Uncertainty Analysis of Commonly Reported Wave Energy Converter Performance Metrics

Asian Wave and Tidal Energy Conference 2024

Busan, Korea

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PMEC
Pacific Marine Energy Center

UAF UNIVERSITY OF ALASKA FAIRBANKS

Oregon State University

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Outline

- Intro to uncertainty analysis in experimental testing
- Define metrics of interest and nonlinearities
- Present case study WEC and tank
- Discuss & quantify sources of uncertainty
- Results on wave power uncertainty
- Conclusions and future work

Uncertainty Background

IEC TS 62600-103

Edition 1.0 2018-07

TECHNICAL SPECIFICATION

Marine energy – Wave, tidal and other water current converters – Part 103: Guidelines for the early stage development of wave energy converters – Best practices and recommended procedures for the testing of pre-prototype devices

INTERNATIONAL TOWING TANK CONFERENCE	**ITTC – Recommended Procedures and Guidelines**	7.5-02 -07-03.12 Page 1 of 13	
	Uncertainty Analysis for a Wave Energy Converter	Effective Date 2017	Revision 00

INTERNATIONAL TOWING TANK CONFERENCE	**ITTC – Recommended Procedures and Guidelines**	7.5-02 -01-01 Page 1 of 17	
	Guide to the Expression of Uncertainty in Experimental Hydrodynamics	Effective Date 2008	Revision 01

Coleman, H. W., & Steele, W. G. (2009). *Experimentation, Validation, and Uncertainty Analysis for Engineers* (3rd ed.). John Wiley & Sons, Inc.

Uncertainty Background – Model Experiments

INTERNATIONAL TOWING TANK CONFERENCE	ITTC – Recommended Procedures and Guidelines	7.5-02 -07-03.12 Page 1 of 13	
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Orphin et al. (2017-2021) – Oscillating Water Column

J. Orphin, J. Nader, and I. Penesis, "Uncertainty analysis of a WEC model test experiment," Renew. Energy, vol. 168, pp. 216–233, 2021, doi: 10.1016/j.renene.2020.12.037.

J. Orphin, "Uncertainty in Hydrodynamic Model Test Experiments of Wave Energy Converters," Australian Maritime College, University of Tasmania, 2020.

J. Orphin, I. Penesis, and J.-R. Nader, "Uncertainty Analysis for a Wave Energy Converter: the Monte Carlo Method," AWTEC 2018 Proc., pp. 1–10, 2018.

J. Orphin, J. Nader, I. Penesis, and D. Howe, "Experimental Uncertainty Analysis of an OWC Wave Energy Converter," Eur. Wave Tidal Energy Conf., no. August, pp. 1–11, 2017.

- Example of wave gauge uncertainty

- ± 30% uncertainty in capture width ratio
- Demonstrated Monte Carlo Method
- General and detailed uncertainty analysis

Motivation

- Uncertainty analysis…
  - Is expected by IEC standards
  - Is important for confidence in performance metrics
  - Has not been demonstrated on many WEC devices or testing tanks
  - Lacks discussion of nonlinear effects

Focus: How do wave nonlinearities affect the uncertainty of incident wave power?
And thus, capture width?

Capture Width

$$L = \frac{P_{WEC}}{P_W} = \frac{WEC\ power}{Wave\ energy\ flux\ (power)}$$

$$P_W = Ec_g = wave\ energy\ *\ group\ velocity$$

International Electrotechnical Commission. (2012). *IEC/TS 62600-100, Marine energy – Wave, tidal and other water current converters – Part 100: Electricity producing wave energy converters – Power performance assessment*.

Incident Wave Energy Equations

Linear wave energy

$$E = \frac{1}{8}\rho g H^2 \quad \left[\frac{J}{m^2}\right]$$

wave height only

Incident Wave Energy Equations

Linear wave energy

$$E = \frac{1}{8}\rho g H^2 \quad \left[\frac{J}{m^2}\right]$$

wave height only

Mohtat et al. derived the equations for nonlinear wave energy

$$\overline{PE} = \rho g\left\{\frac{1}{2}h^2 + H^2\left(\frac{1}{16} - \frac{1}{1024}\varepsilon^2 \underline{M_4} + \frac{1}{131,072}\varepsilon^4 \underline{M_6}\right)\right\} \quad (12)$$

$$\overline{KE} = \frac{\rho g}{4}H^2\left\{\frac{1}{4} + \varepsilon \underline{KE_3} + \varepsilon^2 \underline{KE_4} - \varepsilon^3 \underline{KE_5} + \varepsilon^4 \underline{KE_6} + \varepsilon^5 \underline{KE_7}\right\}$$

$\underline{M_x(T,h) \text{ and } KE_x(T,h)}$ (14)

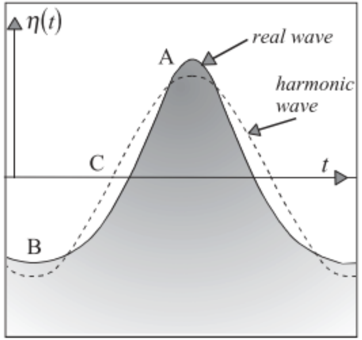
wave height, water depth, and wave period

Mohtat, A., Yim, S. C., & Osborne, A. R. (2022). Energy Content Characterization of Water Waves Using Linear and Nonlinear Spectral Analysis. *Journal of Offshore Mechanics and Arctic Engineering*, *144*(1). https://doi.org/10.1115/1.4051860

