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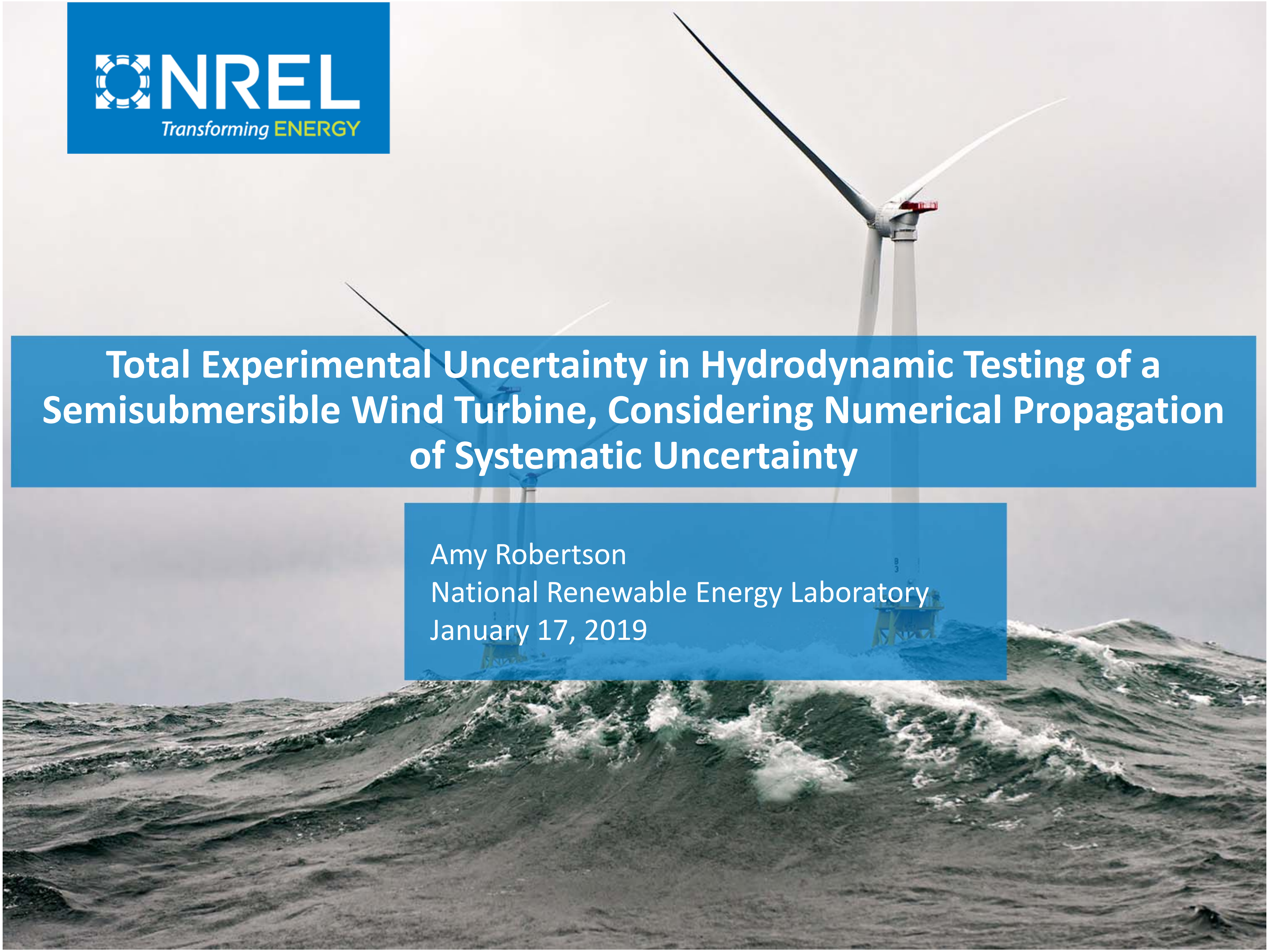

Total Experimental Uncertainty in Hydrodynamic Testing of a Semisubmersible Wind Turbine, Considering Numerical Propagation of Systematic Uncertainty

