Wake Meandering Effects for Floating Wind Turbines

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Outline

- Introduction
- Motivation
- Background/Theory
- Modeling setup, results, conclusions
- Current work

My Background

- Exchange year at Lund University, Sweden
- Internships at NREL and GE Renewable Energy
- Bachelors in Mechanical Engineering from Virginia Tech in May 2018
- Fulbright Scholarship to NTNU!
- Beginning MS/PhD at UC Berkeley this fall

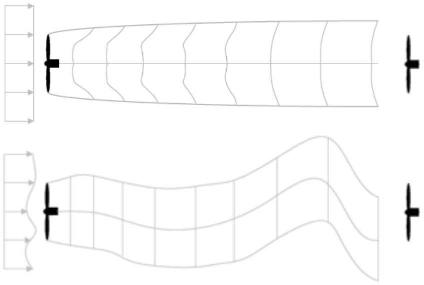
Fulbright Program

- The Fulbright Program is the U.S. government's flagship international educational exchange program. It was created in the aftermath of World War II, to increase mutual understanding between the peoples of the United States and other countries through the exchange of persons, knowledge and skills.
- Each year approximately 40 Norwegians receive grants to study, teach, or conduct research in the US, and some 30 Americans receive grants to do the same in Norway
- Grants are awarded in science and technology, the arts and humanities, education, journalism, media, government, law, and virtually every academic discipline
- Students at the Masters and PhD level and scholars (post-PhD or equivalent) are eligible to apply
- Text from https://fulbright.no/

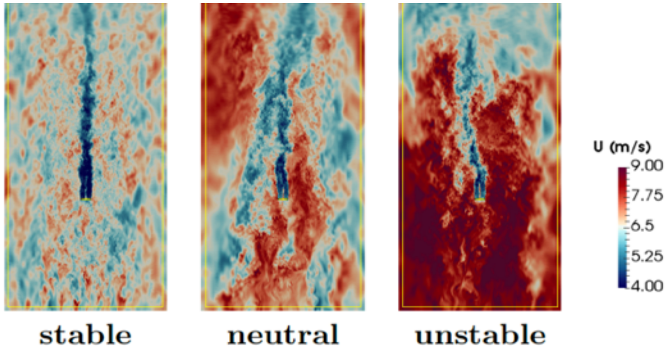
Motivation

- Wake effects have been observed for many years
- Recent developments in modeling wake meandering
- Little published work on floating wind turbine (FWT) wake interaction
  - **How will the slow meandering movement affect structures with long natural periods?**

Horns Rev II Wind Farm



Uniforms vs. meandering wake deficit. Jonkman et al. (2017)

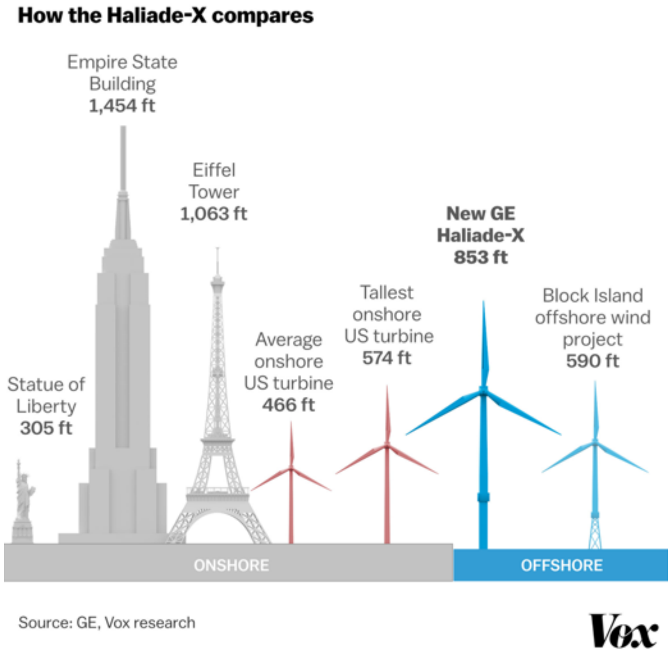


Wake meandering behavior in different atmospheric stability conditions. Churchfield et al. (2016)