Wave Nonlinearity

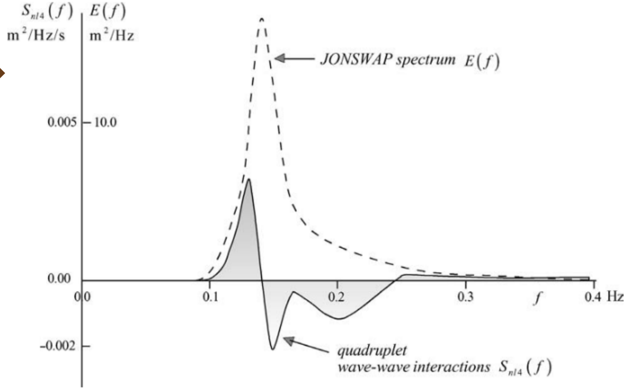
Skewness

- Wave height and water depth
- Peakier peaks, shallower troughs



Wave-wave interactions

- Wave components resonating and redistributing energy over the spectrum



Asymmetric

- Wave height and wave length
- Steepness "leaning"

Holthuijsen, Leo. H. (2007). *Waves in Oceanic and Costal Waters*. Cambridge University Press.

Case Study WEC: Laboratory Upgrade Point Absorber (LUPA)

- Open-source
- Two-body point absorber
- Realtime PTO damping and stiffness control
- Moored 6 DOF

O.H. Hinsdale Wave Research Laboratory
Large Wave Flume
Oregon State University
Corvallis, OR, USA

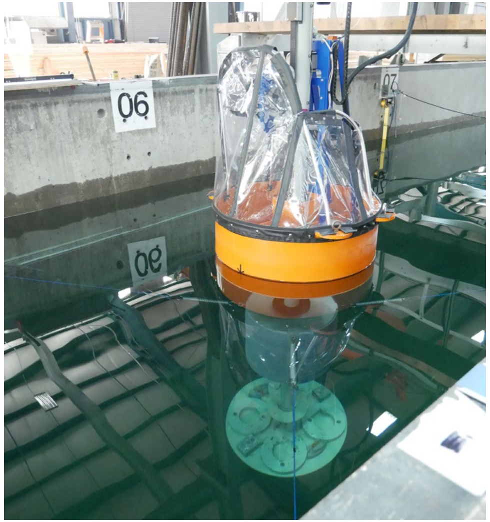
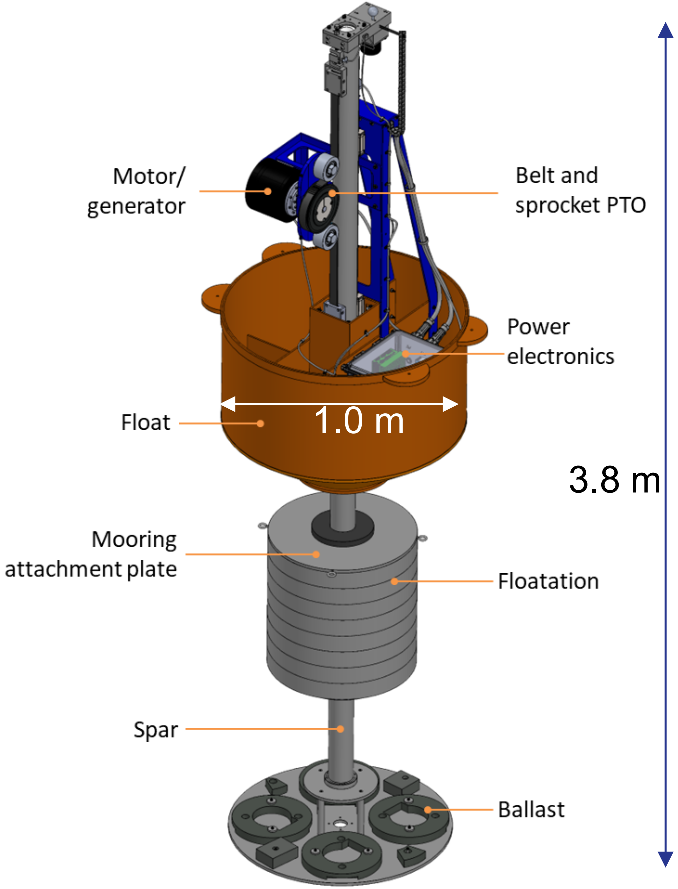


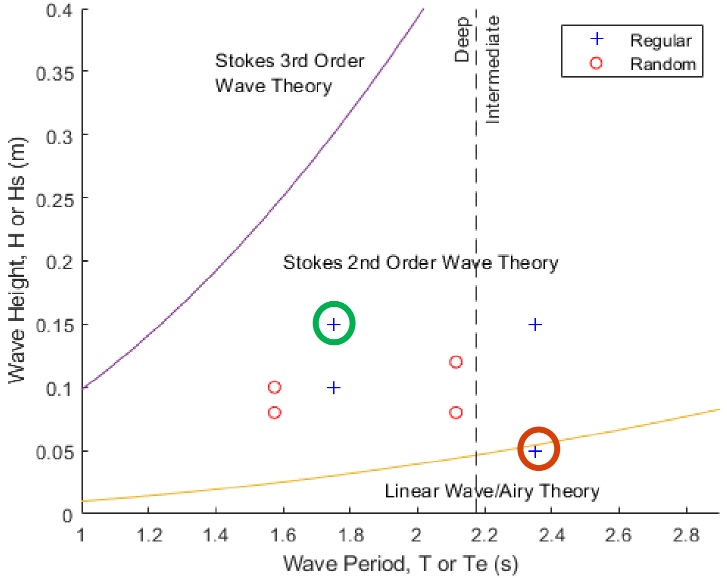
Photo by Samantha Quinn



Wave Conditions

- Regular waves of varying degrees of nonlinearity
- Scaled from PacWave Test Site on Oregon Coast
- 3.7 m tank water depth

