National Renewable Energy Laboratory
Innovation for Our Energy Future

Wind Turbine Modeling Overview for Control Engineers

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Patrick Moriarty
Sandy Butterfield

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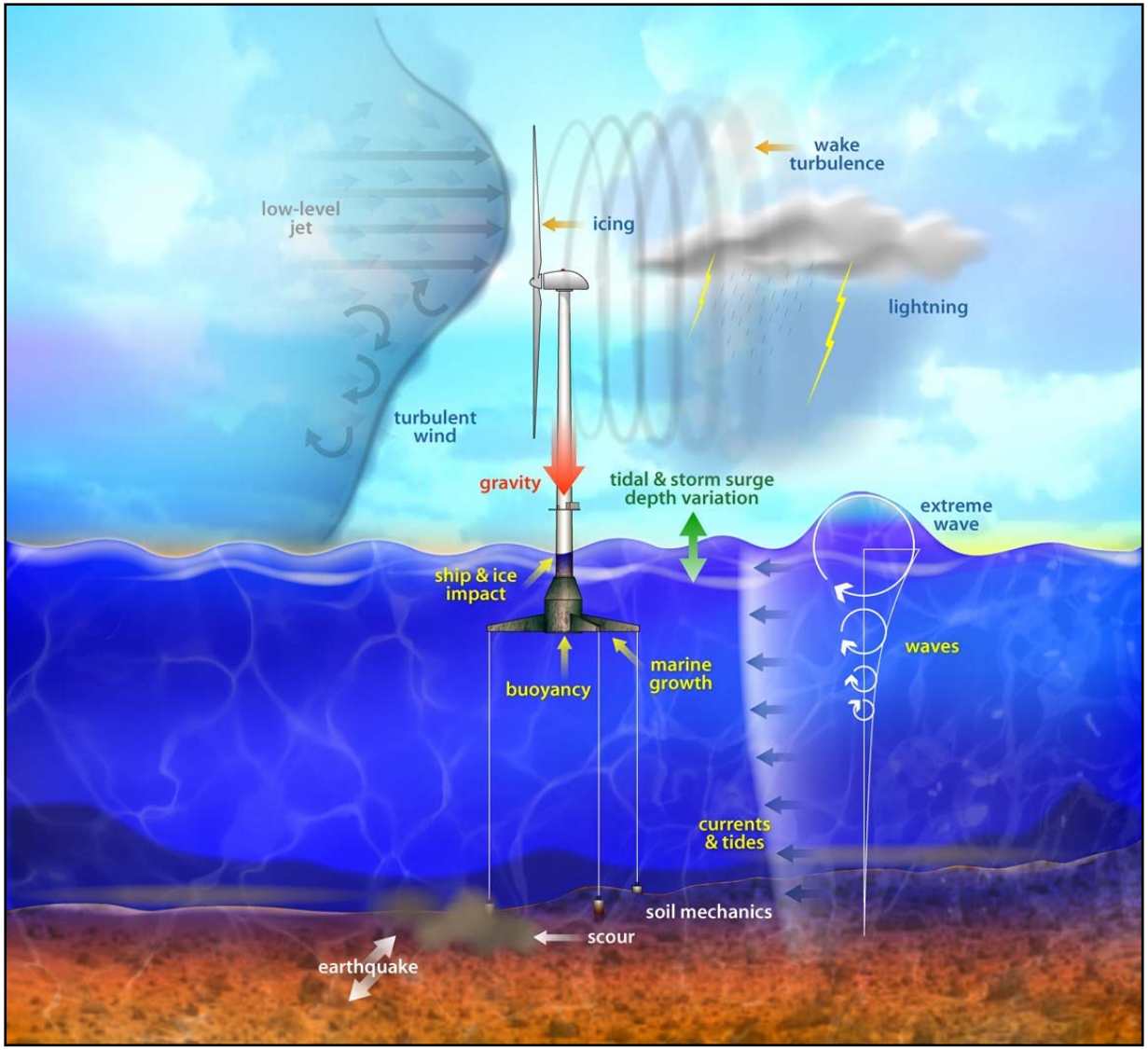
NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

Introduction & Background

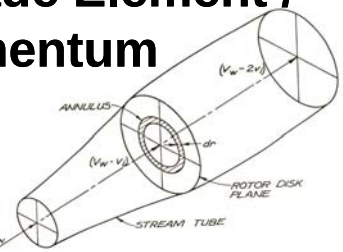
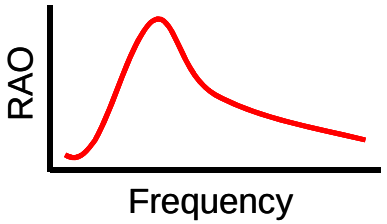
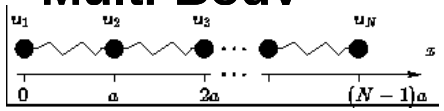
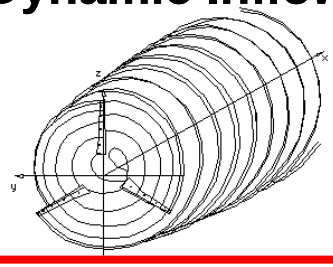
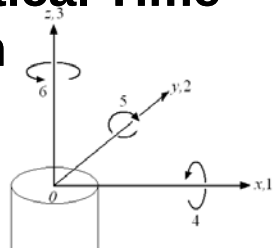
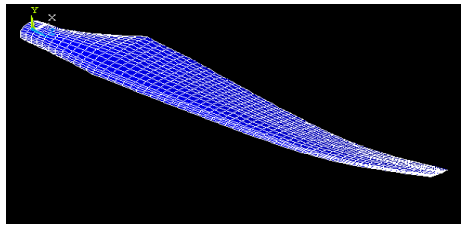
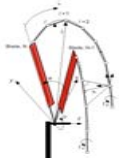
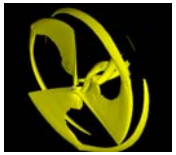
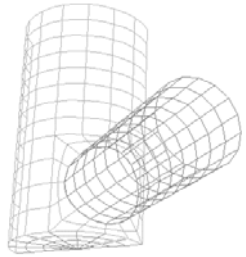
Simulation Requirements



- Coupled aero-hydro-servo-elastic interaction
- Models originate from different disciplines
- Wind-Inflow:
  - discrete events
  - turbulence
- Waves:
  - regular
  - irregular
- Aerodynamics:
  - rotational augmentation
  - skewed wake
  - dynamic stall
- Hydrodynamics:
  - diffraction
  - radiation
  - hydrostatics
- Structural dynamics:
  - gravity / inertia
  - elasticity
  - foundations / moorings
- Control system:
  - yaw, torque, pitch