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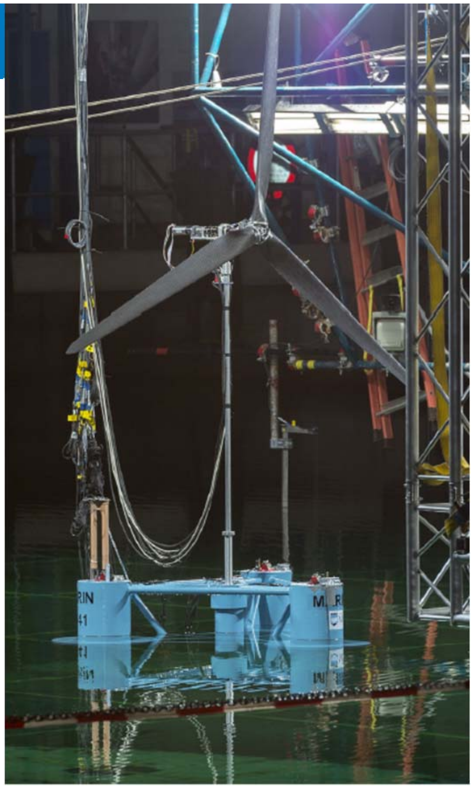
Background

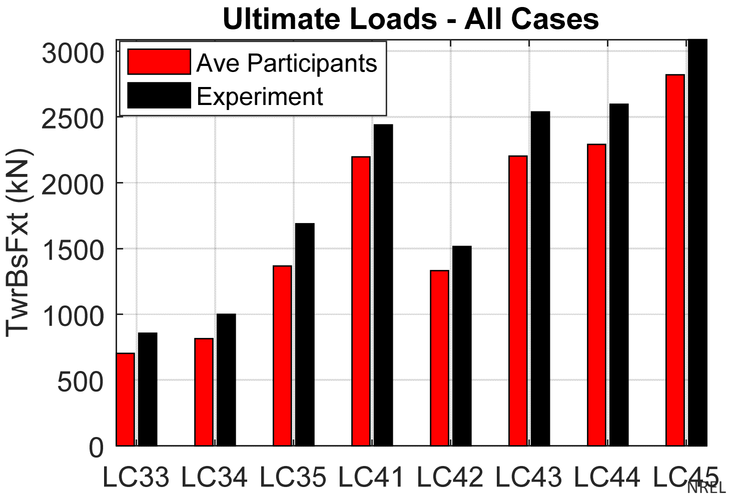
Instrumented OC5-DeepCwind model in basin
(Helder, et al. 2013)



- Floating wind fast becoming a new industry
- To push the TRL of new designs, validation campaigns in wave tanks common

QUESTION: How do you define a successful validation – how close do simulations need to match measurements?

- **EXAMPLE:** In OC5, validation of a floating wind semisubmersible was performed
  - Tower-base force compared – simulations/measurements
  - Modeling tools under-predicted the loads by about 20%
  - Low-frequency response at its pitch and surge natural frequencies (nonlinear hydrodynamics) – biggest cause



ANSWER: Uncertainty assessment

- Define a bound on measurements
- Understand level of certainty in response characteristics

Overview

Objective: Assess uncertainty in load/motion response of OC5-DeepCwind semisubmersible, with special focus on low-frequency behavior

Approach:

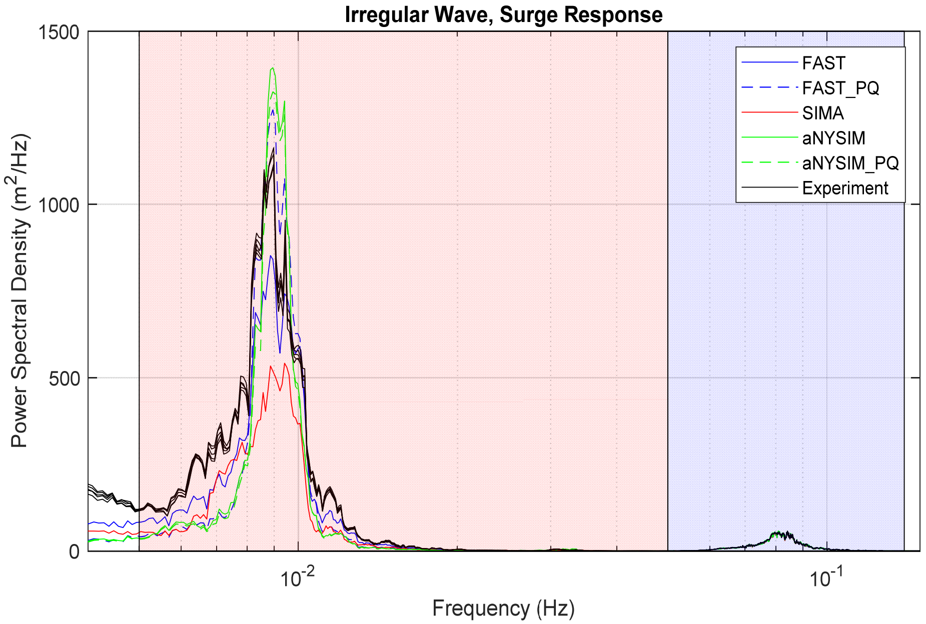
- OC5-DeepCwind semisubmersible re-tested by sub-group. Two test campaigns:
  - Constrained
  - Simple moored
- Uncertainty assessment of motion response of floating configuration
  - ASME uncertainty approach
  - *Random uncertainty* calculated through repeat tests
  - ***Systematic uncertainty* assessed on all components of test, and propagated to response metrics**
  - Response metrics used for direct comparison between simulations/ measurements – and uncertainty bounds for these metrics were calculated