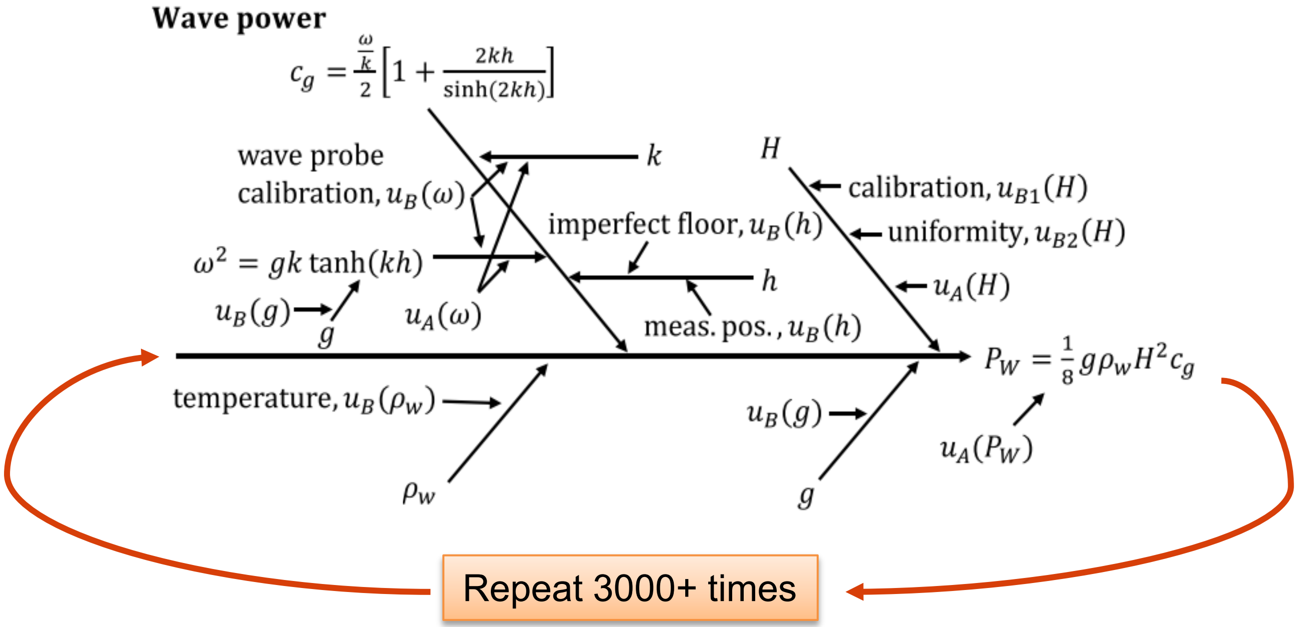
Wave Period (s)	Wave Height (m)	Steepness (m/m)	2nd Order wave height percent of 1st order (%)
1.75	0.15	0.099	4.9
2.35	0.15	0.055	2.8
2.35	0.05	0.018	0.9
1.75	0.10	0.066	3.3



Sources of Uncertainty

- *Measurement uncertainty (Type A and Type B)*
  - Gravity
  - Water density
  - Wave gauges
  - Pressure sensor for water depth
  - Tank floor variations
  - Wave maker consistency
- *Nonlinear effects*
  - Skewness
  - Asymmetry (steepness)

Monte Carlo Method



J. Orphin, "Uncertainty in Hydrodynamic Model Test Experiments of Wave Energy Converters," Australian Maritime College, University of Tasmania, 2020.

Measurement Uncertainty

Type A: statistical

"variability in repetition"

$$u_A = \frac{\sigma}{\sqrt{n}}$$

$$\sigma = standard\ deviation$$
$$n = number\ of\ observations$$
ITTC $n > 10$

Measurement Uncertainty

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ITTC $n > 10$

Example: Wave height from gauge

- Desired wave:
  - H = 0.15 m
  - T = 1.75 s
- 10 trials, >20 regular waves each
- Nominal measured:
  - H = 0.13 m
  - T = 1.75 s
- $\pm 2\ mm$ observed wave heights

$u_A(H) = \pm 0.23\ mm$ **(0.18%)**

Normally distributed

Measurement Uncertainty

Type B: epistemic

"lack of information"

$$u_B = \sqrt{\frac{\left(y_j - \widehat{y}_j\right)^2}{M-2}}$$

$$y_j - \widehat{y}_j = \textit{difference between measured and fitted value}$$

$$M = \textit{number of calibration points}$$

Measurement Uncertainty

Example: Wave height from gauge

1. Calibrate wave gauge on tank fill and drains
2. Plot voltage vs pressure sensor water depth
3. Find error of linear fit
4. Combine type B wave gauge & pressure sensor

