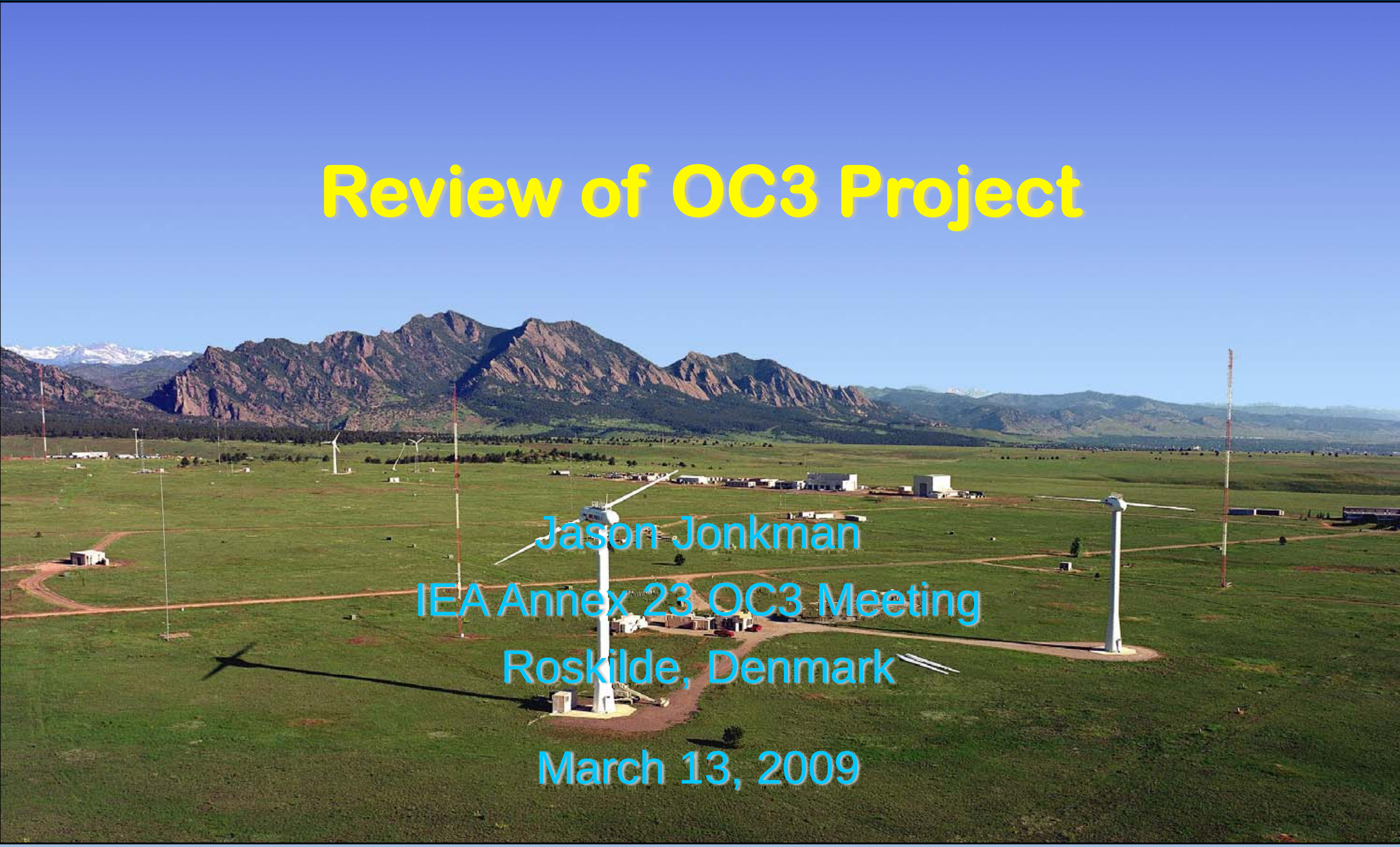

Review of OC3 Project

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IEA Annex 23 OC3 Meeting

Roskilde, Denmark

March 13, 2009

Overview of OC3
Introduction

- The "***O**ffshore **C**ode **C**omparison **C**ollaboration*" (OC3) was established as an international forum for offshore wind code verification:
  - Operates under IEA Wind Annex 23 Subtask 2
  - Coordinated by NREL