Simplified configuration of OC5-DeepCwind Semi (Robertson)

Tests and Metrics

Test Name	Waves	Number Repeats
Regular wave 1	H=7.1 m, T=12.1 s	5
Regular wave 2	H=4 m, T=9 s	2
White noise	Hs=7.1 m, T=6-26 s	2
Irregular wave	Hs=7.1 m, Tp=12.1 s	5

- **RAO**: the response amplitude operator (RAO) in surge, heave, and pitch at 6 discrete frequency points within the wave energy range;
- **PSD Sum, Low Frequencies**: the integral of the power spectral density (PSD) of surge and pitch motions over the low-frequency range (pink);
- **PSD Sum, Wave Frequencies**: the integral of the PSD of surge and pitch motions over the wave-frequency range (blue)
- **Mean Surge Offset**



Power spectral density (log scale abscissa) of platform response in surge for irregular wave excitation

**** Note: Simulation models not fully tuned, and therefore do not represent the best results that could be obtained by the modeling tool**

Systematic Uncertainty Sources

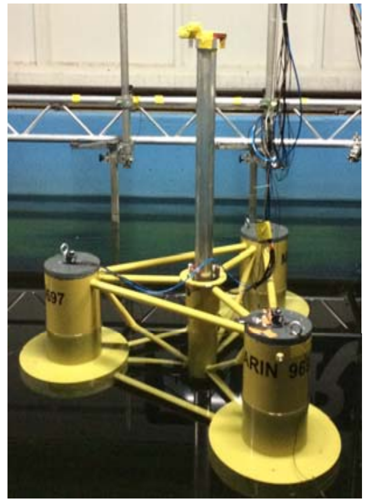
Category	#	Parameter	Baseline Value	Uncertainty Level
Structure Properties	1	Platform mass [kg]	1.4196E+7	8.75E+4
	2	CM, x direction [m]	0	0.22
	3	CM, y direction [m]	0	0.22
	4	CM, vertical [m]	-7.53	0.21
	5	Platform inertia, Ixx abt CM [kg-m^2]	1.2898E+10	1.2898E+8
	6	Platform inertia, Iyy abt CM [kg-m^2]	1.2851E+10	1.2851E+8
	7	Platform inertia, Izz abt CM [kg-m^2]	1.4189E+10	1.4189E+8
	8	Draft [m]	20	0.25
	9	Column angle, [deg]	0	0.5
	10	Column diameter, [m]	12 or 24	0.1
	11	Mooring stiffness [kN/m]	48.9	5.2
	12	Mooring pretension [kN]	1122.5	62
Configuration	13	Anchor position x [m]	Radially outward	0.25
	14	Anchor position y [m]	Radially outward	0.25
	15	Anchor position z [m]	Up/down	0.25
	16	Mooring fairlead position [m]	Radially outward	0.05
	17	Initial position [m]	0	0.12
	18	Initial orientation [deg]	0	0.062
	19	Water depth [m]	180	2
	20	Water density [kg/m^3]	1025	10.25
Wave Excitation	21	Wave elevation – due to sensor drift [m]	measured	0.03
	22	Wave elevation – due to probe location and tilt [m]	measured	negligible
Measurements	23	Translation measurement [m]	0	0.03
	24	Rotation measurement [deg]	0	0.3

Down-selected Systematic Sources

- Parameters down-selected based on their influence on the response metrics according to simulations.
- Thresholded by examining the total combined systematic uncertainty of the response metrics.
  - Parameters causing less than 10% change in total combined systematic uncertainty on any metric were removed.
- Original set of 24 parameters down-selected to 8
- Parameters were adjusted to try to make them independent of each other