$u_B(H) = \pm 0.21\, mm$ **(0.16%)**

Normally distributed

Type B: epistemic

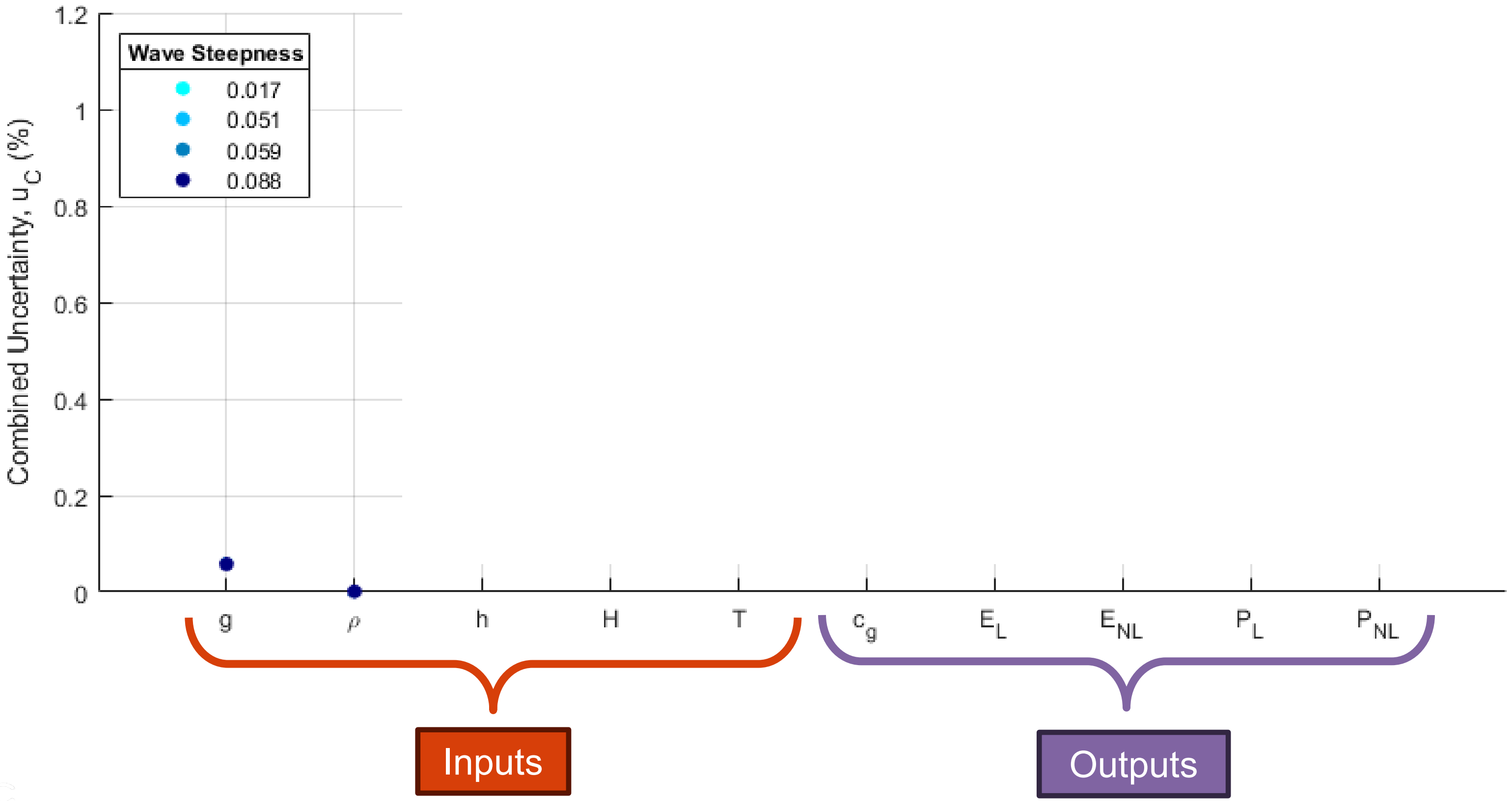
"lack of information"

$$u_B = \sqrt{\frac{(y_j - \hat{y}_j)^2}{M-2}}$$

$$y_j - \hat{y}_j = difference\ between\ measured\ and\ fitted\ value$$
$$M = number\ of\ calibration\ points$$

Results

$$steepness = \varepsilon(H,T,h) = \frac{\pi H}{L(T,h)}$$



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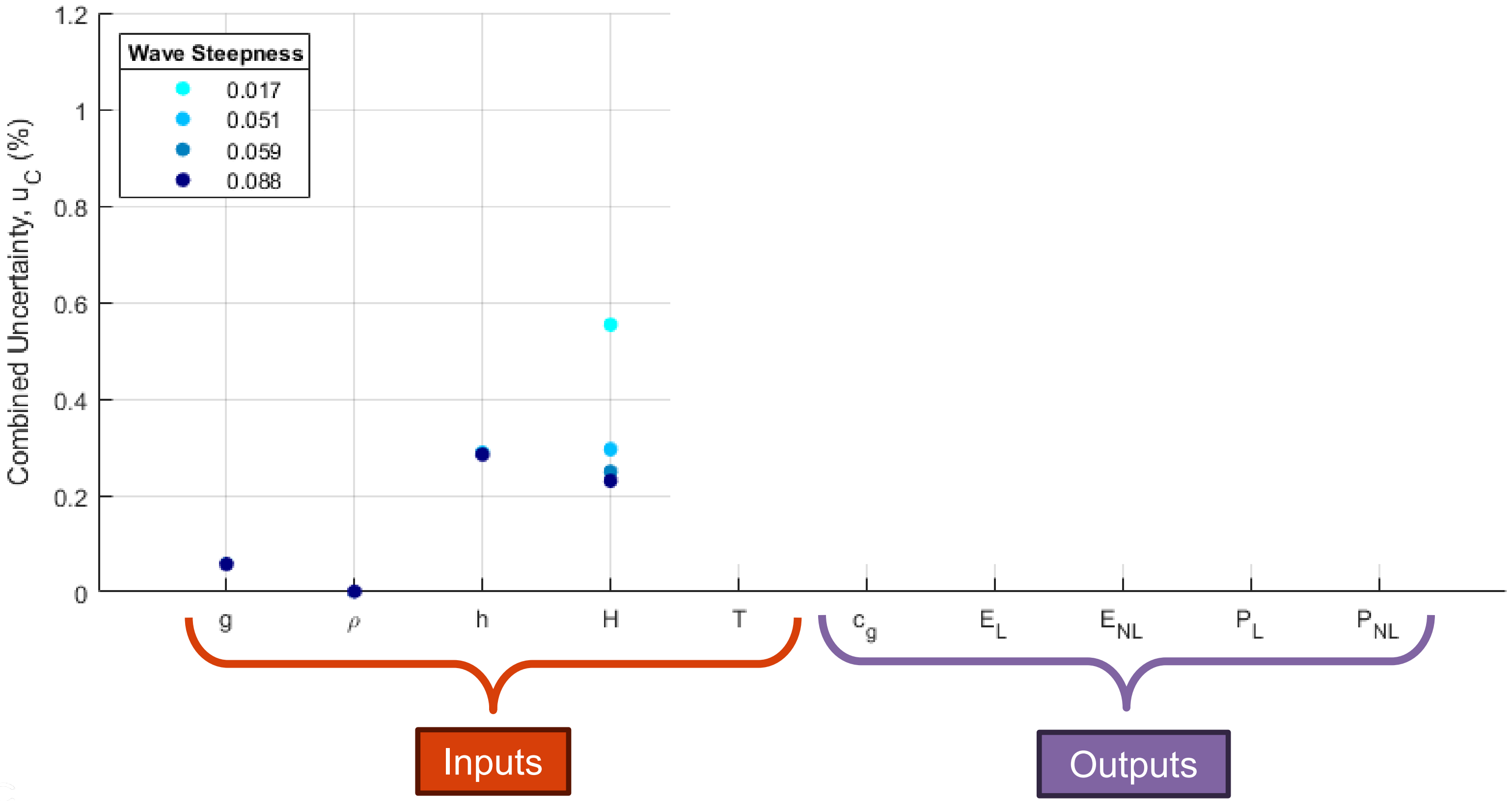