- Main participants (others have come & gone):

- Main aero-hydro-servo-elastic codes:
  - FAST, Bladed, FLEX5, ADAMS, HAWC2, BHawC, ADCoS

Overview of OC3

Project Activities & Objectives

Activities

- Discussing modeling strategies
- Developing a suite of benchmark models & simulations
- Running the simulations & processing the results
- Comparing the results

Objectives

- Assessing the accuracy & reliability of results obtained by simulations to establish confidence in the predictive capabilities of the codes
- Training new analysts how to run & apply codes correctly
- Investigating the capabilities / limitations of implemented theories
- Refining applied analysis methodologies
- Identifying further R&D needs

Overview of OC3
Project Approach

- All inputs to the codes are controlled:
  - NREL 5-MW wind turbine, including control system, predefined
  - Variety of support structures predefined
  - Wind & wave datasets predefined
- A stepwise verification procedure is applied:
  - Load cases selected to test different features of the models:
    - Structural dynamics
    - Aerodynamics
    - Hydrodynamics
    - Aero-servo-elastics
    - Hydro-elastics
    - Aero-hydro-servo-elastics
  - Results compared side-by-side

Overview of OC3
Project Phases & Status

Phase I – Monopile + Rigid Foundation

- Winter 2005 – Summer 2006
- Paper presented at Science of Making Torque from Wind, 2007

Phase II – Monopile + Flexible Foundation

- Summer 2006 – Fall 2007
- Paper presented at European Offshore Wind, 2007

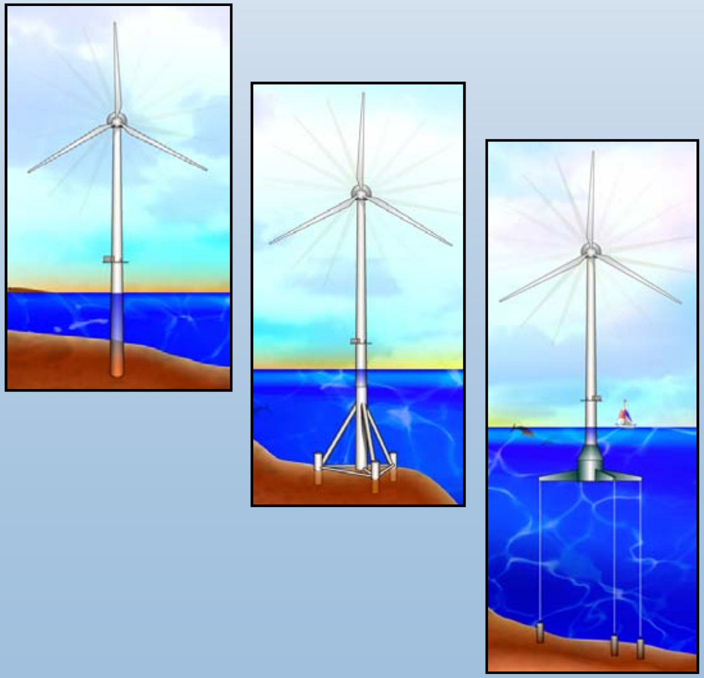
Phase III – Tripod

- Winter 2007 – Fall 2008
- Paper presented at AIAA, 2009

Phase IV – Floating Platform

- Platform defined
- Load cases to be finalized soon
- Summer 2008 – Fall 2009 (planned)

Final Report – Winter 2009 (planned)



Overview of OC3
Load Cases

1.X – Full-System Eigenanalysis
- Full-system flexibility
- Elastic response only
- Compared natural frequencies & damping ratios

2.X – Rigid
- Rigid turbine
- Aerodynamics without hydro:
  - Steady & turbulent winds
- Hydrodynamics without aero:
  - Regular & irregular waves

3.X – Onshore Wind Turbine
- Flexible tower, drivetrain, & rotor
- Rigid substructure
- Aero-servo-elastics without hydro:
  - Steady & turbulent winds