Model Fidelity for Multi-Physics Simulation Tools

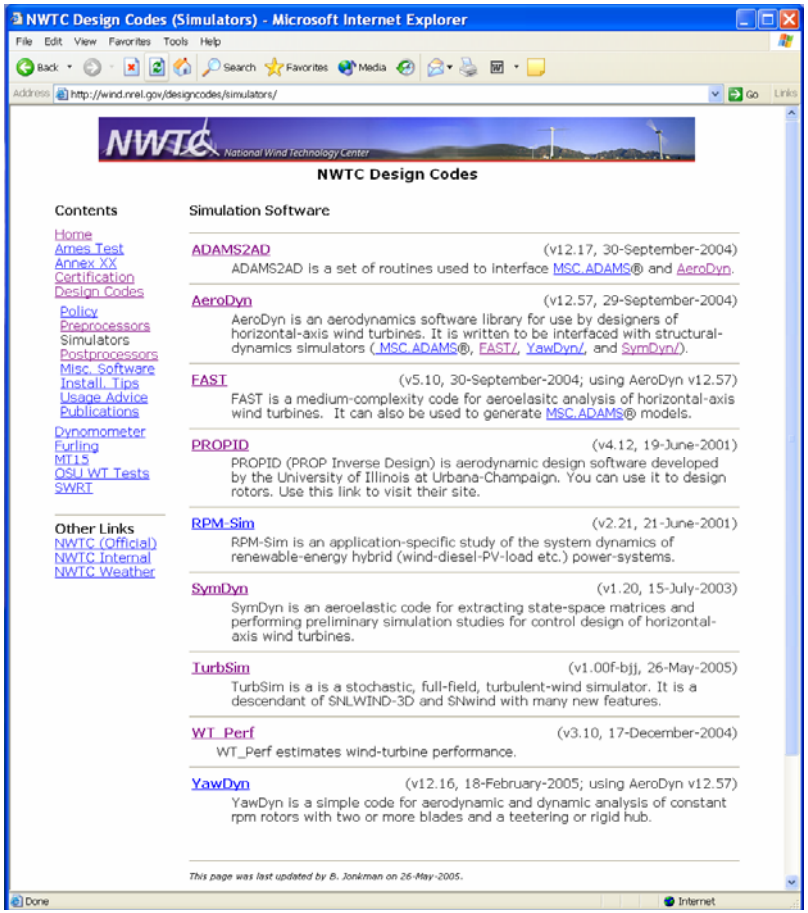
Increasing Complexity

	Structural Dynamics	Rotor Aerodynamics	Platform Hydrodynamics
Preliminary Design	• None	• Blade Element / Momentum 	• Freq. Domain 
Detailed Design	• Modal • Multi-Body 	• Dynamic Inflow 	• Analytical Time Domain 
Research	• Finite Element Method 	• Vortex Method • Computational Fluid Dynamics  	• Numerical Panel Method 

Introduction & Background

NREL Design Codes

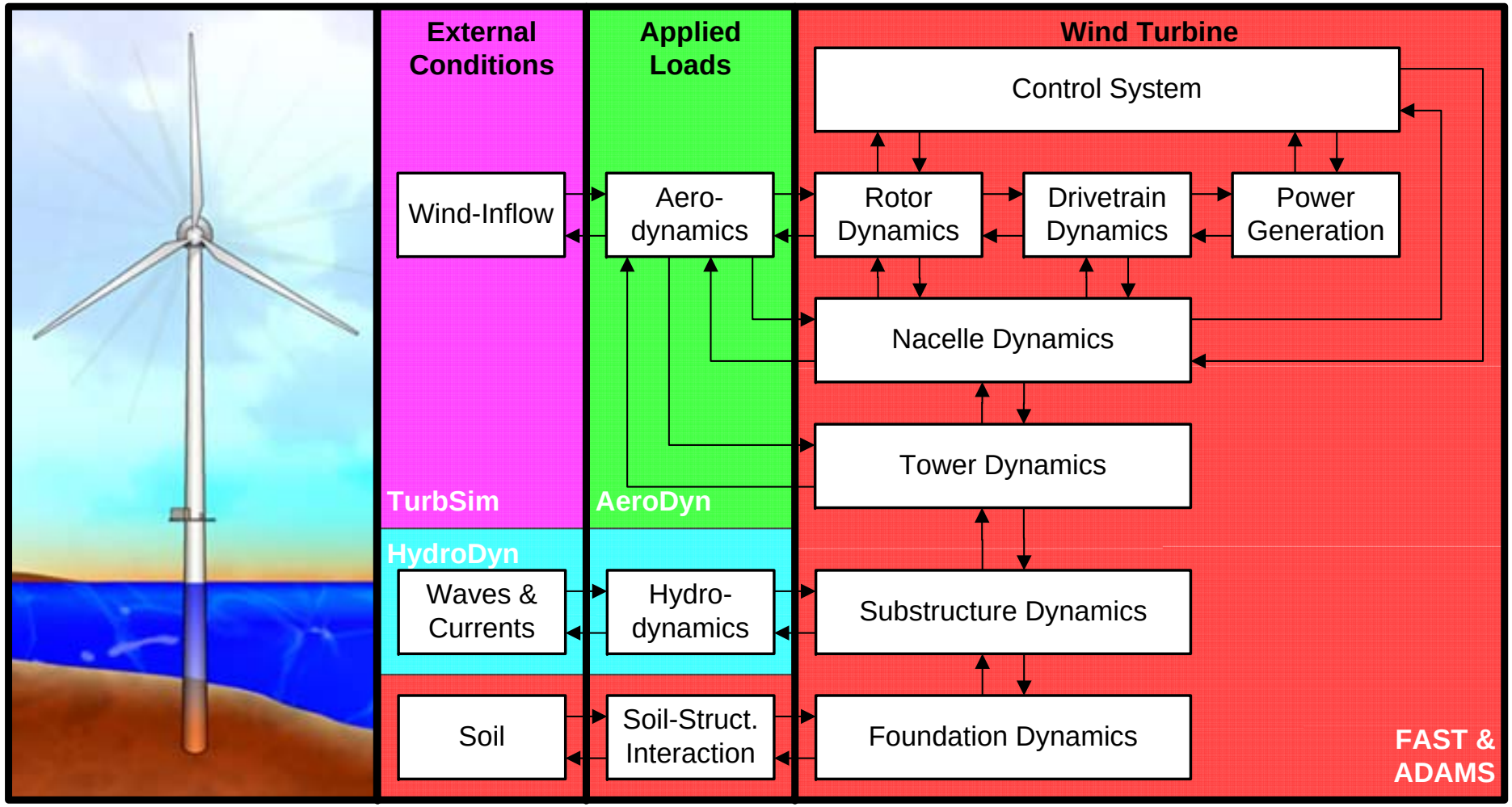
- One set of models
  - FAST – aeroelasticity
    - AeroDyn – aerodynamics
    - HydroDyn - hydrodyanmics
  - TurbSim – turbulent inflow
  - Others include:
    - ADAMS (MSC)
    - Bladed (Garrad Hassan)
    - Hawc2 (Risø)
    - FLEX5 (DTU)
    - Many similarities between codes
- Freely available
- Used heavily in industry, academia and other governmental research organizations
- Certified by Germanischer Lloyd
  - IEC Certification body
- Knowledge of strengths and weaknesses important for control systems design



