SAND2016-3920C

Exceptional service in the national interest

Sandia National Laboratories

Photos placed in horizontal position with even amount of white space between photos and header

A comparison of WEC control strategies for a linear WEC model

Giorgio Bacelli, Ryan G. Coe, David Wilson, Ossama Abdelkhalik, Umesh A. Korde, Rush D. Robinett III, Diana L. Bull

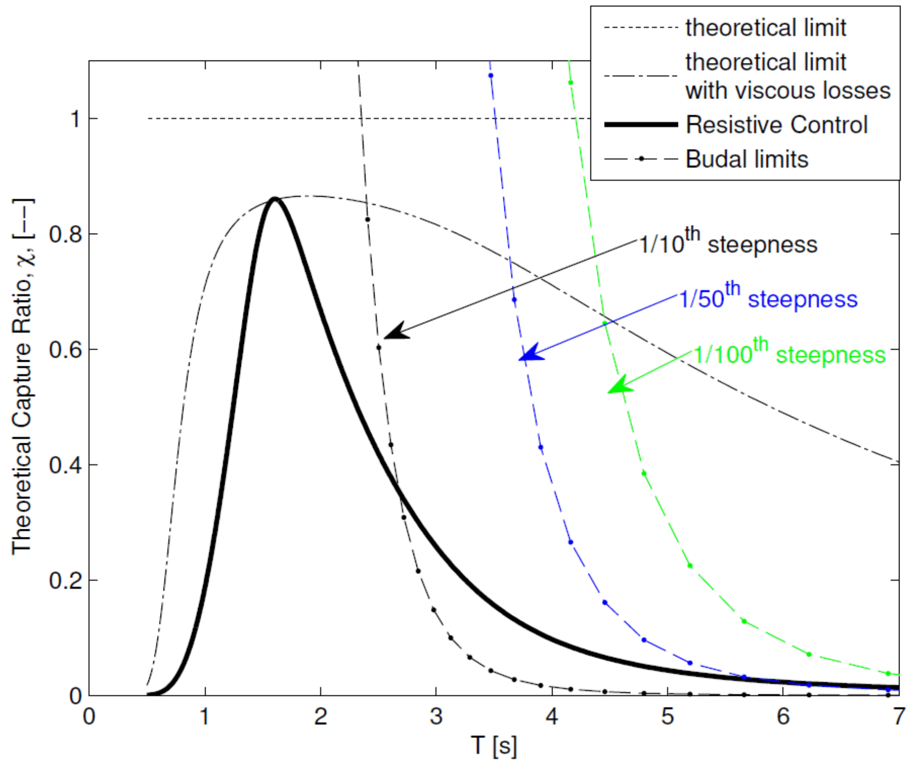
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

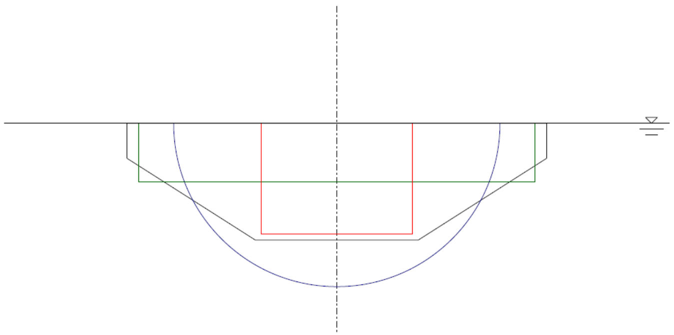
Advanced WEC Control

- Goal
  - What is the potential of control systems in WECs?
    - Validate the extent to which control strategies, given real world limitations, can increase the energy production of WEC devices.