	Parameter	Abbreviation
1	Center of mass, x direction	**CMx**
2	Center of mass, vertical	**CMz**
3	Mooring stiffness	**Stiff**
4	Draft	**Draft**
5	Column diameter	**ColDia**
6	Wave elevation – due to sensor drift	**WaveElev**
7	Platform inertia, Iyy abt CM	**Iyy**
8	Platform mass + Displaced Volume	**Mass+Buoy**

Systematic Uncertainty Propagation



RESPONSE METRICS

INPUT
(Wave Elevation)

TEST SPECIMEN
(CMx, CMz, Stiff, Draft, ColDia, Iyy, Mass+Buoy)

OUTPUT

- Systematic uncertainty of the response metrics due to a given uncertainty source:
  - Simulate model using the baseline properties and calculate associated response metrics.
  - Simulate model using a new value for given uncertain parameter, and calculate response metrics.
  - Difference between response metrics calculated using baseline properties and when changing one of the uncertain parameters is the systematic uncertainty for that parameter.
  - Variations performed in positive and negative directions -> asymmetric uncertainty bounds
- Sum all propagated uncertainty sources

Modeling Approaches

Propagation affected by the fact we are using a model. Addressed by:

- Using multiple models
- Using multiple modeling approaches
- Taking largest variation across all approaches

Model ID	Global linear and quadratic drag	Morison drag on vertical columns	Morison drag on heave plates	Wave loads above still water level
FAST		x	x	Morison-type drag up to 1^{st} order free surface based on constant potential
FAST_PQ	x			
SIMA		x	x	Morison-type drag up to 1^{st} order free surface based on constant potential
aNySIM			x	Morison loads applied on heave plate only, Therefore, no wave loads act above still water level.
aNySIM_PQ	x			

Total Uncertainty Calculation

- Combined random and propagated systematic uncertainty

$$u_C = \sqrt{(b_R)^2 + (s_{\bar{x}})^2}$$

- Expanded uncertainty: multiply standard uncertainty by a coverage factor
  - $k = 2,$ level of confidence of approximately 95 %

$$U = ku_C \qquad X = \bar{X} \pm U$$ Response metric uncertainty band

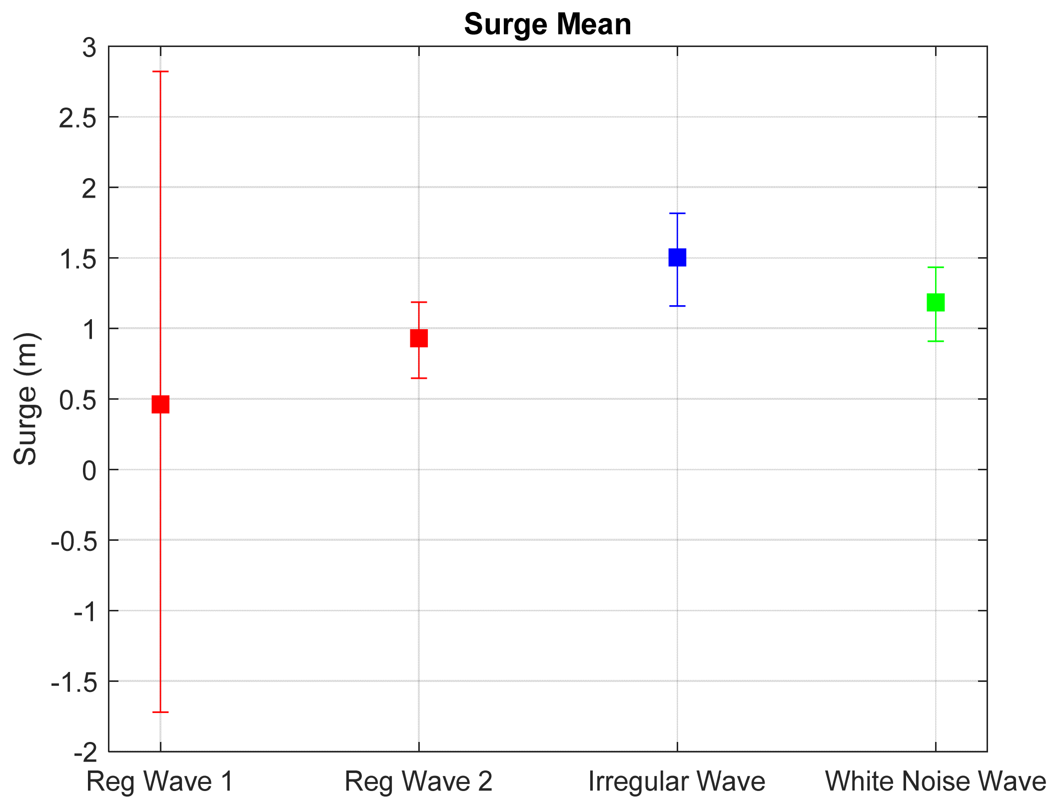
  - For asymmetric uncertainty:

$$q_i = \frac{(\bar{X} + b_i^+) + (\bar{X} - b_i^-)}{2} - \bar{X}$$

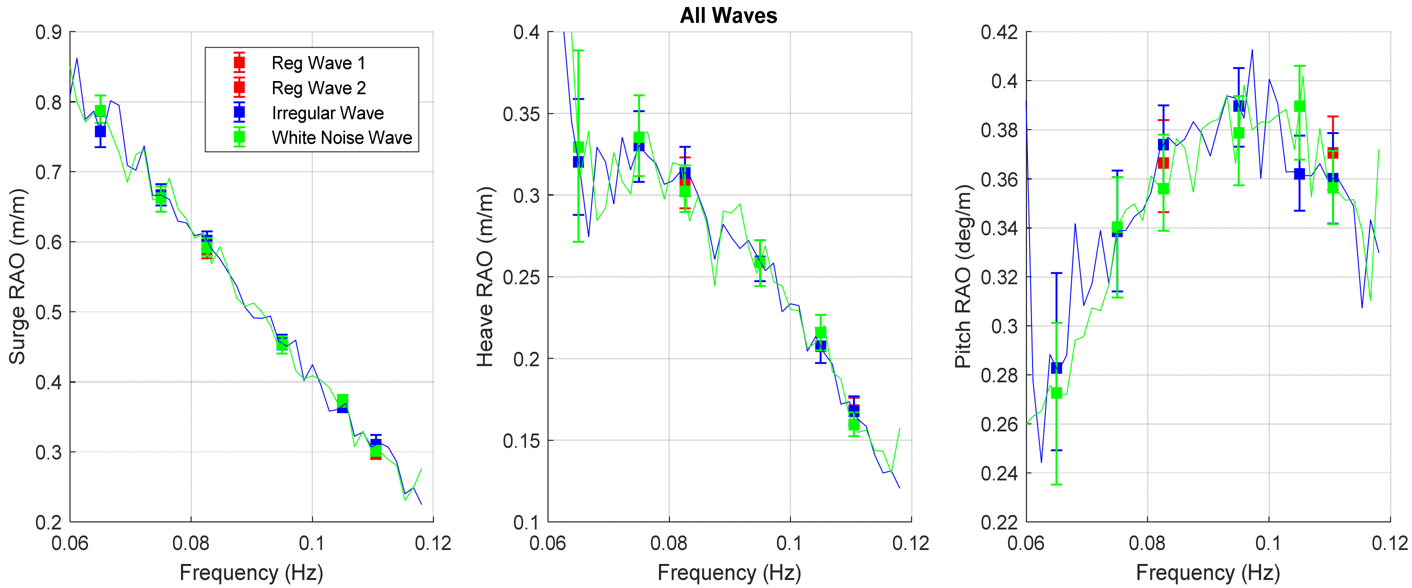
$$X = \left(\bar{X} + \sum_{i=1}^{N} q_i\right) \pm U$$

Metric: Mean Surge

- Uncertainty in mean surge in regular wave case 1 is probably overstated
  - large variation was only seen for one of the simulation tools
  - much of the difference is likely related to static effects (which would have been zeroed out in the experimental measurements)