NWTC Design Codes Website
http://wind.nrel.gov/designcodes

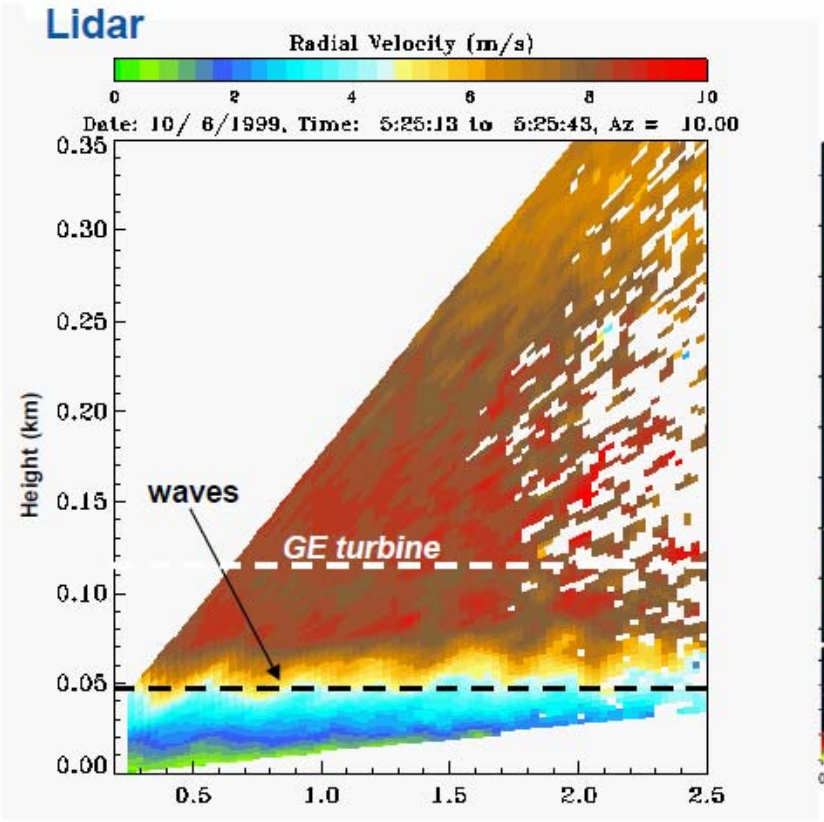
Design Codes

Coupled Aero-Hydro-Servo-Elastic Simulation



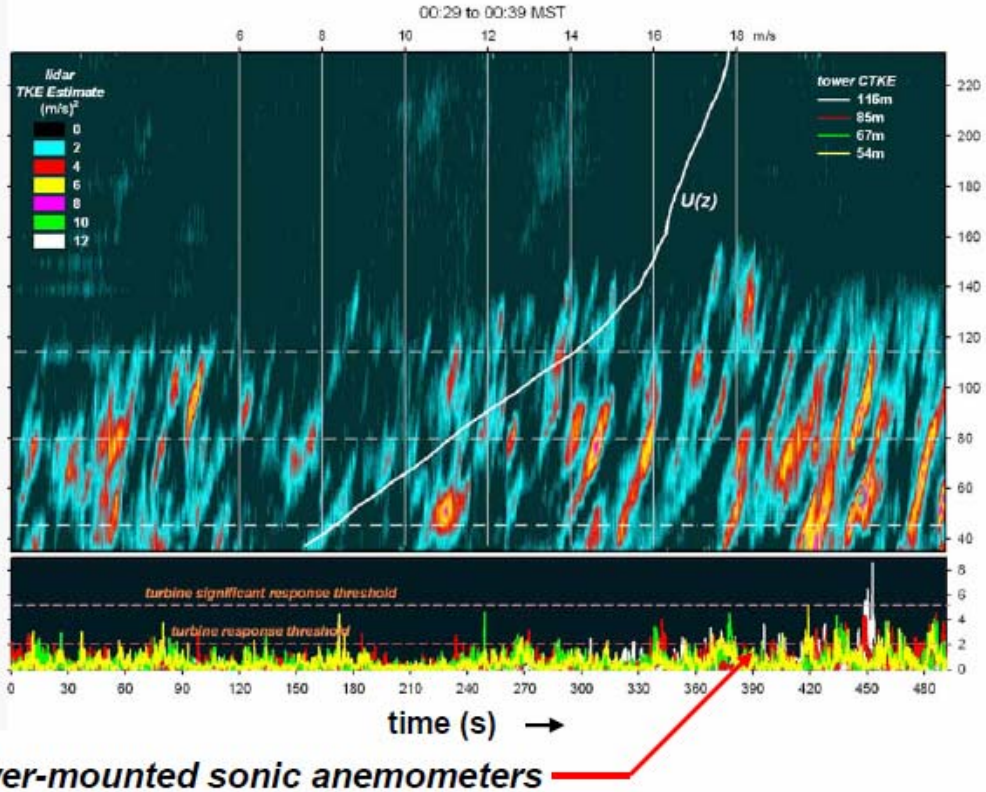
Turbulent Inflow

Observation of Wave Motions Associated with Low-Level Jet in Southern Kansas Using NOAA HRDL Lidar



Courtesy: R. Banta, NOAA/ESRL

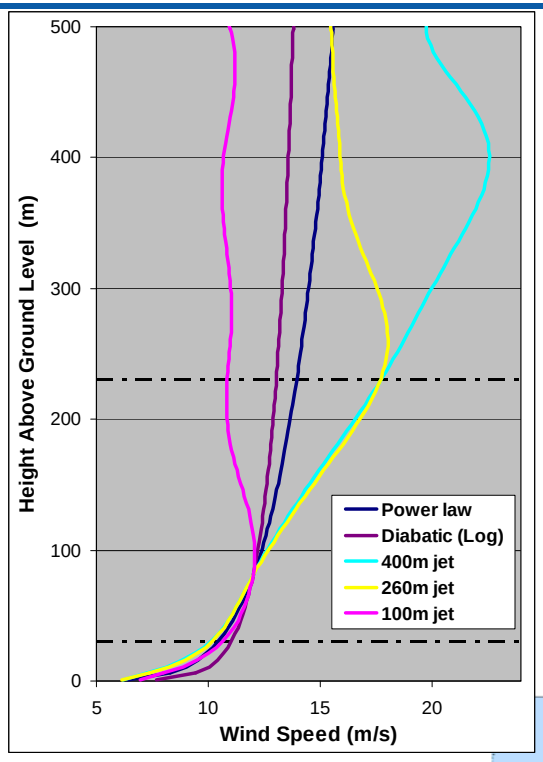
Coherent Turbulent Structures Under Low-Level Jet in Southeast Colorado From NOAA HRDL Lidar Data

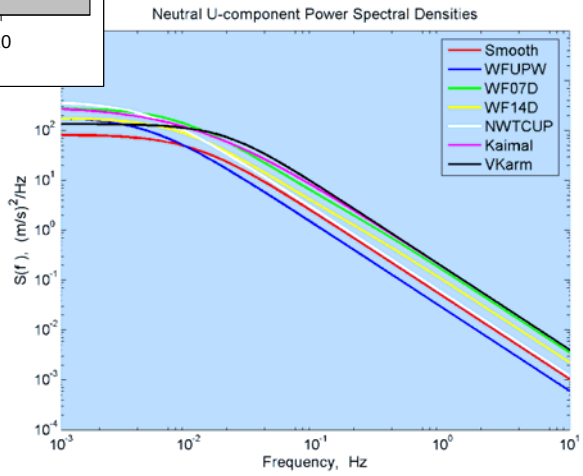


tower-mounted sonic anemometers

Turbulent Inflow

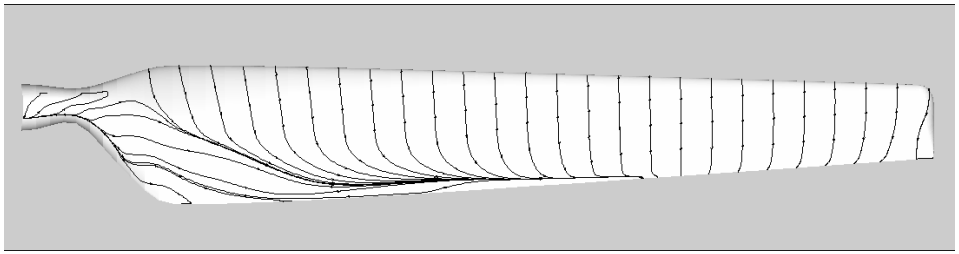
- Standard classifications (IEC)
  - Mean profile
    - Often assume power law
      - $U \sim z^{0.2}$
  - Stochastic turbulence
    - IFFT to match spectra
  - Coherent structures
    - KH waves
  - Extreme events
  - Wind farm effects
- Limitations
  - Every site is different
  - Decoupled from turbine
    - Important as turbine get larger