Combined Uncertainty, u_C (%)
1.2
1
0.8
0.6
0.4
0.2
0
Wave Steepness
0.017
0.051
0.059
0.088
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ρ
h
H
T
c_g
E_L
E_{NL}
P_L
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Inputs
Outputs

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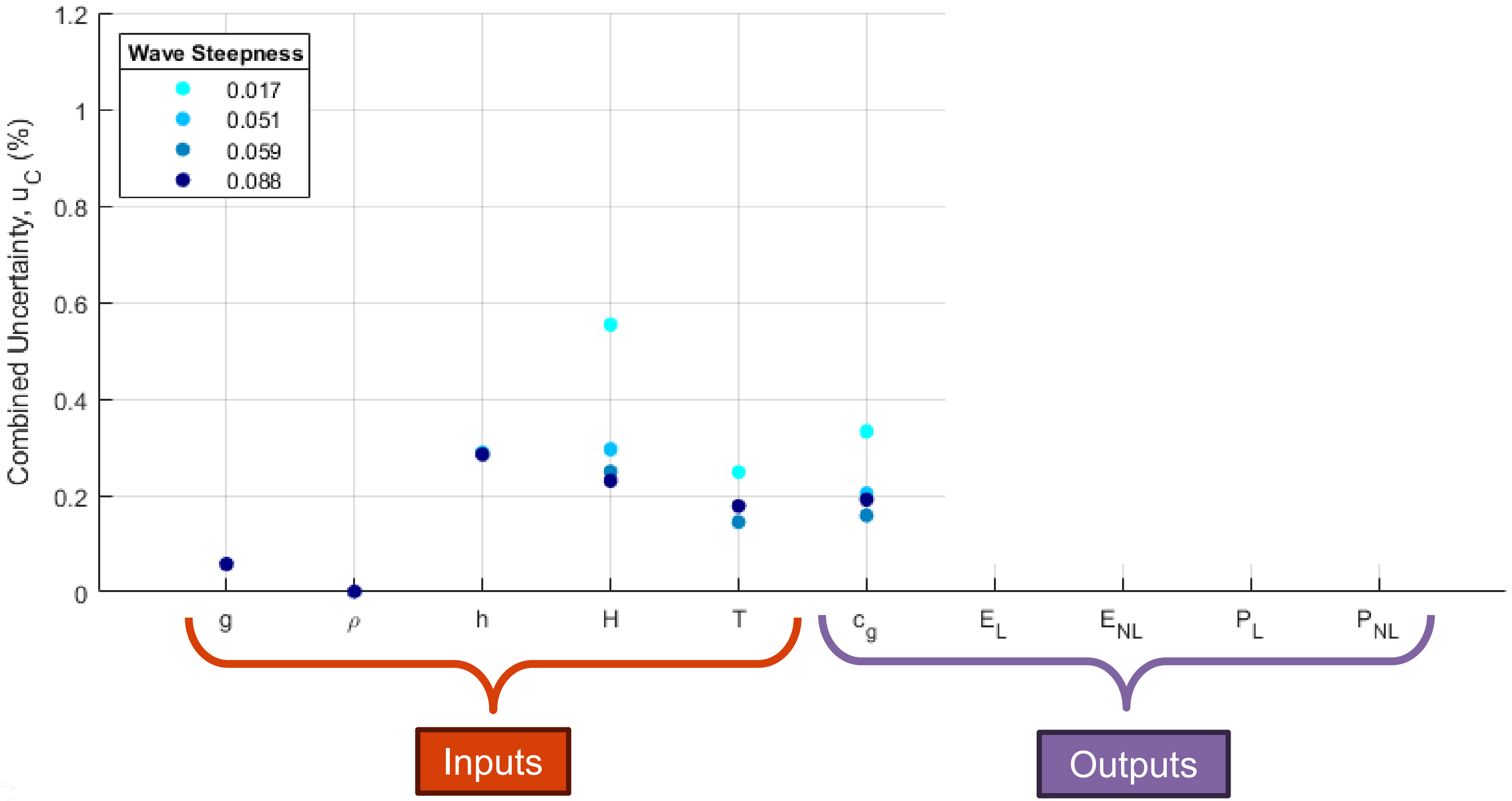