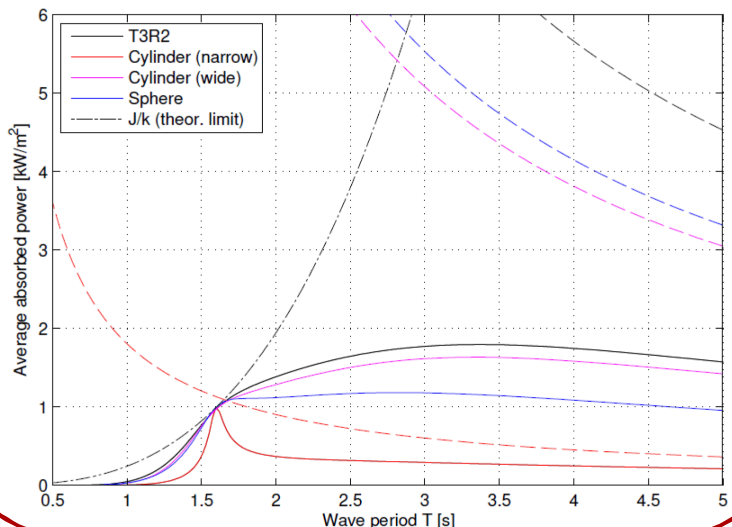


Buoy design

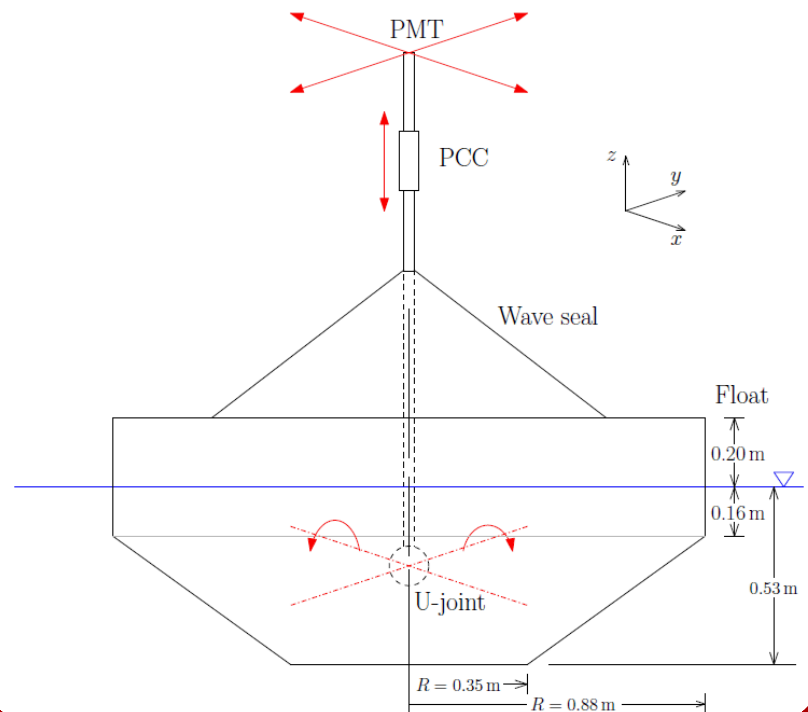
Axisymmetric shapes



Absorption: comparison

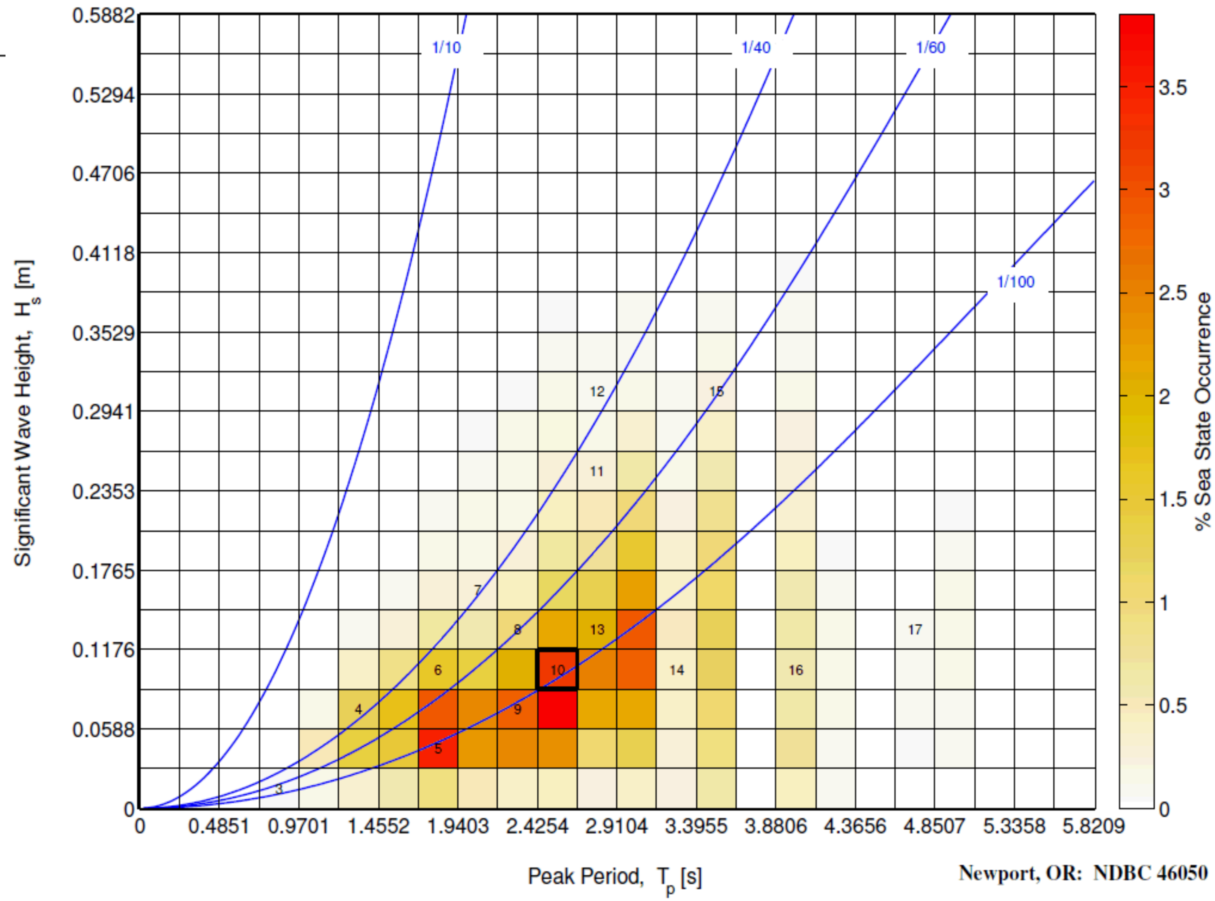


Final design



Sea states

Sea-State index	Peak period, T_p [s]	Significant wave height, H_s [m]
1	1.00	0.0247
2	1.00	0.0148
3	1.00	0.0370
4	1.53	0.0871
5	2.00	0.0594
6	2.05	0.1039
7	2.25	0.1875
8	2.50	0.1545
9	2.50	0.0927
10	2.58	0.1194
11	2.89	0.2523
12	3.00	0.3337
13	3.03	0.1363
14	3.46	0.1283
15	3.60	0.3195
16	4.02	0.1320
17	4.86	0.1617



Newport, OR: NDBC 46050

Control Strategies

- Baseline (Resistive)
- Model Predictive Control (MPC)
- Dynamic Programming (DP)
- Shape Based (SB) Control
- Linear Quadratic (LQ) Control
- PDC3
- Latching

Model Predictive Control

- Optimization based control strategy
  - Can be computationally expensive
- The control signal is optimal for the predicted excitation force for a linear system.
  - Requires estimator/predictor
  - If the prediction is perfect, the control algorithm provides the maximum energy absorption
- The control algorithm is capable including constraints (motion, force) in the formulation of the optimization problem
- Requires PTO capable of generating reactive power
  - Requires energy storage

Dynamic Programming

- It can be implemented for <u>nonlinear systems</u>
- Optimization based control strategy
  - Computationally <u>very</u> expensive
- The control signal is optimal for the predicted excitation force for a linear system.
  - Requires estimator/predictor
  - If the prediction is perfect, the control algorithm provides the maximum energy absorption
- The control algorithm is capable including constraints (motion, force) in the formulation of the optimization problem
- Requires PTO capable of generating reactive power
  - Requires energy storage

Shape Based Control

- It can be implemented for <u>nonlinear systems</u>
- Optimization based control strategy