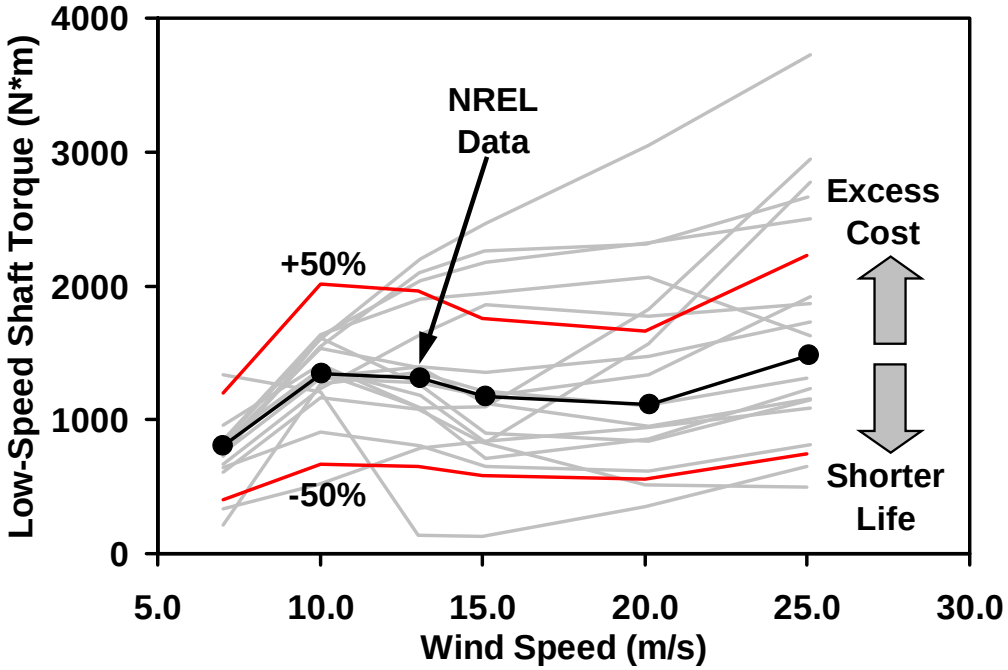


Aerodynamics

- Largest model uncertainty
- Blade element momentum theory is industry standard
  - Much empiricism
  - Particularly for off design conditions
- Non-linear effects
  - Important for
    - Yaw
    - Gusts
    - High wind speeds
    - Turbine faults
  - Rotational augmentation
  - Dynamic stall
- Large uncertainty where control system is most critical

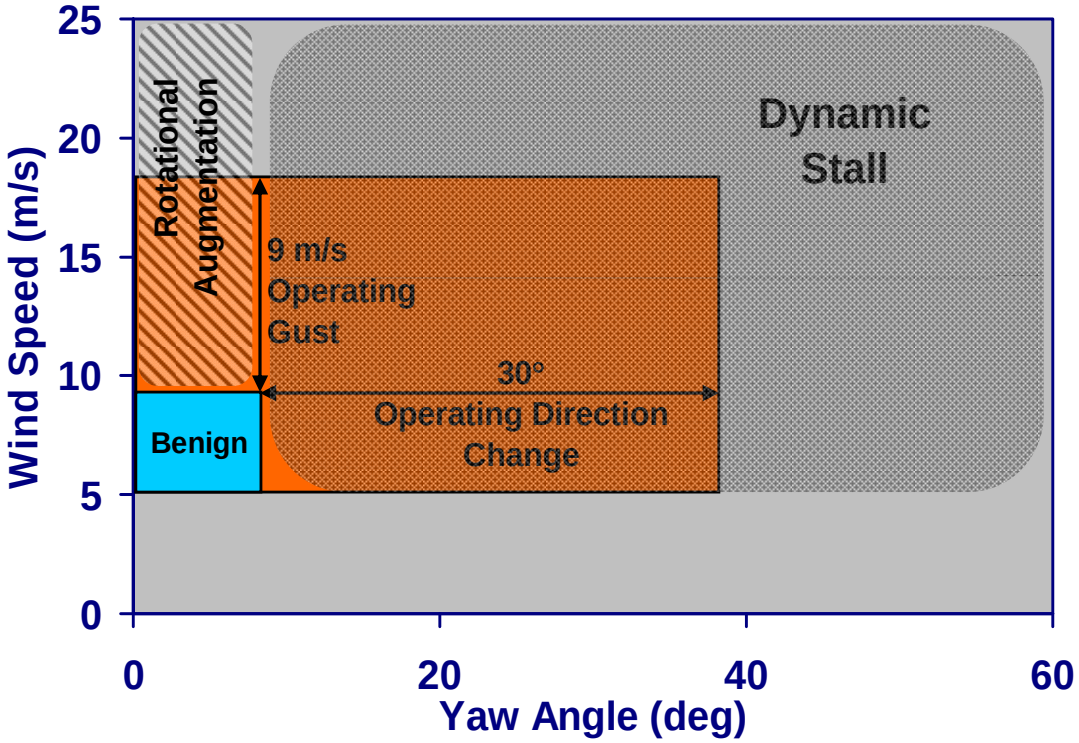


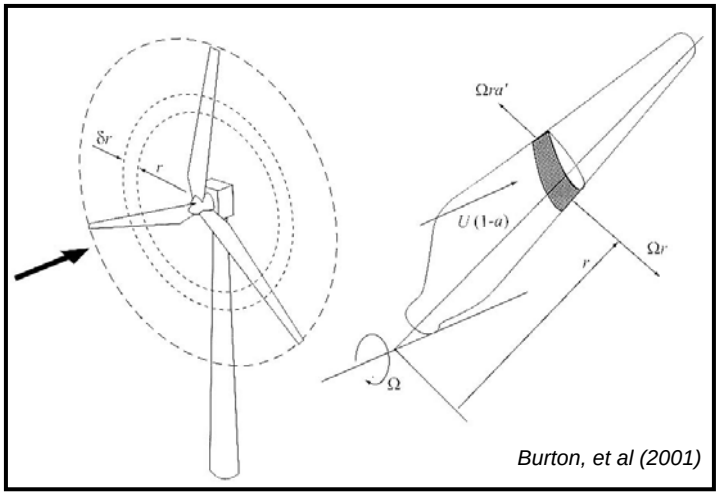
(CFD courtesy of N. Sørensen, Risø National Laboratory)



NREL Blind Comparison

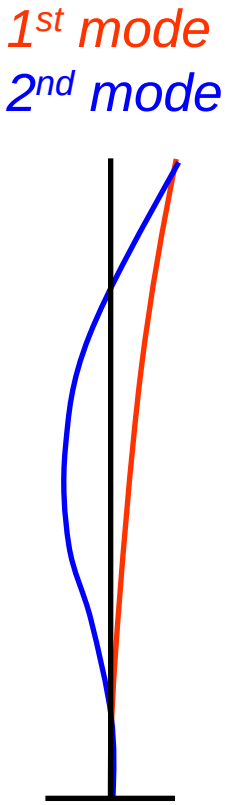
Aerodynamic Model Limitations





- Benign state is small subspace of operating envelope
- Gusts, direction changes drive departure from benign
- Hard to predict outside benign – more basic research needed

Structural Dynamics



Modal Representation

- Modal
  - Beam mode shapes of blades and tower
    - Need beam properties
    - Others rigid (e.g. nacelle)
  - Isotropic materials
  - Straight blades
  - Small to moderate deflections characterized by lowest modes
- Multi-body
  - Unlimited DOFs
  - Anisotropic materials
  - Arbitrary shapes
  - Larger & higher-order deflections
- FEA
  - Flexible elements
  - Stress calculations