Backround and Theory

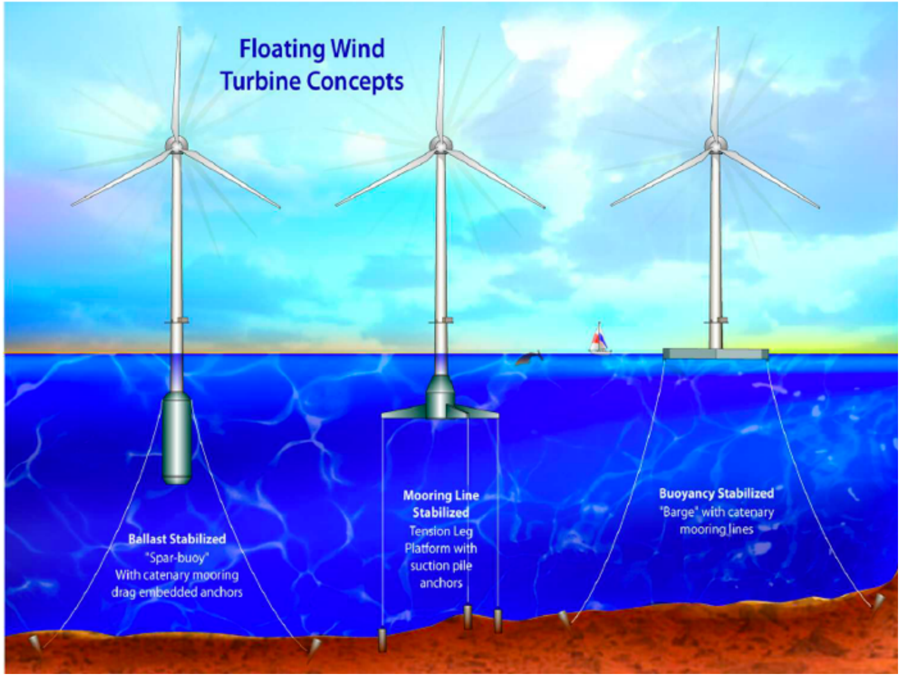
State of Wind Energy

- Wind Turbines are getting bigger
- Especially offshore

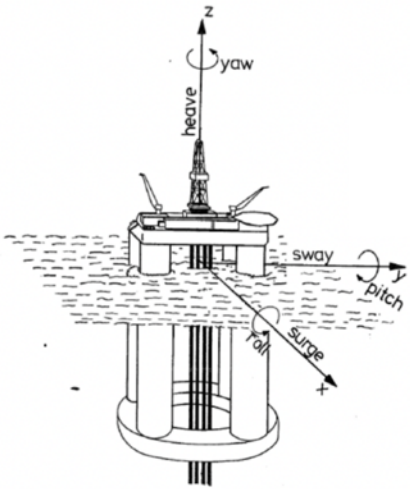


https://www.vox.com/energy-and-environment/2018/3/8/17084158/wind-turbine-power-energy-blades

Offshore Wind Turbines



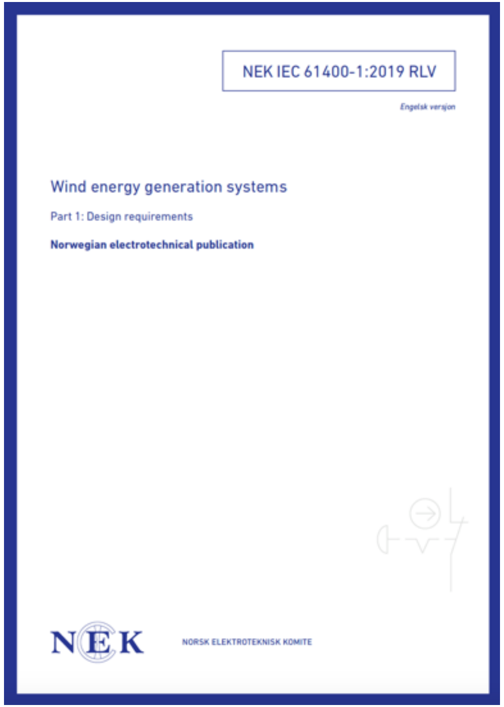
Jonkman and Buhl (2007)



Coordinate system and terminology for a floating platform. From NTNU TMR4215 Sea Loads: Lecture Notes

Wind Turbine Design

- Functionality and safety
- IEC standards govern wind turbine structural design
  - Load cases
  - Design to limit states
  - Time domain simulations are required


NEK IEC 61400-1:2019 RLV

Engelsk versjon

Wind energy generation systems

Part 1: Design requirements

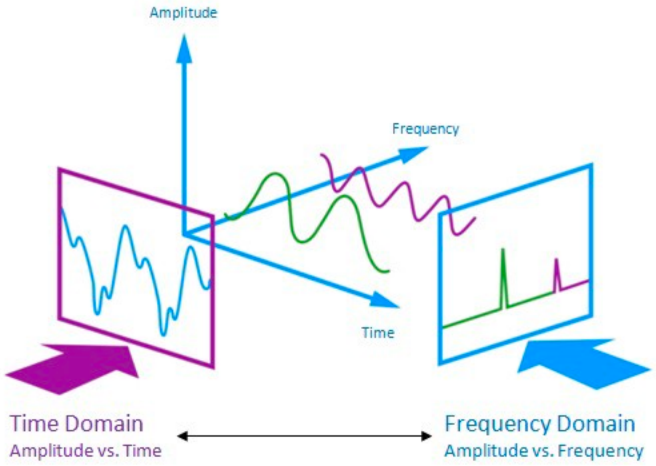
Norwegian electrotechnical publication

NEK

NORSK ELEKTROTEKNISK KOMITE

Dynamic Analysis of (Offshore) Wind Turbines

- Environmental conditions
  - **Turbulent wind**
    - Kaimal
    - Mann
    - CFD: Large-eddy simulations
  - Waves
- Load analysis
  - Aerodynamics (BEM)
  - Hydrodynamics (potential flow, Morison)
- Response analysis
  - Structural dynamics (aeroelasticity)
  - Rigid-body motions and coupled mooring analysis for floaters
- Control theory
  - Maximize power production
  - Constant power/reduce loads
  - Applied in time domain



