergie
- Planned work:
  - Interface to overhauled **AeroDyn**
  - Improve analysis of blades with built-in curvature & sweep
- Future opportunities:
  - Replace rigid with flex bodies (imported from FEA)
  - Utilize linearization in a rotating frame
  - Detailed gearbox modeling



ADAMS Model Created by FAST

Design Codes
MCrunch

- A MATLAB®-based postprocessor for data analysis:
  - Started development new in FY07
  - Merges features from legacy codes (**Crunch**, **GPP**, **GenStats**, & **Fatigue**)
- Current & planned work:
  - Establish basic architecture
  - Implement & test basic features:
    - Scales & offsets, calculated channels, & plotting
  - Implement & test key analyses:
    - Statistics, extreme events, binning, PDFs, PSDs, rainflow counting, DELs, binary files, & life estimates
- Future opportunities:
  - Implement additional analyses:
    - Filtering, load roses, azimuth averages, statistical extrapolation, etc.



Example Outputs from MCrunch

Design Codes

NWTC Subroutine Library

- Contains general-purpose routines for use by all codes:
  - I/O, math, aerodynamic, & compiler-specific routines
  - Used by many of the NWTC codes
  - Reduces development & maintenance time
- Current & planned work:
  - Use within **AeroDyn**, **HydroDyn**, & **FAST**
  - Update as needed in support of codes development
- Future opportunities:
  - Develop new libraries for numerical methods:
    - Newton-Raphson iteration solvers
    - ODE & DAE time-integrators
    - FFT routines
    - Eigen-solvers

Users & Support

Users of NREL-Developed Codes

- There are 100 to 150 domestic & international users

Manufacturers | **Consultants** | **R&D Institutes** | **Universities**

Users & Support

Successful Applications (Only Subset Shown)