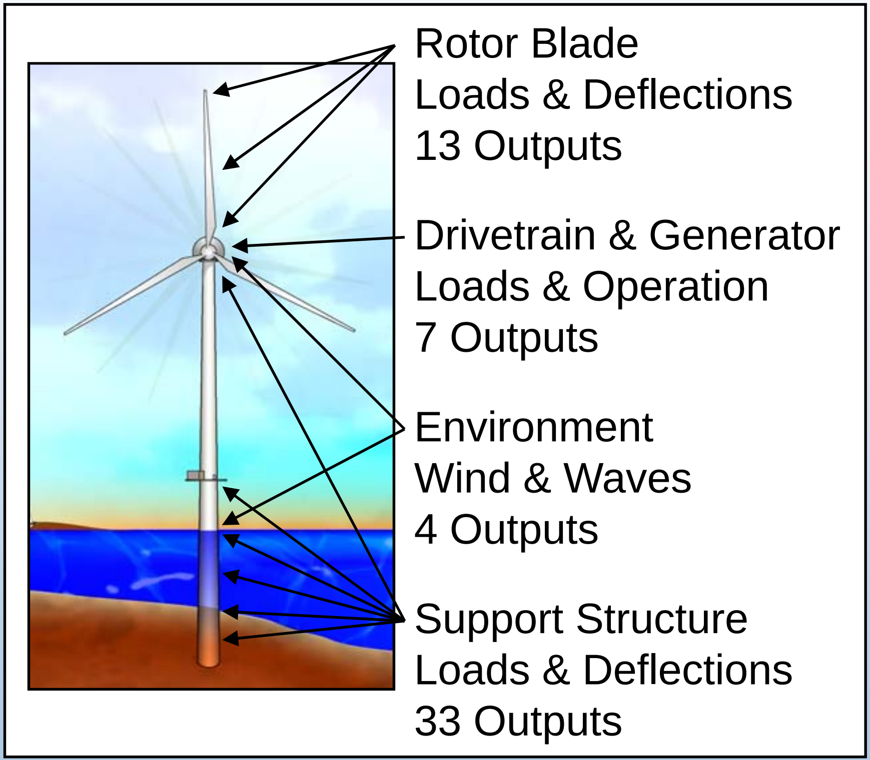
4.X – Inverted Pendulum
- Flexible support structure
- Rigid tower-top
- Hydro-elastics without aero:
  - Regular & irregular waves

5.X – Full-System Dynamics
- Full-system flexibility
- Full aero-hydro-servo-elastics:
  - Steady winds with regular waves
  - Turbulent winds with irregular waves

Overview of OC3

Output Parameters

- Time series compared with steady winds & regular waves
- Statistics, DELs, & PSDs compared with turbulent winds & irregular waves



Outputs for Monopile (57 Total)

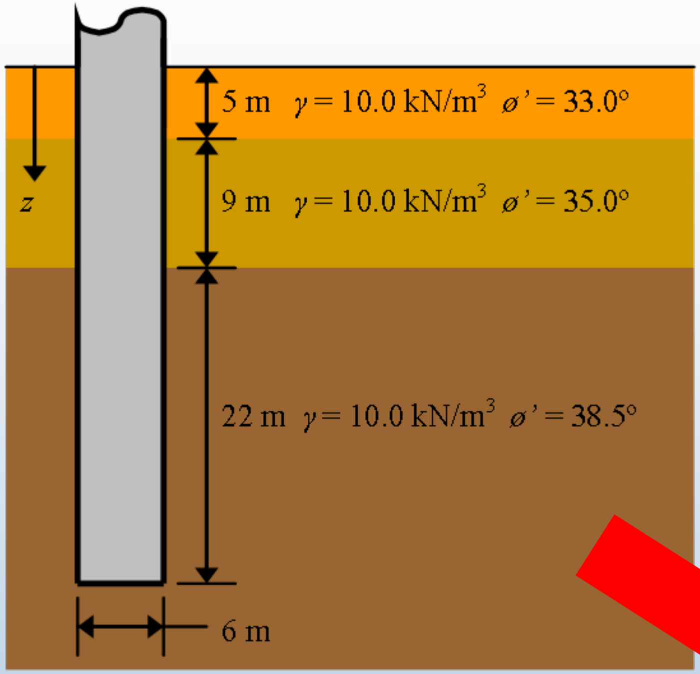
Review of Phase I Results

Overview

- Modal-based codes predict different 2nd (& higher) eigenmodes than the higher fidelity multibody- & FEM-based codes
- Codes using full-field wind in polar coordinates predict smoother aerodynamic loads than codes using rectangular coordinates:
  - Because of the method used to generate the wind datasets
- Differences in implementation of aerodynamic models attributed to variations among the codes in mean turbine loads
- The pitch controller compensates somewhat for variations that might have been caused by codes that lack blade-twist DOFs
- Differing model discretizations lead to differing code predictions:
  - Most apparent in substructure loads that depend highly on the discretization of hydrodynamic loads near the free surface
- User error happens