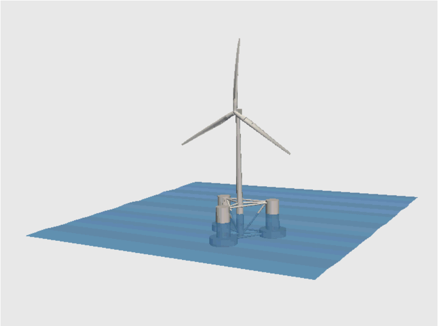
https://towardsdatascience.com/extract-features-of-music-75a3f9bc265d

Text from NTNU TMR4195 Design of Offshore Structures: Lecture Notes

Wind Turbine Modeling

Code	FAST	Simo/Riflex/ Aerodyn	HAWC2	Bladed	3Dfloat
Developer	NREL	NTNU+ Marintek (NREL)	Riso	Garrad Hassan	IFE, Norway
Aero-dynamics	BEM (or GDW) DS	BEM (or GDW) DS	BEM DS	BEM DS	BEM DS
Hydro-dynamics	A, UD ME, PT1	A, UD PT12	AW, UD ME	AW ME	A ME
Structural dynamics	Modal + MBS RSS	FEM + MBS RSS	FEM + MBS FSS	Modal + MBS FSS	FEM FSS
Control interface	DLL, UD, MS	DLL	DLL, UD, MS	DLL	DLL
Mooring system	NS	FEM	NS	NS	NS, FEM

* **BEM** (Blade Element Momentum theory); **GDW** (Generalized Dynamic Wake); **DS** (Dynamic Stall)
* **AW** (Airy theory with Wheeler stretching); **A** (Airy theory); **UD** (User-Defined); **ME** (Morison's Equation); **PT1**(Potential Theory using WAMIT, 1st-order wave force only); **PT12**(Potential Theory using WAMIT, 1st- and 2nd-order wave forces);
* **Modal** (Modal superposition); **MBS** (Multi-Body System); **FEM** (Finite Element Method); **RSS** (Rigid Supporting Structure); **FSS** (Flexible Supporting Structure when using Morison's equation)
* **DLL** (Dynamic Link Library); **UD** (User-Defined); **MS** (interface to Matlab/Simulink)
* **NS** (Nonlinear Spring); **FEM** (Finite Element Method)



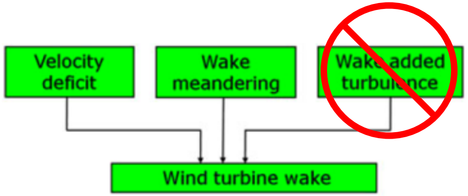
https://nwtc.nrel.gov/FAST8

From NTNU TMR4195 Design of Offshore Structures: Lecture Notes

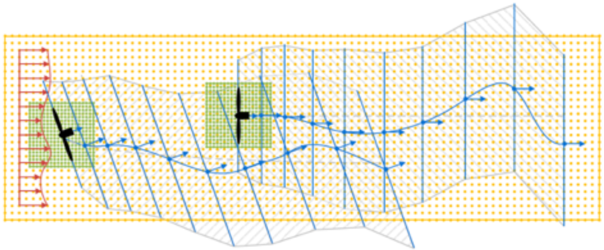
Dynamic Wake Meandering

- Larsen et. al (2008) DWM added in the annex of IEC 61400-1 Ed. 4

- Development of FAST.Farm
  - OpenFAST + wake dynamics + ambient wind and array effects
  - Built on principles of DWM, but with some differences
    - Wake deficit updated based on wind turbine motions!



Components of the Larsen et. al (2008) DWM model



Example FAST.Farm domain. Image from FAST.Farm user manual

Approach

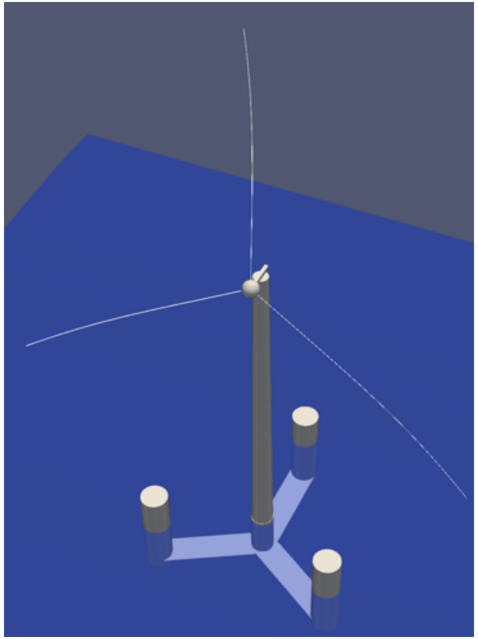
- **Research question: How will slow meandering movement affect structures with long natural periods?**