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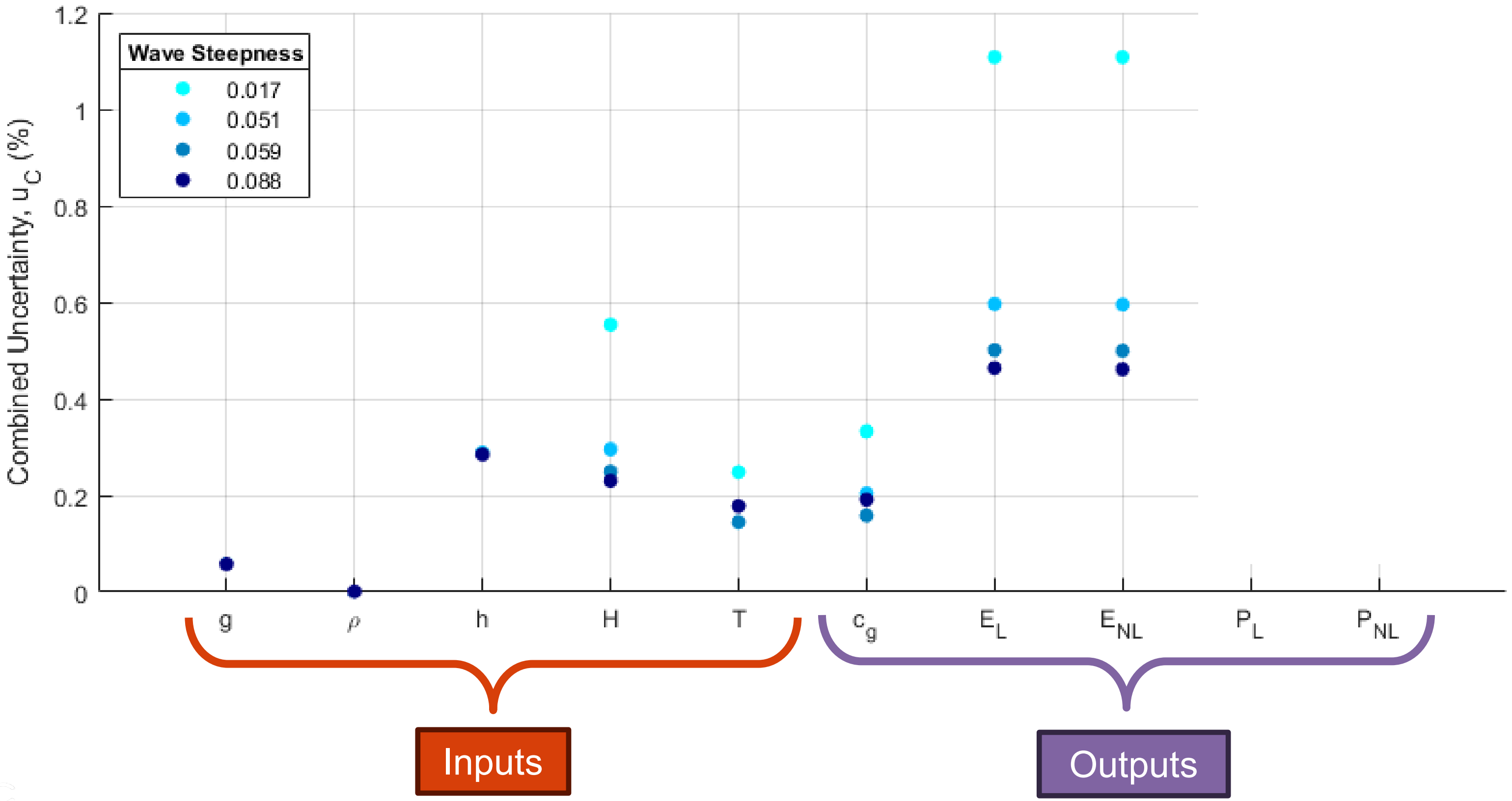
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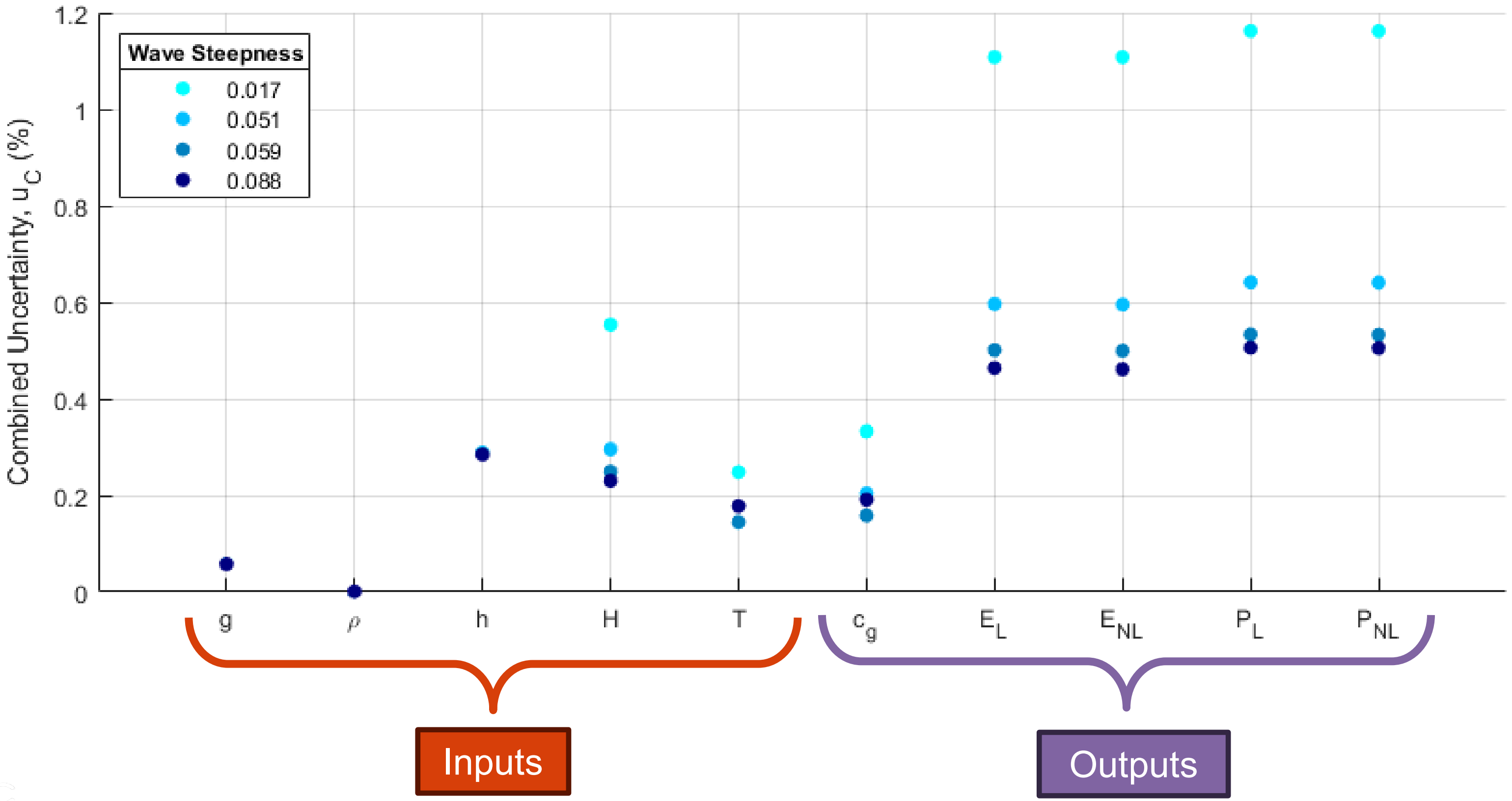