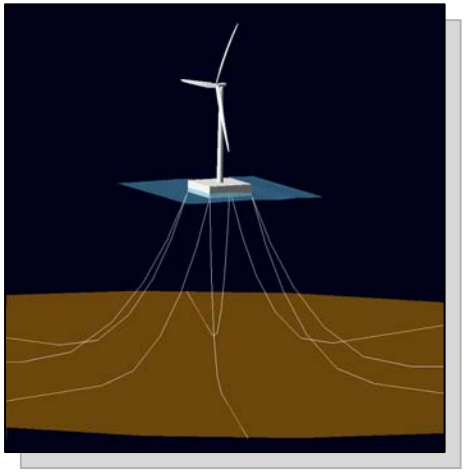
Southwest Windpower Skystream

CART2

Clipper 2.5-MW Liberty

NorthWind 100

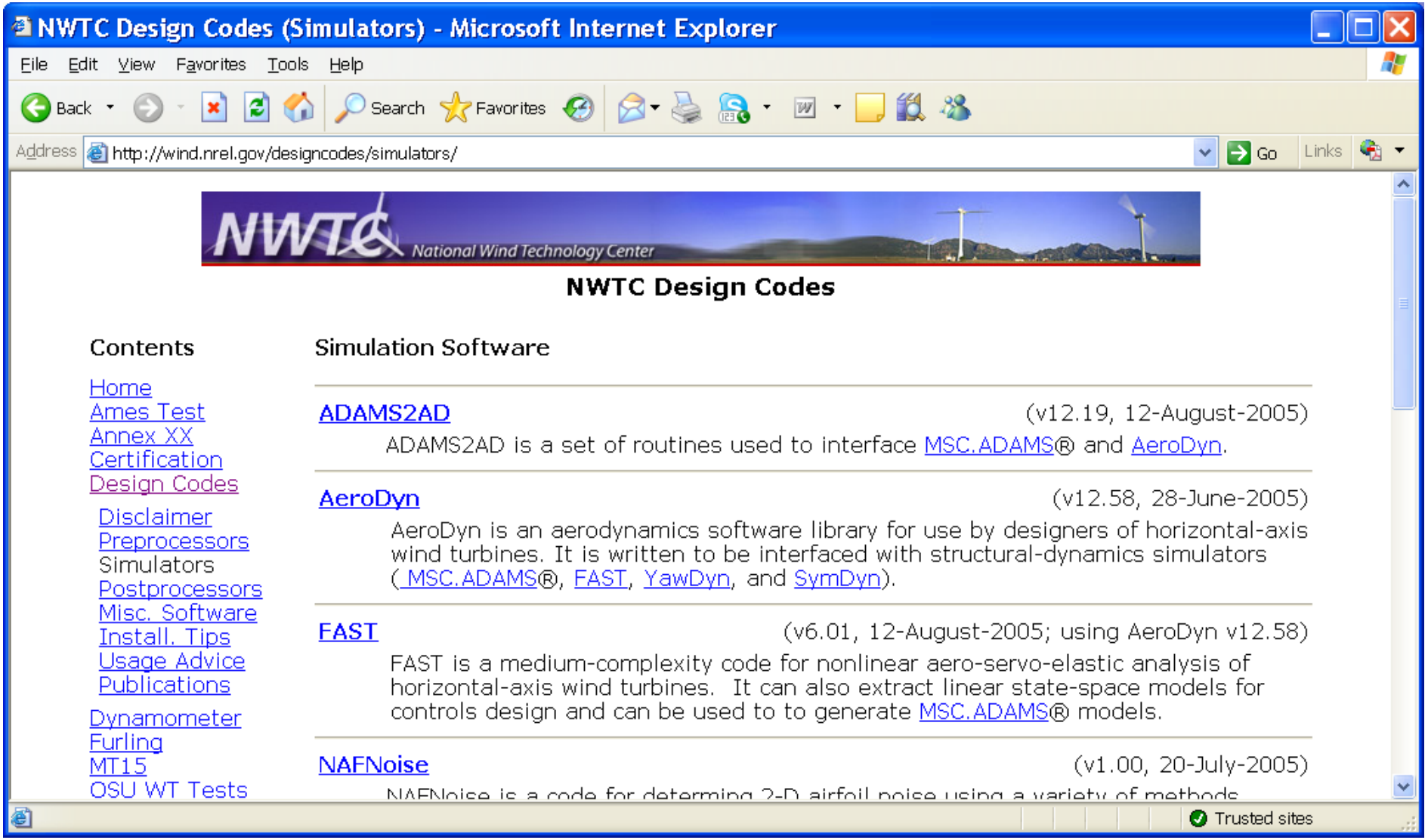
GE 1.5 MW



NREL 5-MW Turbine on ITI Energy Barge

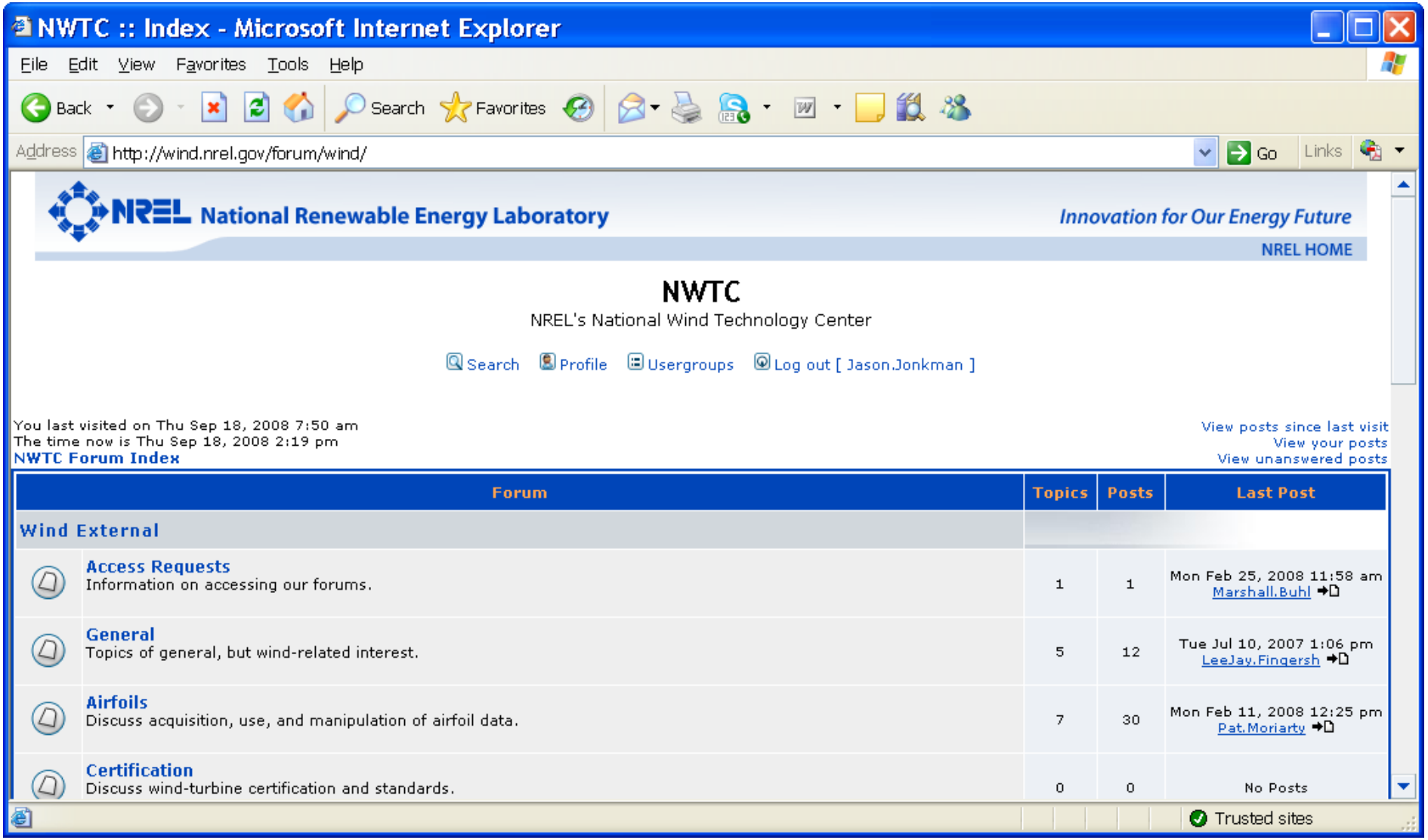