Metric: RAOs



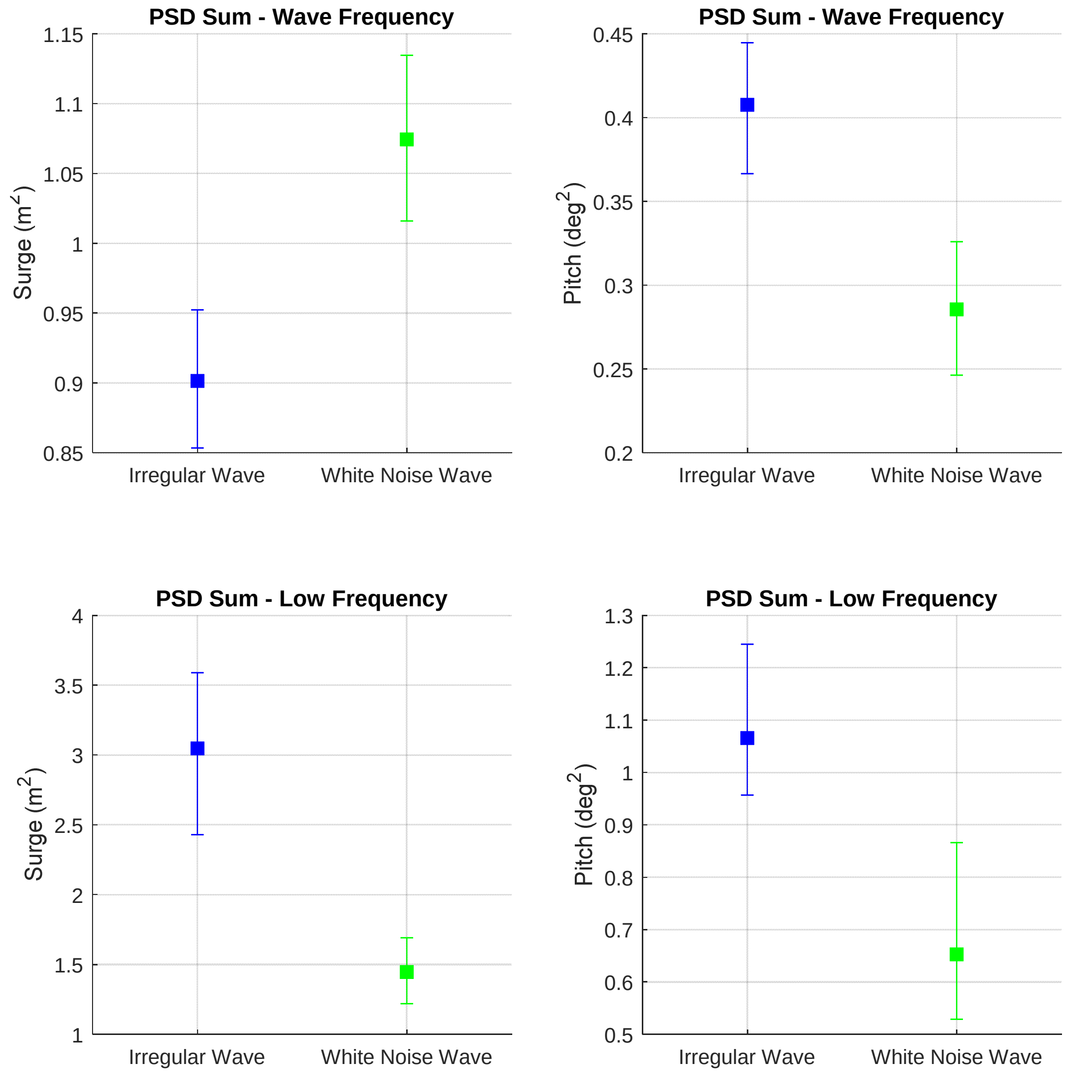
- RAO calculations shown based on all waves
  - 6 points chosen for uncertainty assessment
- Frequencies on low end showed most uncertainty
  - Closeness to natural frequencies
  - Cancellation effects in the excitation
- Pitch response shows larger uncertainty than other DOFs