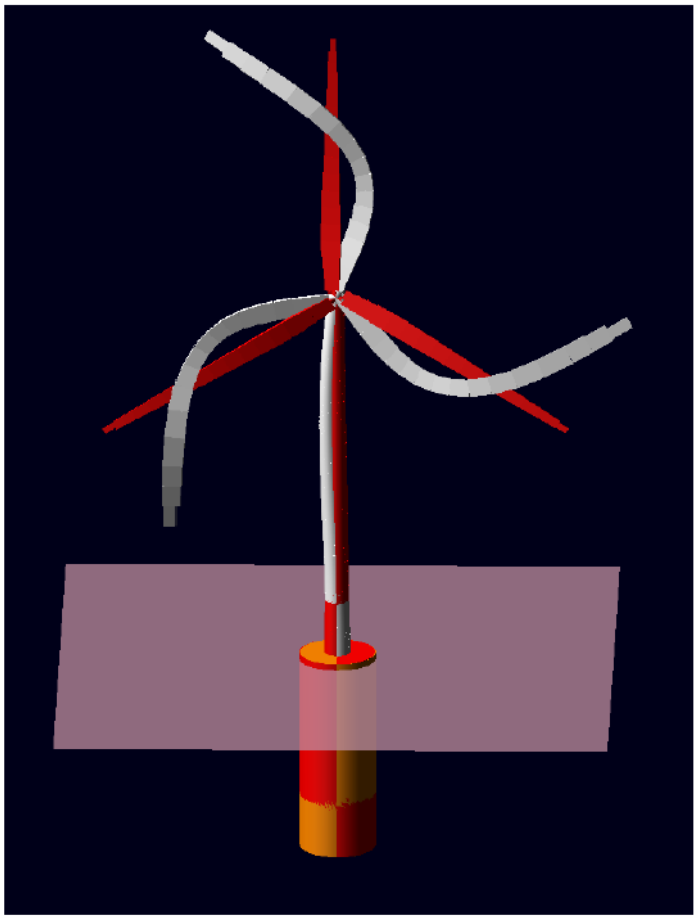


Figure 3.8: ADAMS visualization of 2nd side-to-side tower bending mode

Linearization

- Linear representation of nonlinear system model
- Applications:
  - Full-system modal analysis:
    - Frequencies
    - Damping
    - Mode shapes
  - Controls design:
    - State-space representation of wind turbine “plant”
    - Includes control inputs, wind disturbances, & output
  - Stability analysis
- Linear model is only valid in the local vicinity of an operating point
- When rotor is spinning, the linear system is periodic:
  - Azimuth-averaging averages-out the periodic effects

Nonlinear EoM:

$$M\left(\underline{q},\underline{u},t\right)\underline{\ddot{q}} + \underline{f}\left(\underline{q},\underline{\dot{q}},\underline{u},\underline{u}_d,t\right) = \underline{0}$$

1st order model:

$$\underline{\dot{x}} = A\underline{x} + B\underline{\Delta u} + B_d\,\underline{\Delta u}_d$$

$$\underline{y} = C\underline{x} + D\underline{\Delta u} + D_d\,\underline{\Delta u}_d$$

2nd order model:

$$M\,\underline{\Delta\ddot{q}} + C\,\underline{\Delta\dot{q}} + K\,\underline{\Delta q} = F\,\underline{\Delta u} + F_d\,\underline{\Delta u}_d$$

$$\underline{y} = VelC\,\underline{\Delta\dot{q}} + DspC\,\underline{\Delta q} + D\,\underline{\Delta u} + D_d\,\underline{\Delta u}_d$$

Structural Stability

- Stability analysis
  - Involves linearizing the system, & eigenanalysis:
    - determines full-system modes, frequencies, & damping
  - Identifies sources of instabilities:
    - Modes with negative damping
    - Couplings between system modes can lead to self-excitation
  - Helps identify design changes to eliminate instabilities

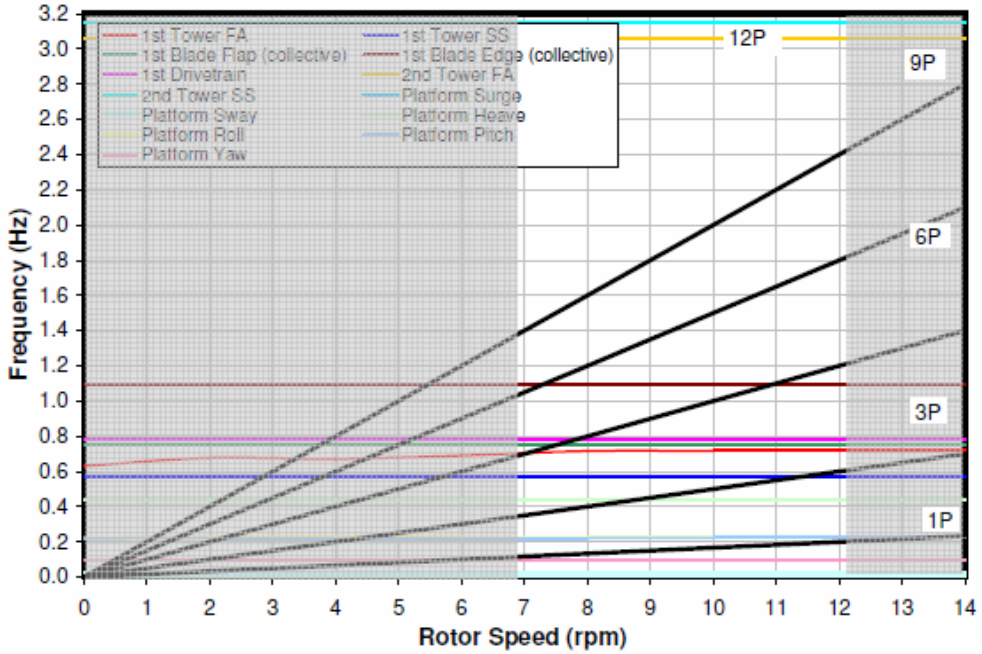
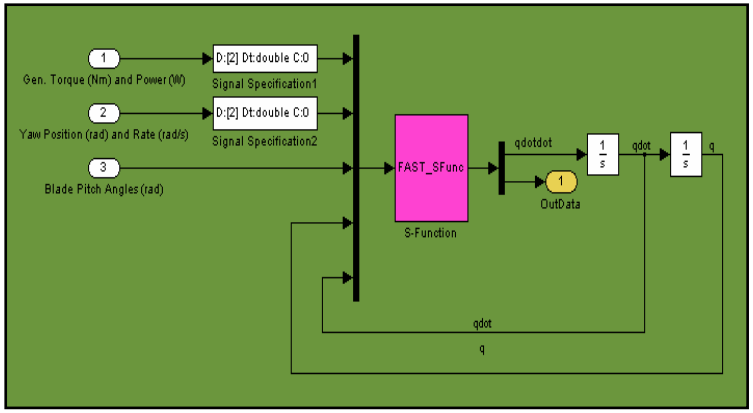