Users & Support

NWTC Design Codes Website



Users & Support

NWTC Forum



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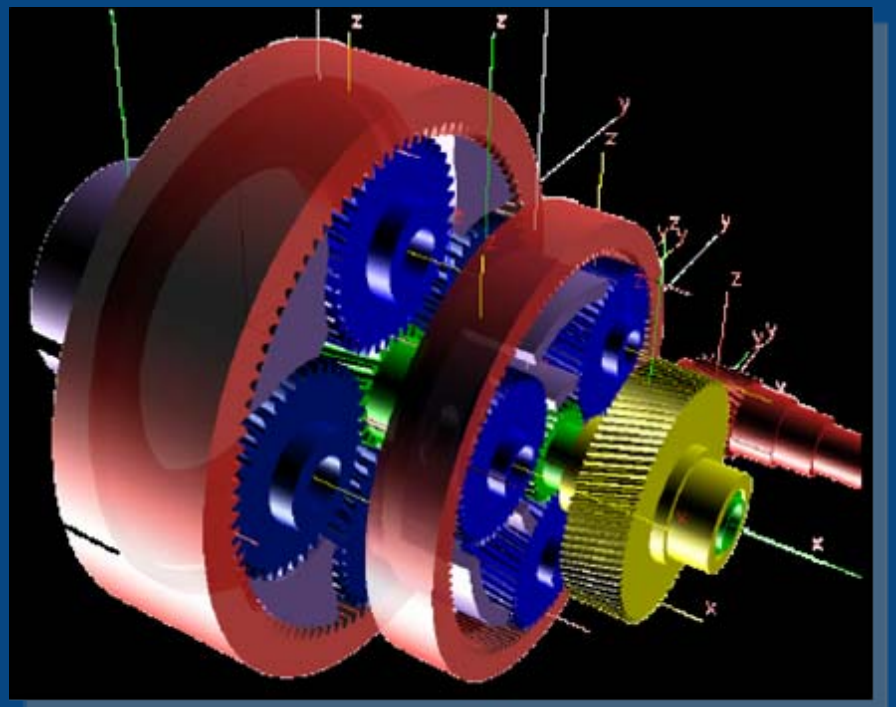

Questions?

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