- Two 10 MW semi-submersible FWTs modeled in FAST.Farm

- 10 m/s wind, moderate wave conditions with synthetically generated turbulent inflow from TurbSim and the Mann Model

- Compare platform motions and structural loading in the tower and mooring lines for the upstream and downstream FWTs

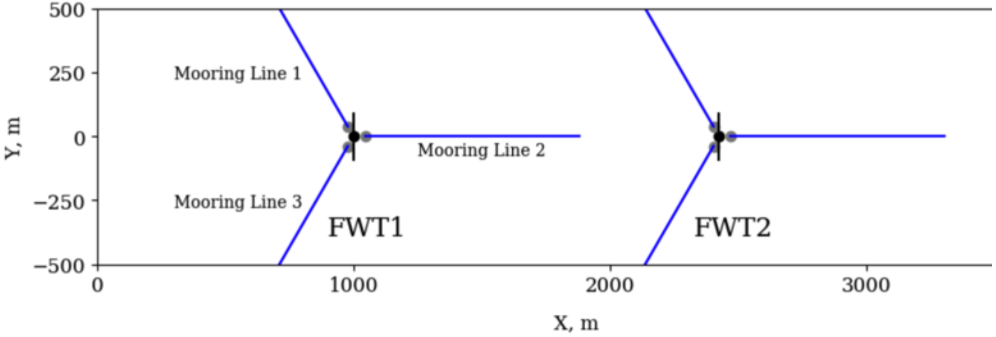
FAST and FAST.Farm Model



Computational model of the CSC 10 MW visualized in OpenFAST

CSC 10 MW natural periods in OpenFAST

Degree of Freedom	OpenFAST
Surge (s)	85.1
Pitch (s)	24.8
Yaw (s)	58.5
Coupled pitch and tower bending (s)	2.5, 2.9



FAST.Farm computational domain (truncated in X)

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Ambient Wind Generation

- Method 1 (Kaimal – Coh u):
  - Turbsim, Kaimal turbulence model, spatial coherence only in u

Exponential spatial coherence function in the Kaimal turbulence model:

$$Coh_{i,j_K} = \exp\left(-a_K \sqrt{\left(\frac{fr}{\bar{u}_{hub}}\right)^2 + (rb_K)^2}\right)$$

- Method 2 (Kaimal – Coh u, v, w):
  - Turbsim, Kaimal turbulence model, spatial coherence specified in u, v, and w

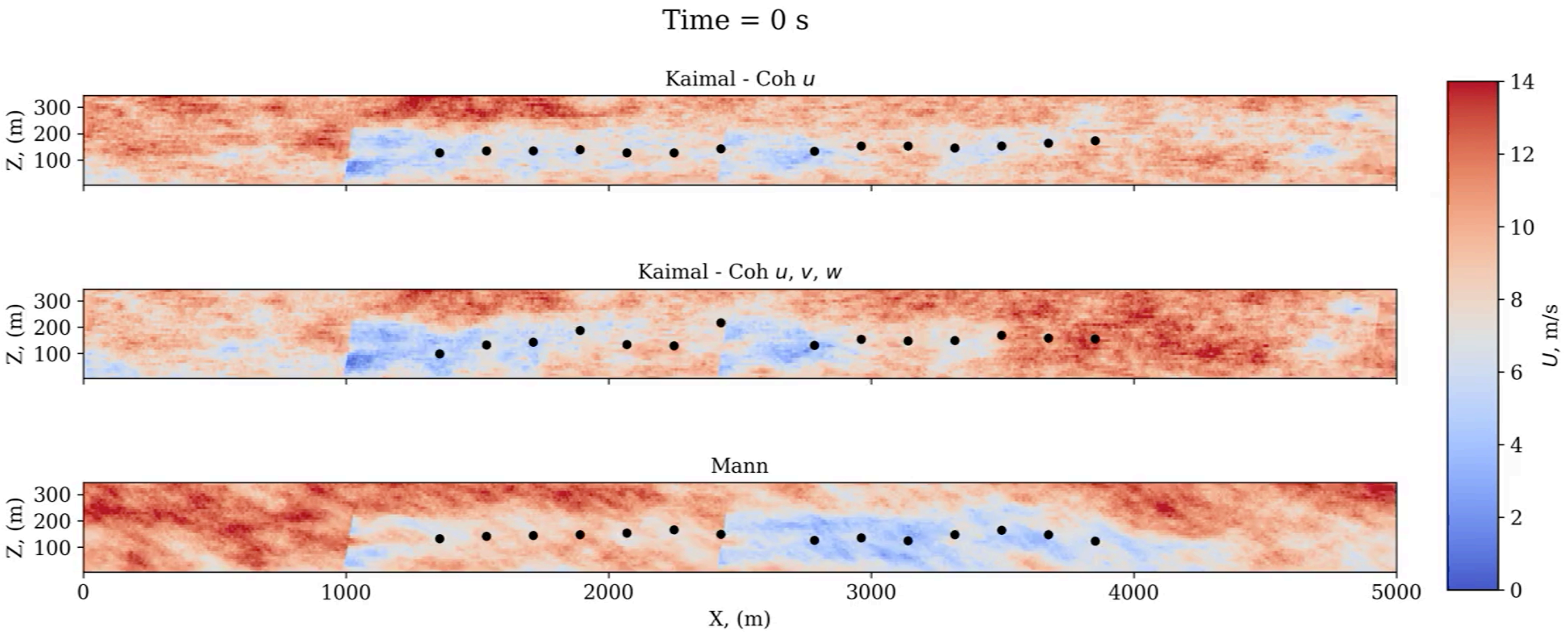
Spatial coherence parameters specified in TurbSim