Metric: PSD Sum

- $S_{sum} = \sum_{i=j}^{k} S_{resp}(f_i)\,\Delta f$

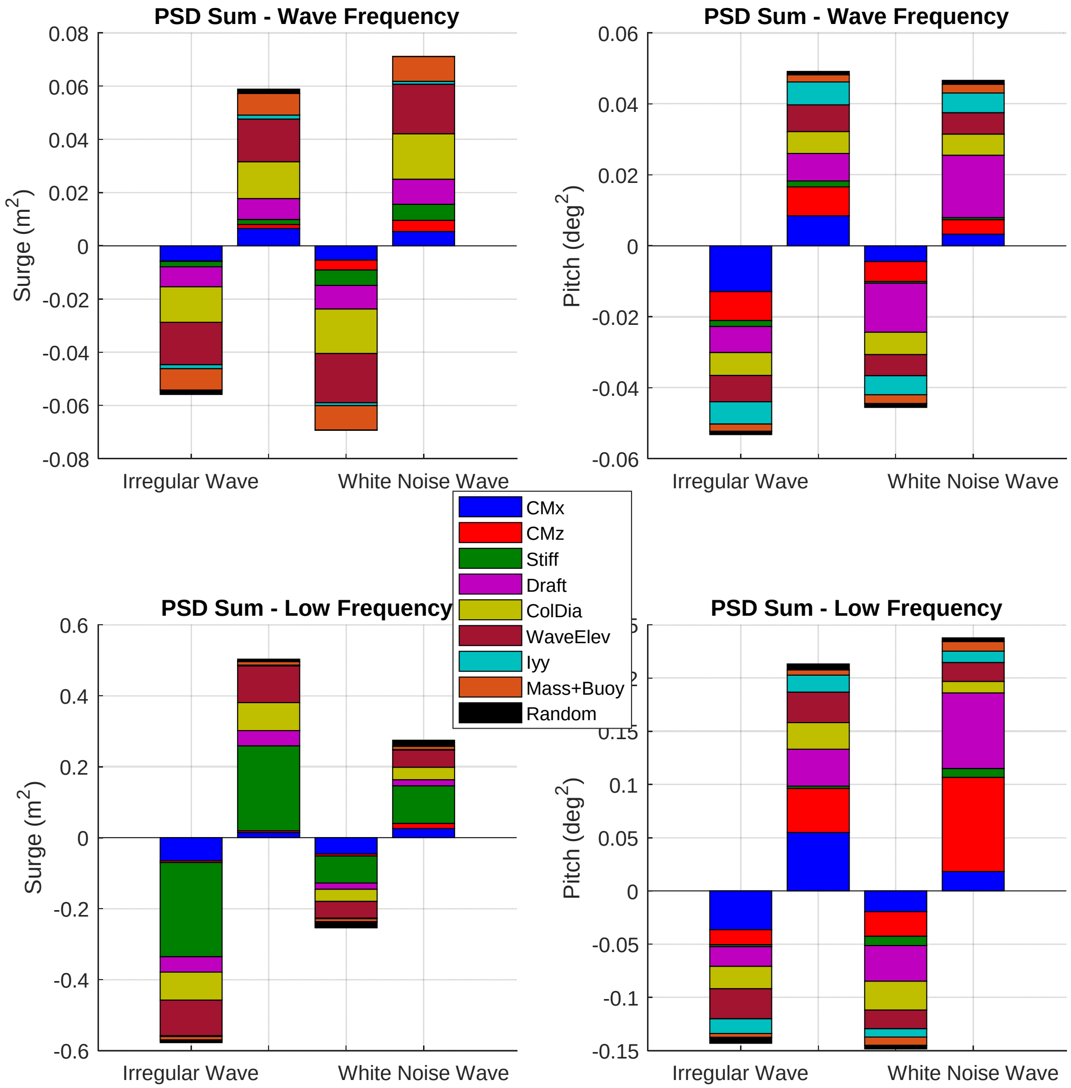
- Uncertainty levels vary between the two irregular waves (irregular and white noise)
  - Difference especially pronounced in the low-frequency **surge** metric

- Amplitude of the total uncertainty:
  - wave-frequency : <20%,
  - **low-frequency:** 30-40%