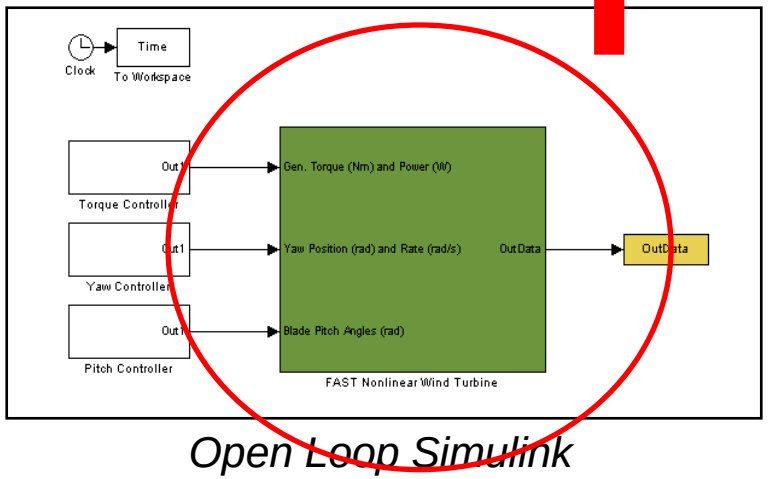
Figure 3.13: Campbell Diagramm of Final Redesigned TLP#1

Interfacing Active Controllers

- Fortran subroutine:
  - Separate routines for each controller:
    - I.e.: Separate routines for pitch, torque, & yaw
  - Requires recompile with each change to controller
- Dynamic link library (DLL):
  - DLL interface routines included with FAST archive
  - DLL compiled separately from **FAST**:
    - Can be Fortran, C++, etc.
  - DLL is a master controller:
    - I.e.: Pitch, torque, & yaw controlled with same DLL
- **MATLAB/Simulink**:
  - **FAST** implemented as S-Function block
  - Controls implemented in block-diagram form



FAST Wind Turbine Block



Open Loop Simulink Model

Offshore: The Next Frontier

Onshore Wind Turbines

- Flexible and dynamically active
- Turbulent winds in analysis
- Nonlinear time domain analysis
- Controllable

Offshore Fixed-Bottom Turbines

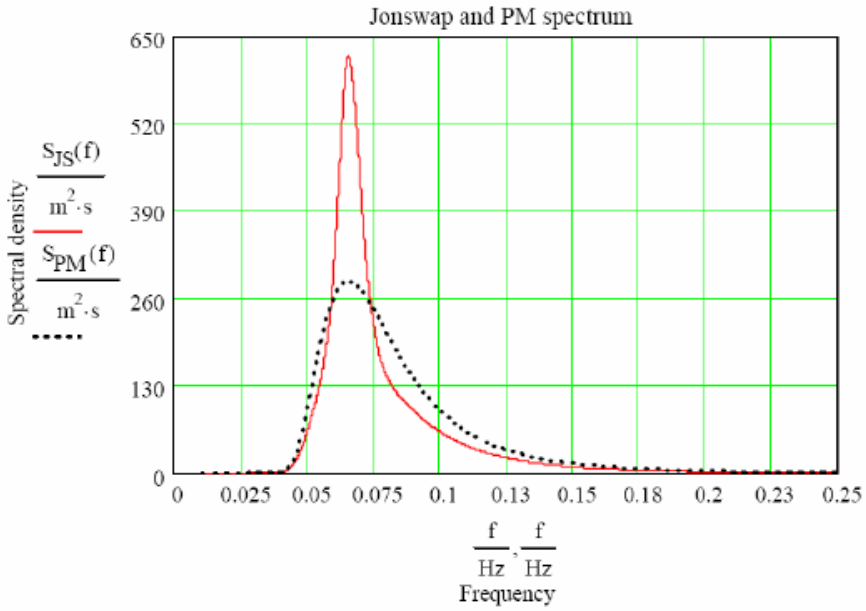
- Rigid support structure
- Little coupling between turbine and support structure motions
- Separation of dynamic response and wave spectra
- Shallow water / breaking waves

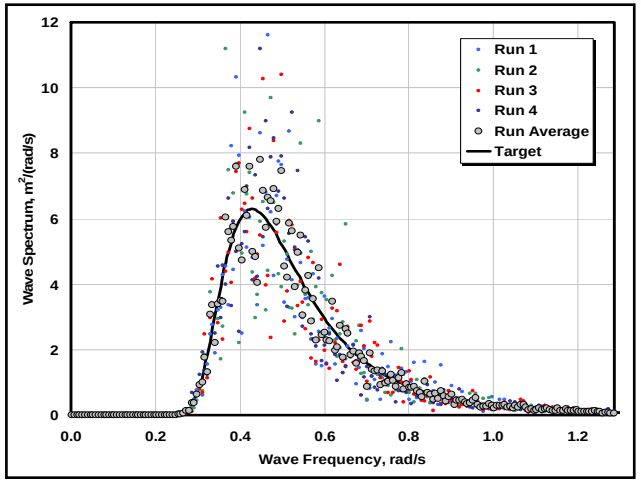
Floating Wind Turbines

- Compliant support structure
- Significant coupling between turbine and platform motions
- Response and wave spectra coalescence
- Deepwater / linear waves

Offshore Environmental Inputs

- Wave kinematics:
  - Linear regular (periodic)
  - Linear irregular (stochastic):
    - Pierson-Moskowitz, JONSWAP
  - Wave direction
  - Nonlinear waves
- Steady sea currents:
  - IEC sub-surface, near-surface, & depth-independent



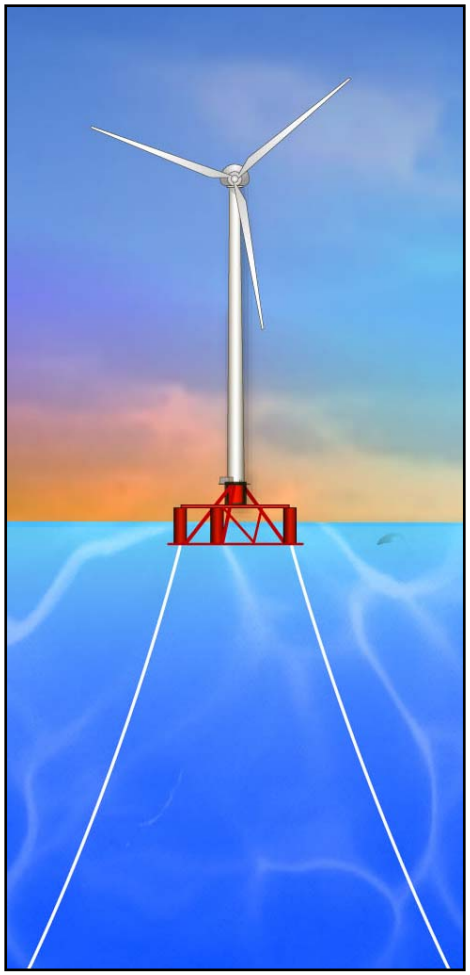


Hydrodynamic loading

Model	Advantages	Disadvantages	Application
Linear Frequency Domain	▪ Many codes available from offshore O&G industry ▪ Results presented in summary form (RAOs or statistics)	▪ Rigid payload ▪ No nonlinear dynamic characteristics ▪ No transient events	
Morison's Equation Time Domain	▪ Easy to implement ▪ Easy to incorporate nonlinear / breaking waves	▪ Diffraction term only valid for slender base ▪ No wave radiation or free surface memory ▪ No added mass-induced coupling between modes	
True Linear Time Domain	▪ Satisfy linearized governing BVPs exactly, without restriction on platform size, shape, or manner of motion ▪ Frequency domain solution used as input	▪ Linear waves only ▪ No 2nd order effects	

Floating Platforms – Mooring System

- Quasi-static mooring system module implemented within **HydroDyn**:
  - Solves catenary equations
  - Fairlead tensions applied as reaction forces on platform
- Accounts for:
  - Array of homogenous taut or catenary lines
  - Apparent weight of line in fluid
  - Elastic stretching
  - Seabed friction
  - Nonlinear geometric restoring
- Neglects:
  - Line bending stiffness
  - Mooring system inertia
  - Mooring system damping