Model name	a_u	b_u	a_v	b_v	a_w	b_w
Kaimal - Coh u	12.0	3.5273E-4	∞	0.0	∞	0.0
Kaimal - Coh u, v, w,	10.0	0.0	7.5	0.0	7.5	0.0

- Method 3 (Mann):
  - HAWC2 precursor, Mann turbulence model, spatial coherence in all three dimensions inherit to the model

Spatial coherence in the Mann turbulence model:

$$Coh_{i,j,Mann}(k, \delta_y, \delta_z) = \frac{\left|\int\int \phi_{i,j} dk_y dk_z e^{-ik_y\delta_y} e^{-ik_z\delta_z} dk_y dk_z\right|^2}{\int\int \phi_{i,i} dk_y dk_z \int\int \phi_{j,j} dk_y dk_z}$$


Time = 0 s
Kaimal - Coh u
Kaimal - Coh u, v, w
Mann
Z, (m)
300
200
100
0
1000
2000
3000
4000
5000
X, (m)
U, m/s
14
12
10
8
6
4
2
0

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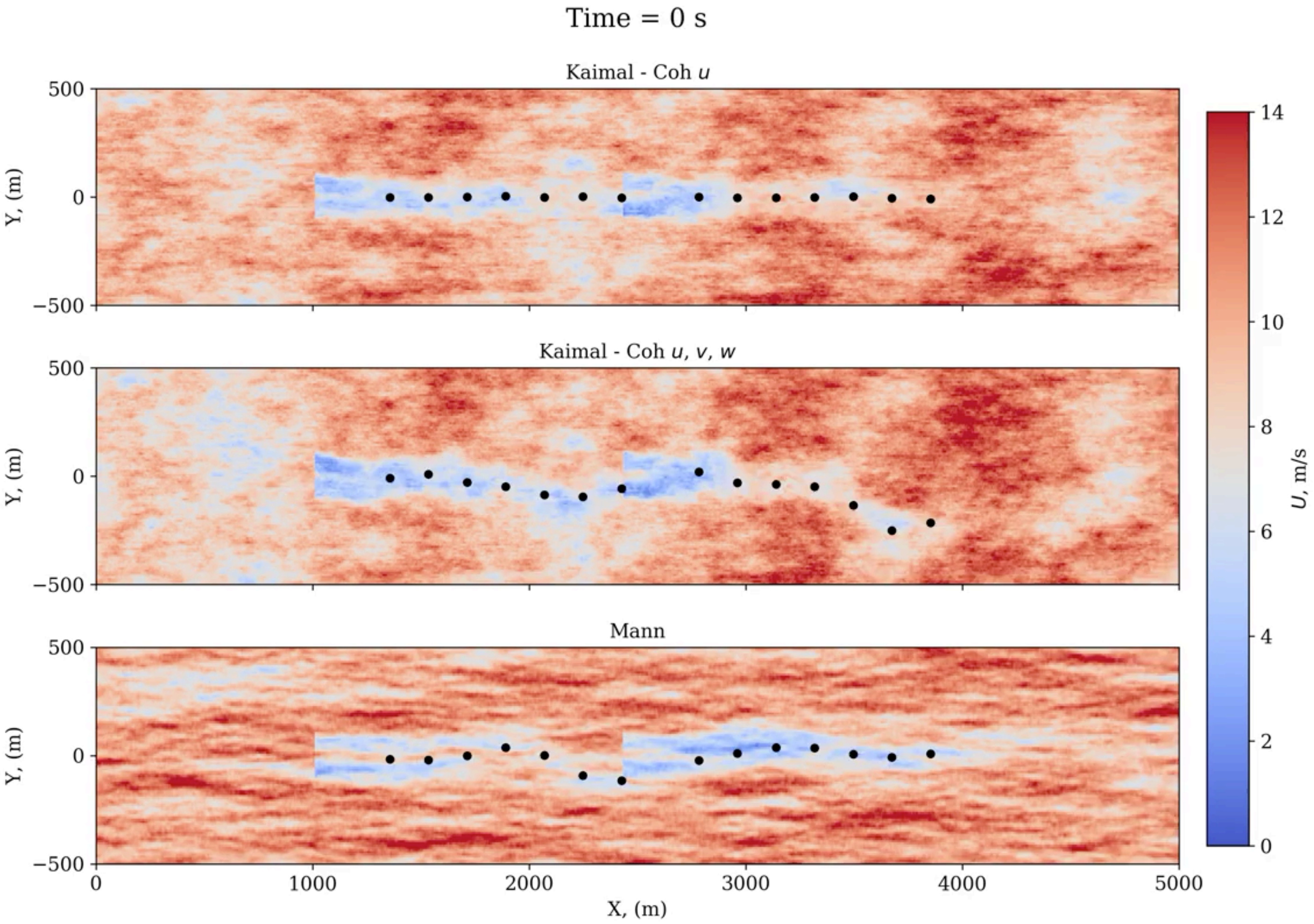
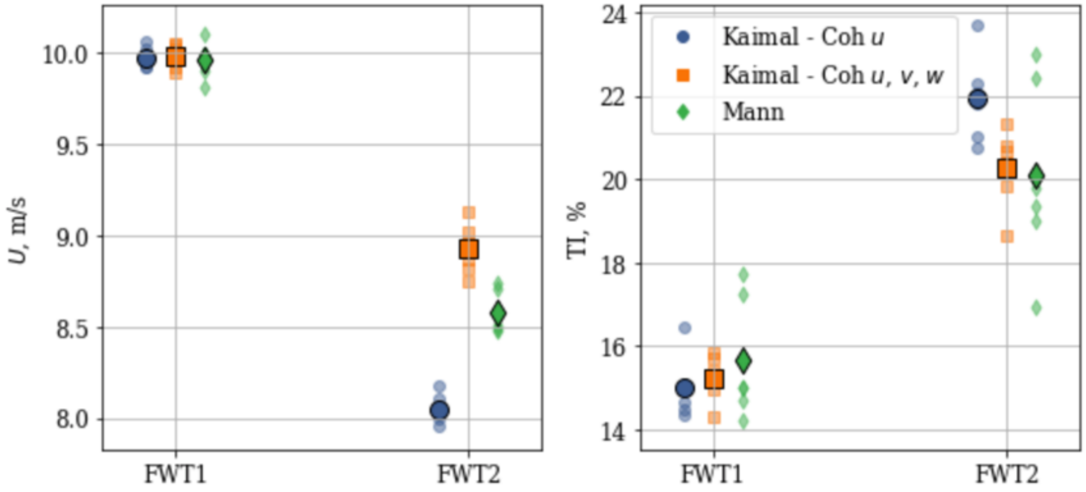