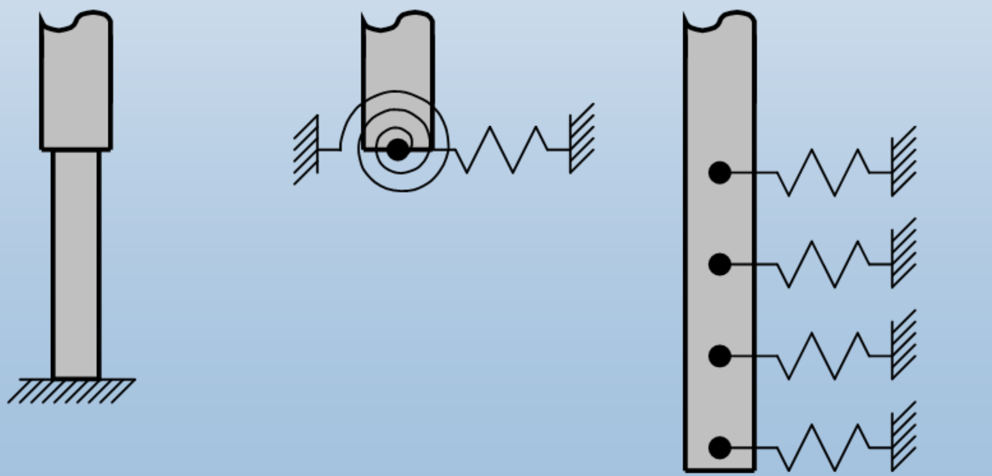
Review of Phase II Results

Foundation Modeling



Soil Profile

- Foundation designed by applying realistic soil properties & typical design procedures
- Design made to have a noticeable effect on the system's dynamic response
  - Needed for facilitation of model testing
- Nonlinear + depth-dependent *p-y* model



Simplified Models of a Monopile with Flexible Foundation

- The *p-y* model not necessarily valid for transient analysis
- Simplified models derived to give equivalent response under particular conditions