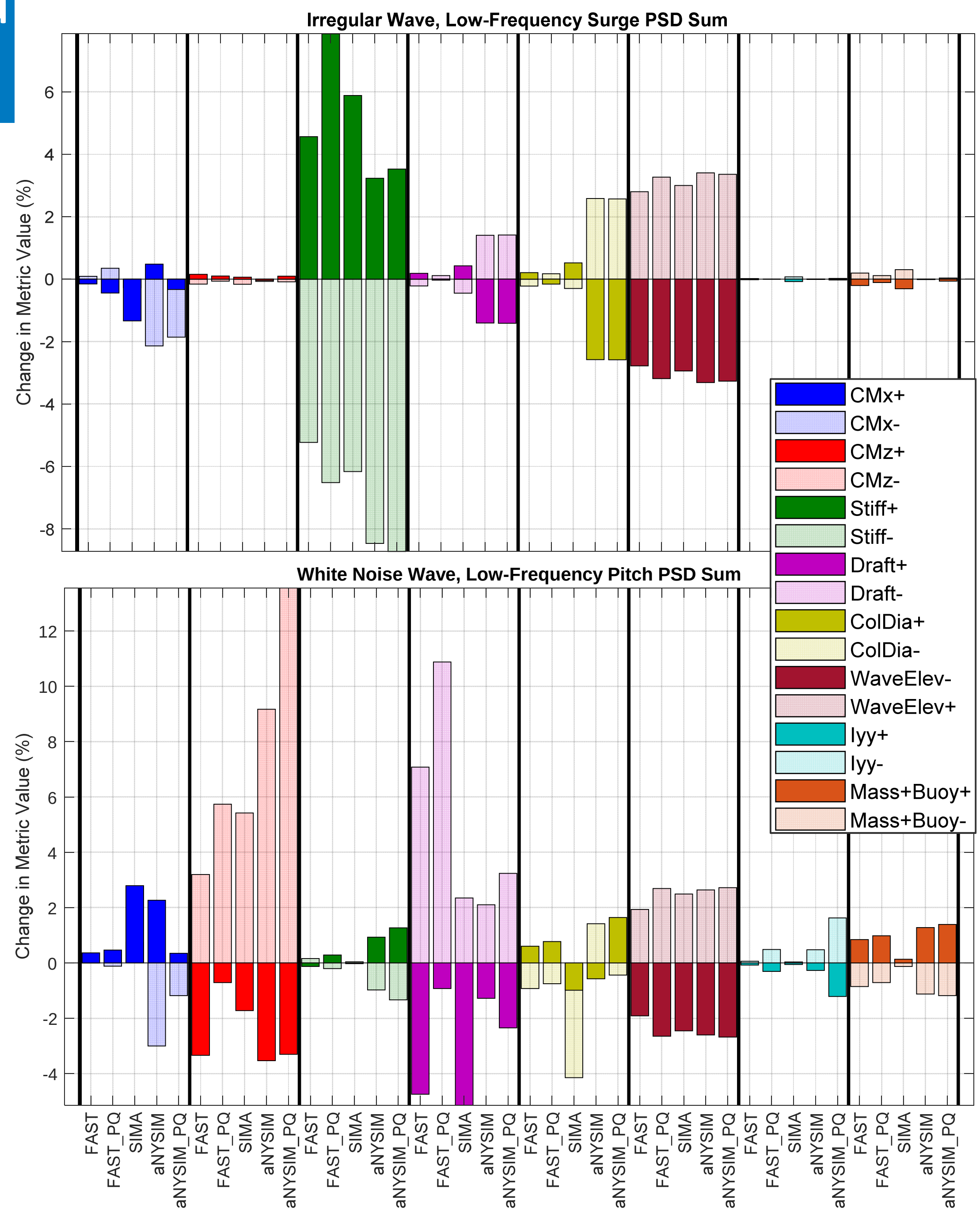
Contributions to Uncertainty

- Random uncertainty negligible
- Surge (Wave):
  - Wave elevation
  - Column diameter
- Surge (Low):
  - Mooring stiffness (affects natural frequency)
  - Wave elevation
- Pitch (Wave)
  - Draft
  - CM – x-dir
- Pitch (Low):
  - CM – z-dir (affects natural frequency)
  - Draft



Variability of Propagated Uncertainty

- Largest change in metric across all simulation approaches taken -> conservative
- No single simulation approach consistently had larger uncertainties than others
- While levels varied between simulations, mainly agreed on the parameters that are the most sensitive



Conclusions

- The total experimental uncertainty for a set of hydrodynamics model tests with a rigid semisubmersible wind turbine has been estimated through propagation of the systematic uncertainties using several numerical simulation tools.
- Wave frequency responses are found to have smaller uncertainty than low-frequency responses
- Random uncertainty, which was found through repeated measurements, is negligible compared to the systematic uncertainty.
- Low-frequency responses were most sensitive to model characteristics that affected the stiffness (natural frequency):
  - Surge: mooring system stiffness
  - Pitch: platform draft and vertical center of gravity
- Simulation tools showed good agreement regarding which parameters were most important, although the magnitude of the propagated uncertainty differed significantly
- The results from this study give a measurement of uncertainty that can be used in future validation efforts
  - The results from previous OC5 study do not fall in the uncertainty bands calculated
  - The data from the present tests will be studied further using both engineering and high-fidelity models through the OC6 project

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Thank You

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$$\theta_i = \partial X / \partial p_i$$

$$b_i = \theta_i \, d_i$$

$$b_R^2 = \sum_{i=1}^{N} b_i^2$$

b_i = systematic uncertainty of output metrics

b_R = total combined systematic uncertainty

p_i = parameter values

d_i = systematic uncertainty sources

X = output response metric

Θ = sensitivity coefficients