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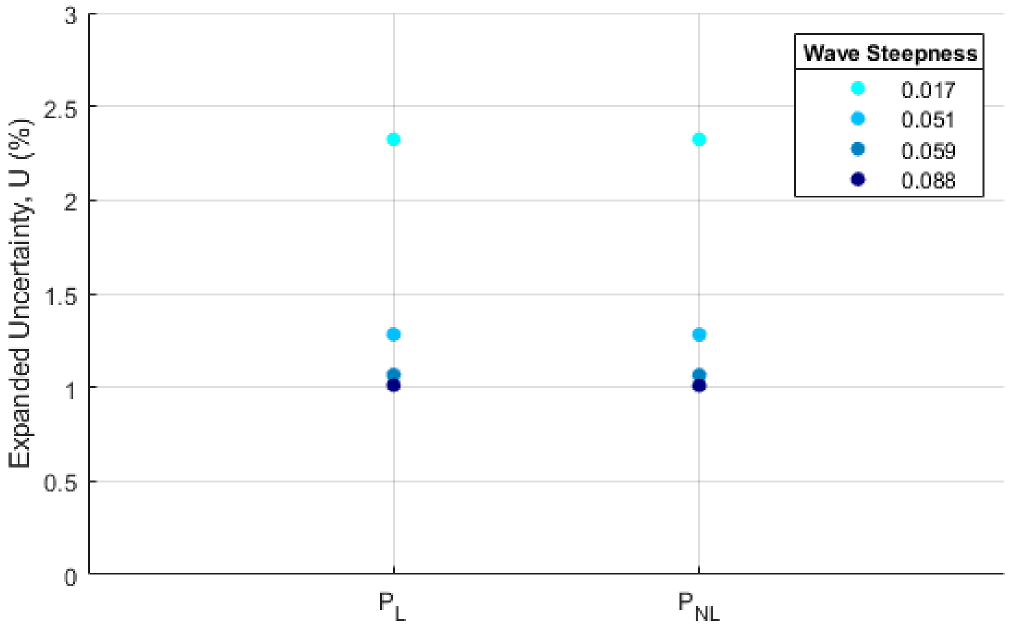
Outputs

Expanded Uncertainty

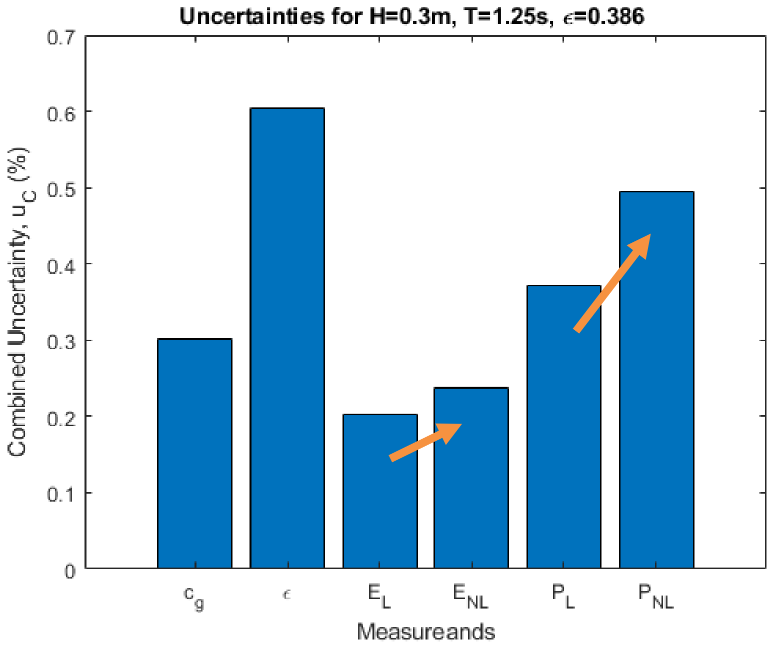
- 95% confidence interval
- Uncertainty in wave power is ±1-2.3%
- Orphin et al. ~7%