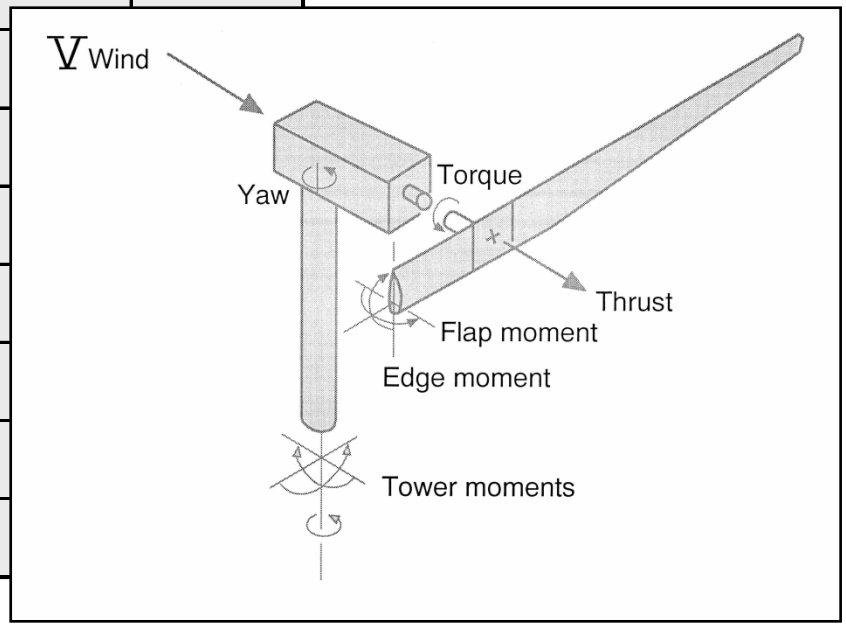
Dutch Tri-Floater

Design Loads Analysis

- Verify structural integrity by running a series of design load cases (DLCs)
- IEC 61400-1 for onshore or IEC 61400-3 for offshore

Design Situation	DLC	Wind Condition	Wave Condition	Directionality	Other Conditions	Type of Analysis
Power production	1.x					
Power production plus occurrence of fault	2.x					
Start up	3.x					
Normal shut down	4.x					
Emergency shut down	5.x					
Parked	6.x					
Parked with fault	7.x					
Transport, assembly, and maintenance	8.x					

Load Case Matrix



Critical Locations

Extreme Loading

- "Rare" events
  - e.g. 1-year gust
- Correlated to extreme environmental simulations
  - Gusts
  - Wind direction change
  - Breaking waves

OR

- Wind turbine faults
  - Pitch system failure
  - Grid fault

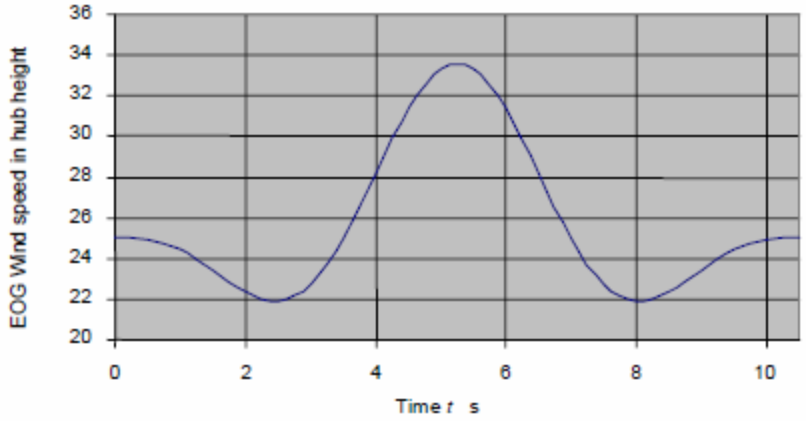


Figure 2 – Example of extreme operating gust

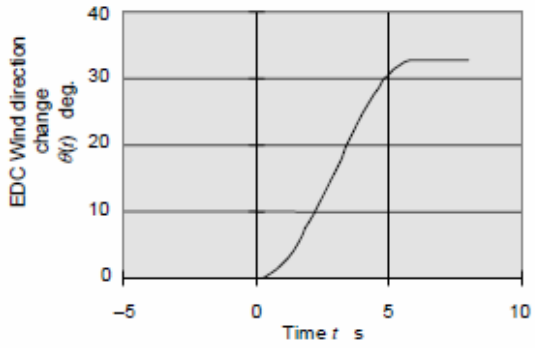
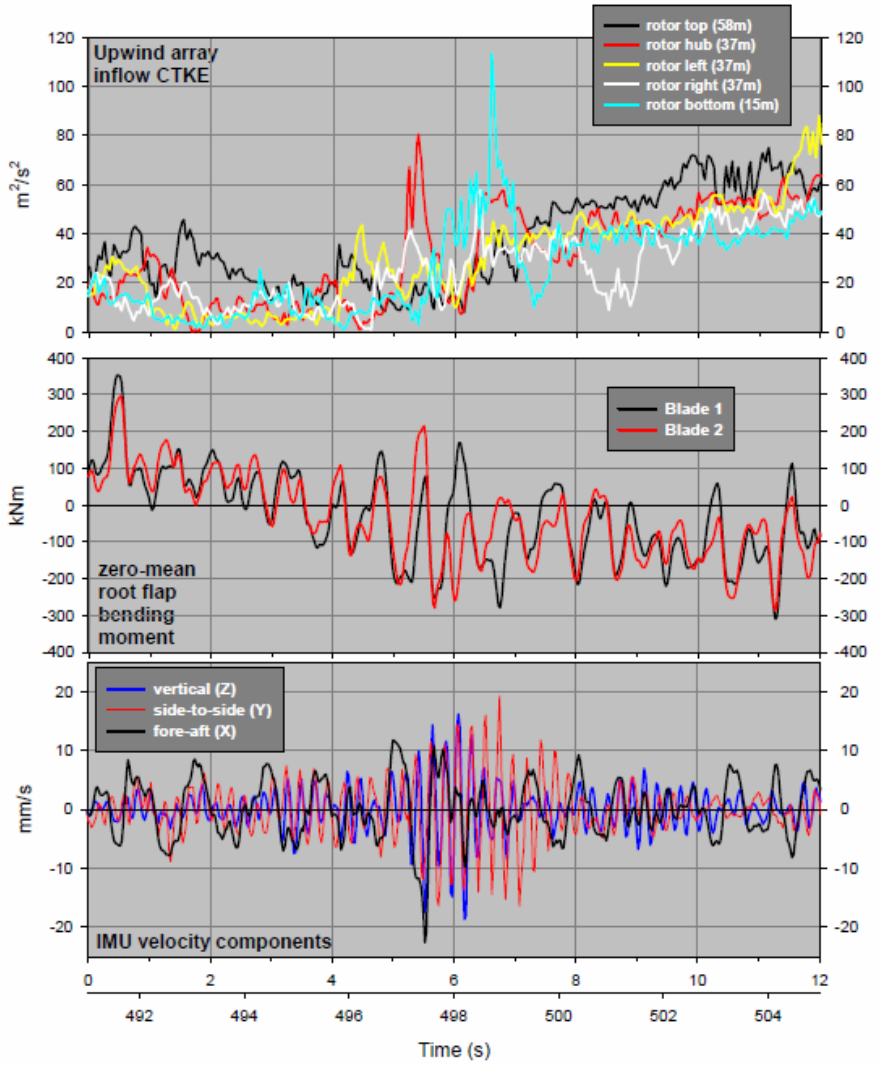