Time = 0 s
Kaimal - Coh u
Kaimal - Coh u, v, w
Mann
Y, (m)
X, (m)
U, m/s
500
0
−500
0
1000
2000
3000
4000
5000
14
12
10
8
6
4
2
0

Velocity Deficit, Turbulence

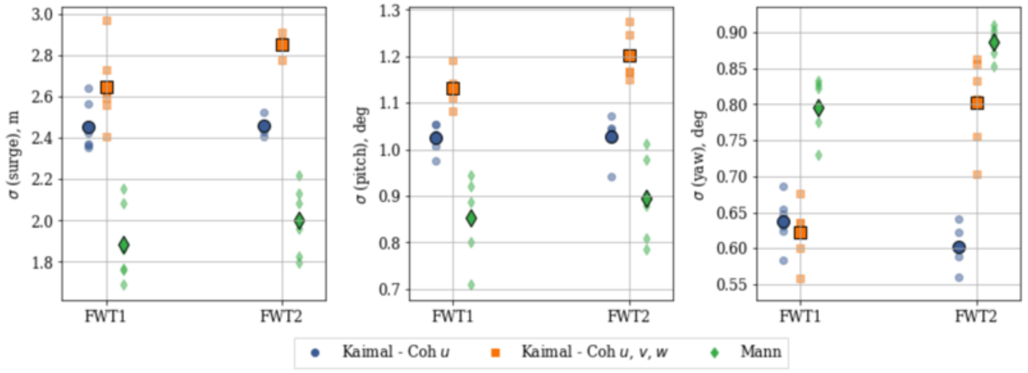


- Velocity deficit is correlated with variance in upstream FWT's lateral wake center

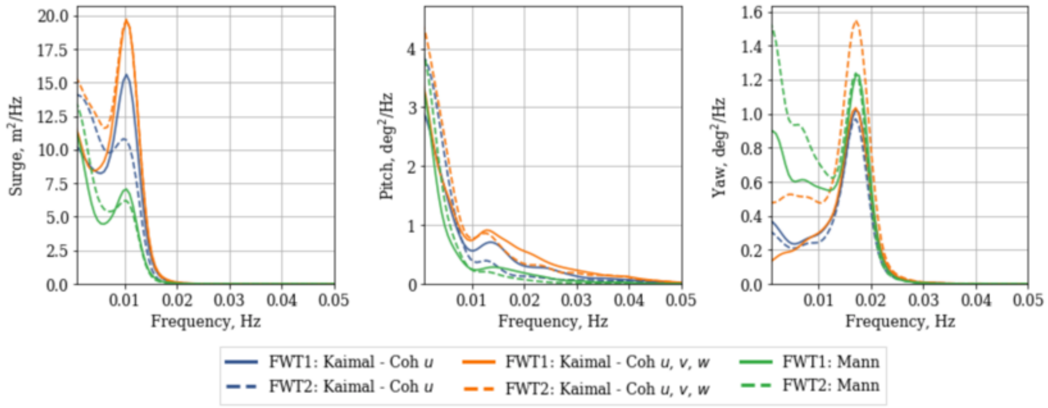
Platform Motions

- Mann model results in lower surge and pitch and greater yaw motions

- Increased surge, pitch, and yaw motions driven by low-frequency response
  - Due to meandering
  - Similar responses for low-frequency tower and mooring loads