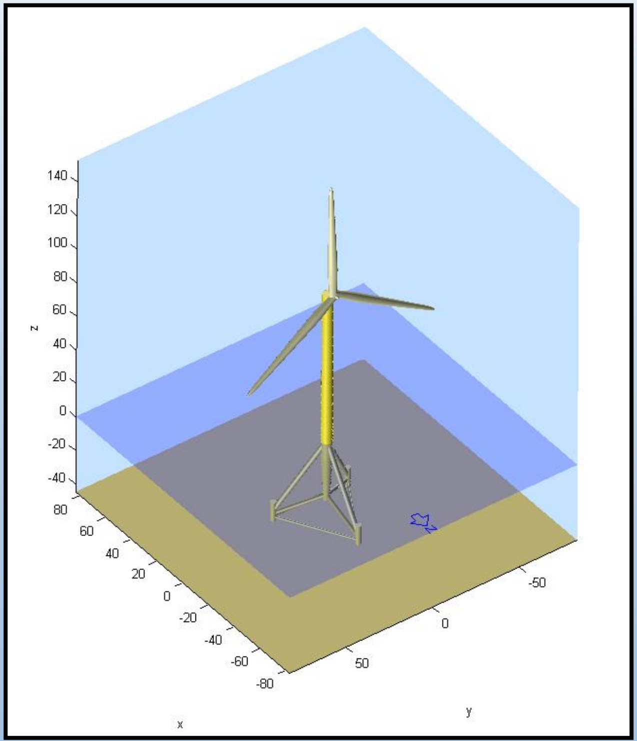
Review of Phases II Results

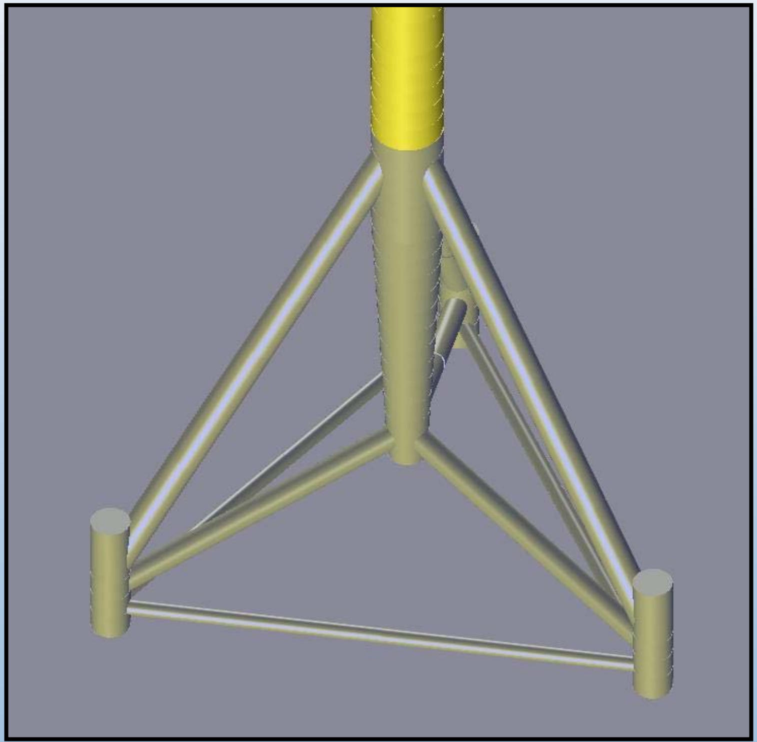
Overview

- All of the results of Phase I also apply to results of Phase II
- The simplified foundation models can be implemented so as to ensure that the overall response of the system above the mudline is the same under a given set of loading conditions:
  - At least for the lowest system eignemodes
- Model discretization problems result in higher excitation in the 2nd eigenmodes of the support structure:
  - This is only so when the turbine is not operating, because of the aerodynamic damping while operating
- Differences in aerodynamic models have more effect on the mean values of loads than on power spectra

Review of Phases III Results
NREL 5-MW Turbine Atop Tripod

- Significant jump in complexity from monopile
- Statically indeterminate
- Loads influenced by relative deflection of members





Review of Phases III Results

Overview

- All of the results of Phase I also apply to results of Phase III:
  - Phase II has less bearing because Phase III doesn't consider the foundation
- Buoyancy in nonflooded multi-member structures should be considered through direct integration of the hydrostatic pressure, dependent on the time-varying wave elevation:
  - Important for nonflooded members that are inclined, tapered, &/or embedded into the seabed (i.e., nonflooded piles)
- Rigid multi-member structure should be considered by increasing the Modulus of Elasticity consistently across all members:
  - Permits one to calculate how the loads are transmitted through what is a statically indeterminate structure (because it is rigid)

Review of Phases III Results
Overview (cont)

- Hydrodynamic and buoyancy loads along tapered members must be finely discretized:
  - Inertia & buoyancy loads depend on D^2, so having too long a length between nodes can cause a large error in the total load
- The member overlap at joints must be accounted for as it has a large effect on the overall loading:
  - For the large diameter members of a tripod, significant surface areas & volumes are duplicated at joints, which distorts the overall level of loading if the intersection is not accounted for
- Local shear deflection of the members in a multi-member support structure has a large effect on the load distribution:
  - Beam members attach rigidly to other members whereby their relative displacement influences the load distribution

Review of Phases III Results

Overview (cont)

- Start-up transients dissipate slowly due to the small amount of tripod damping & the method by which the hydrodynamic loads are initialized:
  - This is only so when the turbine is not operating, because of the aerodynamic damping while operating
  - Each model initializes its solution differently

Conclusions

Summary

- Offshore wind turbines are designed using coupled aero-hydro-servo-elastic codes
- Task of OC3 project to verify these codes
- Several load case simulations were run for the NREL 5-MW turbine atop a monopile with/without flexible foundation & a tripod
- Code-to-code comparisons have agreed quite well
- Differences were traced back to differences in model fidelity, aero. implementation, discretization, & numerical problems
- Current work is aimed at floating turbines in deep water
- Verification is important for advancement of offshore wind