Large Wave Steepness

- Nonlinear energy and power uncertainty slightly greater than linear

- Higher order nonlinear terms have greater effect at large steepness

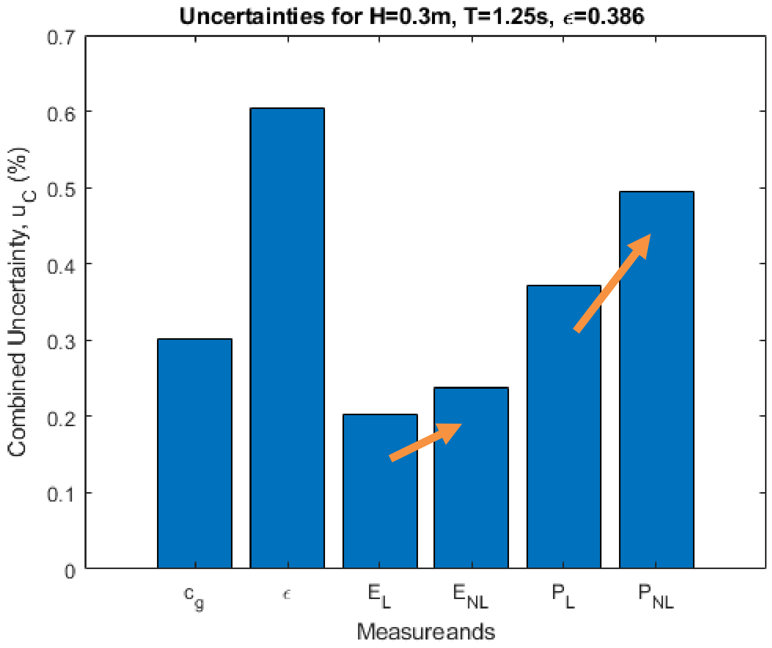


Large Wave Steepness

- Calculated wave power uncertainty 11%

$$P_L = 107\ \frac{W}{m}$$

$$P_{NL} = 95\ \frac{W}{m}$$



Conclusions

1. For this experiment, wave power uncertainty was below 3%
2. High wave steepness (>0.2) has slightly more uncertainty in nonlinear estimation
3. Linear estimation overestimates regular wave power by 11%
   - Capture width is then underestimated in linear assumption

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Future Work

- Steeper wave experiments to find type A
- Irregular wave analysis
- Uncertainty analysis of WEC power for full capture width analysis
- Temperature dependencies on WEC power uncertainty

PMEC

Special thanks to Jarrah Orphin (uncertainty guidance) and Tim Maddux (wave lab researcher)

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Funding

NSF GRFP
NSF GRADUATE RESEARCH FELLOWSHIP PROGRAM

TEAMER
Testing & Expertise for Marine Energy

Extra slides

Discussion

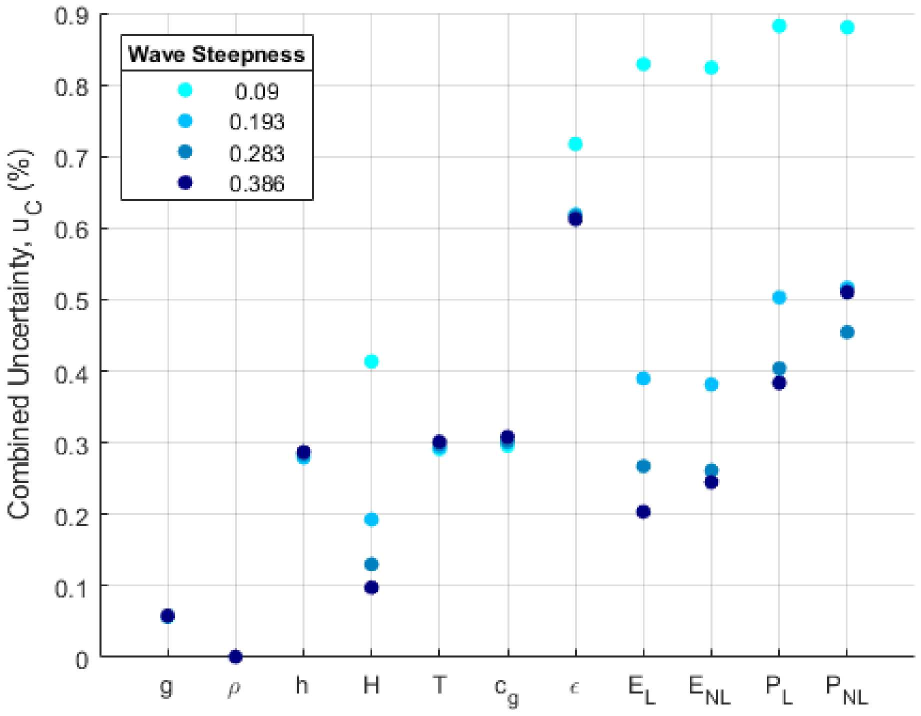
- Low wave steepness has the same uncertainty in linear and nonlinear wave power

$$P_L = E(H) * c_g(T,h)$$
$$P_{NL} = E(H,T,h) * c_g(T,h)$$

- For high wave steepness uncertainty is higher in nonlinear wave power estimation

$$steepness = \varepsilon(H,T,h) = \frac{\pi H}{L(T,h)}$$

Large Steepness



- High wave steepness >0.2 has more uncertainty in nonlinear estimation