Platform surge (left), pitch (middle), yaw (right) motion standard deviations



Platform surge (left), pitch (middle), yaw (right) motion spectra

Conclusions

- Spatial coherence of v- and w-velocity components affect wake meandering behavior

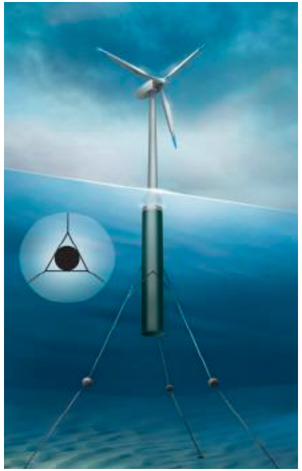
- Low-frequency meandering movement translates to increased low-frequency surge, pitch, and yaw motions

- Increased fatigue damage due to meandering was observed in the top of the tower, but other results were sensitive to the blade-passing frequency
  - See backup

Ongoing Work

- Model an FWT with a more representative structural design of the tower, or with modifications made to the controller
- Comparison with other types of FWTs
- Additional load cases and with more rigorous generation of synthetic turbulent inflow

Lifes50+ OO-Star Wind Floater



Generic spar FWT

Acknowledgements

- Jason Jonkman, Pietro Bartolotti, Kelsey Shaler (NREL)
- Lene Eliassen, Marit Kvittem (SINTEF Ocean)
- Support from the U.S.-Norway Fulbright Foundation

Thank you for your attention

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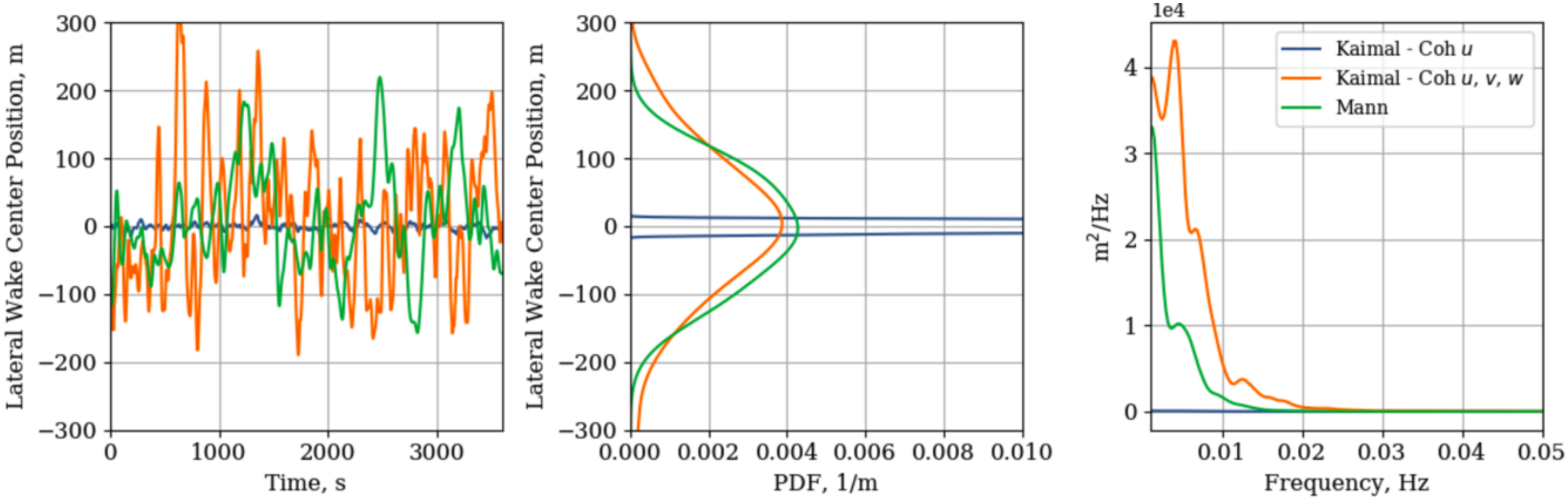
BACKUP SLIDES