Figure 4 – Example of extreme direction change

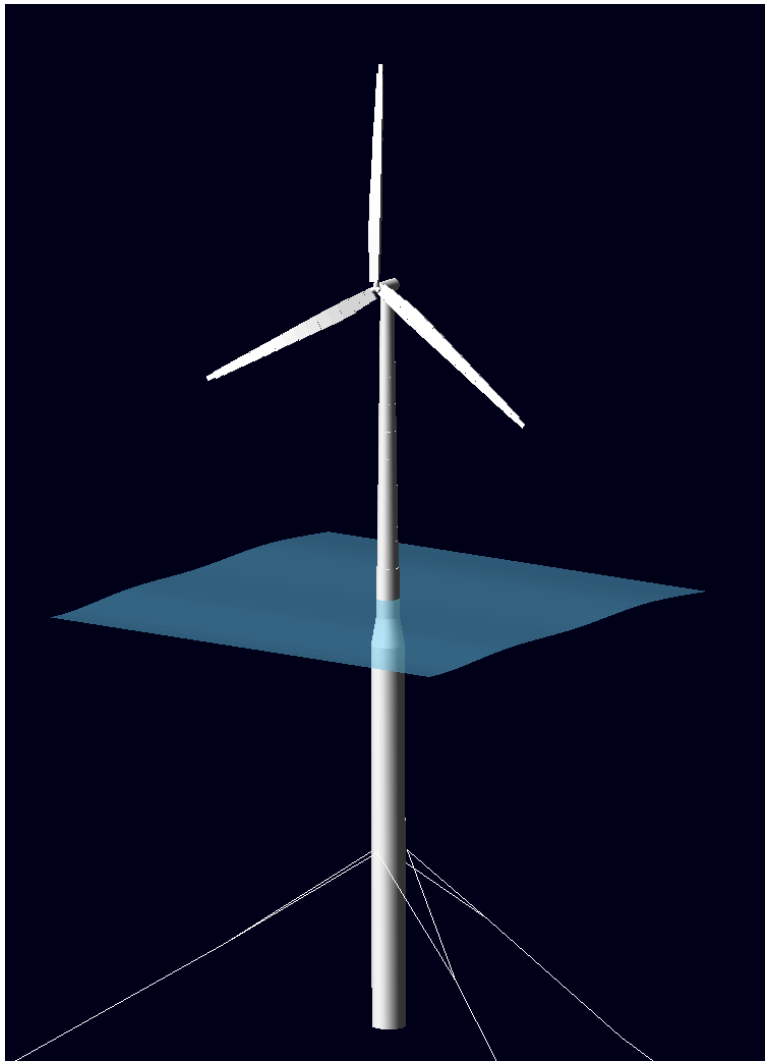
Fatigue Loading

- "Everyday" loading
- Atmospheric turbulence
- Wind Shear
- Gravity Loads
  - More important for 5 MW and larger
- Thousands of simulations
  - 10-minute spectral wind gap

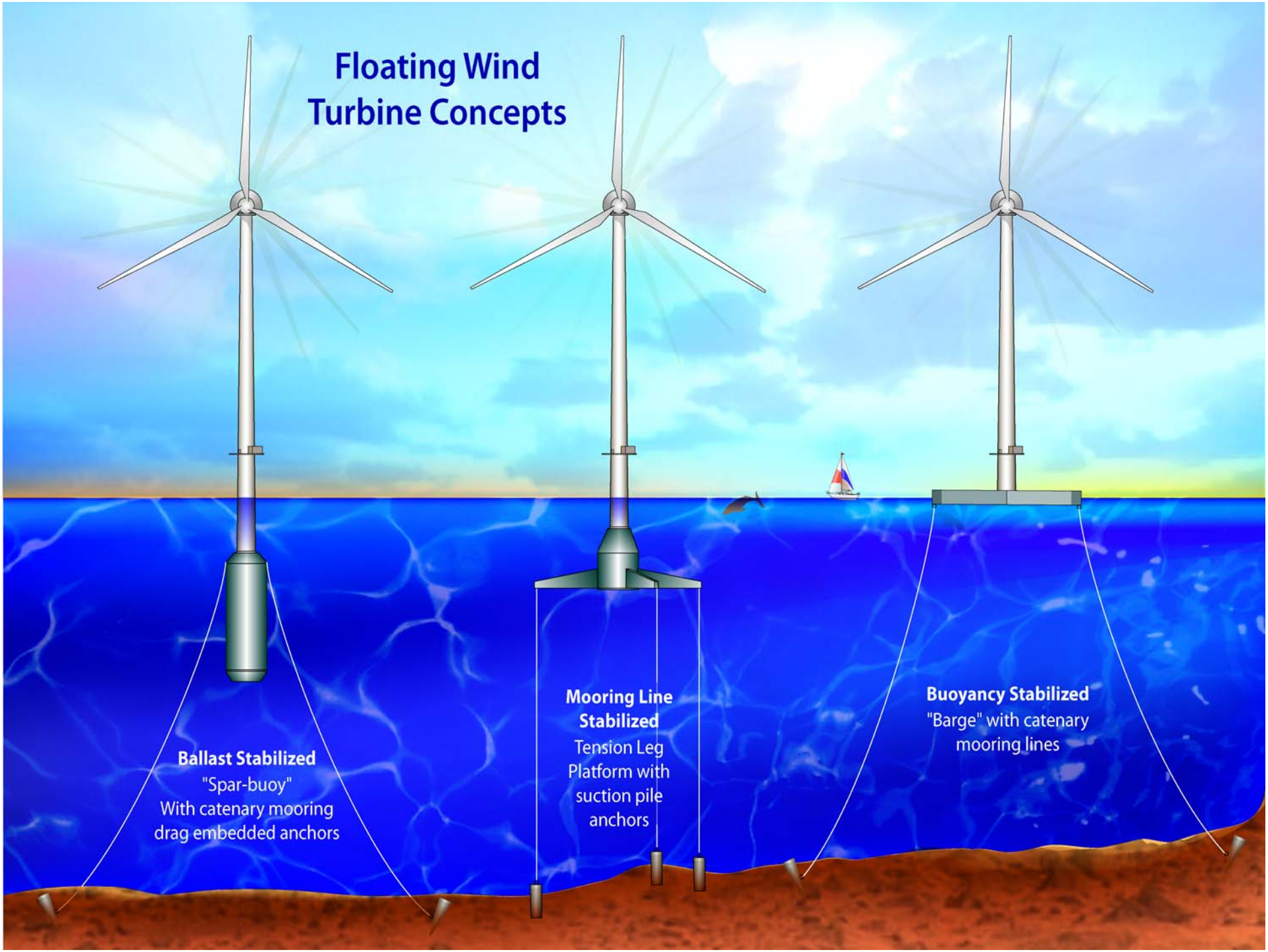


Summary

- Current state-of-the-art design tools combine tools
  - Originate in separate disciplines
  - Often decoupled or loosely coupled
  - Assume small perturbations from mean state
  - Good for turbines that are
    - Operating below rated wind speed
    - Structurally stiff
    - Very little yaw
    - Low turbulence
- Next generation turbines
  - Larger and more flexible
  - More accurate models
  - Closer coupling
  - Advanced control schemes



Questions?


Floating Wind
Turbine Concepts
Ballast Stabilized
"Spar-buoy"
With catenary mooring
drag embedded anchors
Mooring Line
Stabilized
Tension Leg
Platform with
suction pile
anchors
Buoyancy Stabilized
"Barge" with catenary
mooring lines