Wake Meandering



- Slightly greater meandering for Kaimal – Coh u, v, w than Mann

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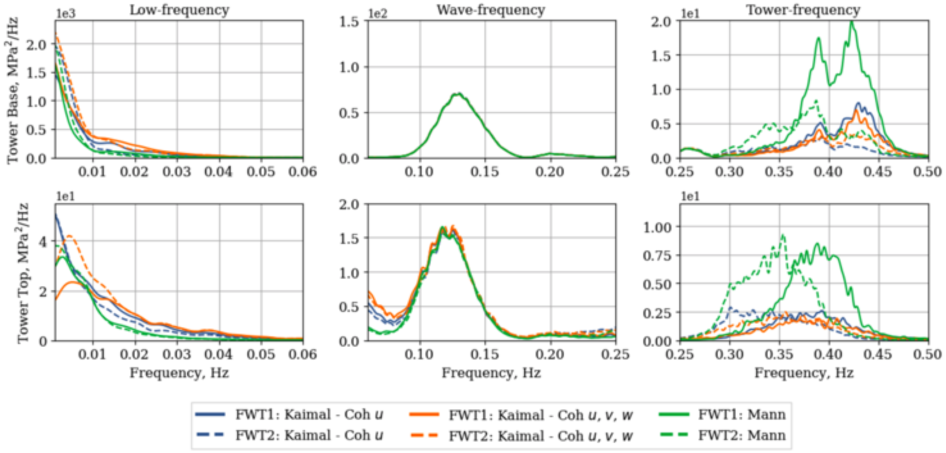
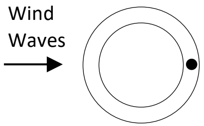
Fatigue - Tower

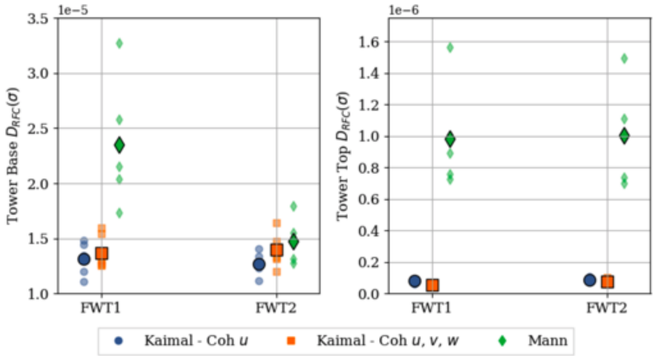
- Increased low-frequency structural loading does not necessarily translate to increased fatigue damage

- Responses in the 3P range contribute to the fatigue damage due to their large number of cycles



Tower base (top) and top (bottom) axial stress spectra





Tower base (left) and top (right) 1-h fatigue damage

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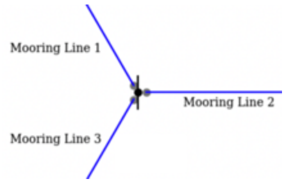
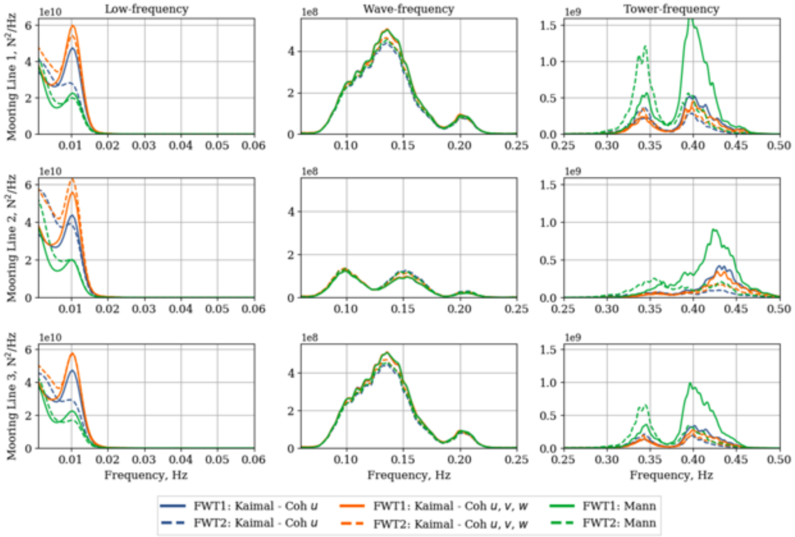
Fatigue - Mooring

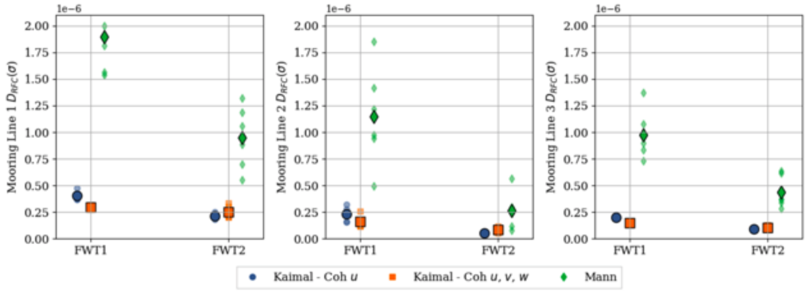
- Similarly affected by responses at 3P



- Mean roll offset increases the stiffness in mooring line 1 resulting in greater high-frequency excitation



Mooring line 1 (top), 2 (middle), and 3 (bottom) tension spectra



Mooring line 1 (left), 2 (middle), and 3 (right) 1-h fatigue damage

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