  - Computationally <u>very</u> expensive, <u>but more efficient than DP</u>
- The control signal is optimal for the predicted excitation force for a linear system.
  - Requires estimator/predictor
  - If the prediction is perfect, the control algorithm provides the maximum energy absorption
- The control algorithm is capable including constraints (motion, force) in the formulation of the optimization problem
- Requires PTO capable of generating reactive power
  - Requires energy storage

Linear Quadratic Control

- Pure feedback control strategy
  - Computationally inexpensive (matrix multiplication)
  - Optimal feedback gain is obtained by offline optimization
- Linear WEC model
- LQ feedback control is well known for good properties (stability, robustness to parameters uncertainty,…)
- Requires PTO capable of generating reactive power
  - Requires energy storage
- NOT capable of dealing with constraints

PDC3

- Potential to demonstrate actual realization of CC control design
  - Implementation will be fundamentally novel and first practical approximation (scheduled for next FY17)
- Wave foreknowledge is not required
- Method is computationally fast and potentially easy to implement
- Uses linear WEC model
- Fundamentally feedback control strategy (PD loops)
- Requires PTO capable of generating reactive power
  - Requires energy storage
- Expansion of strategy to multi-DOF's and more nonlinear cases is essential in order to understand how well strategy can work on real world systems

Latching

- It is a switching control strategy
- It does not require model of the WEC for the calculation for the control signal (in its simplest form)
  - It can be used also for nonlinear systems
- It may require prediction of wave elevation/excitation force to improve performance
- It doe not require PTO capable of generating reactive power
  - Requires energy storage
- NOT capable of dealing with constraints

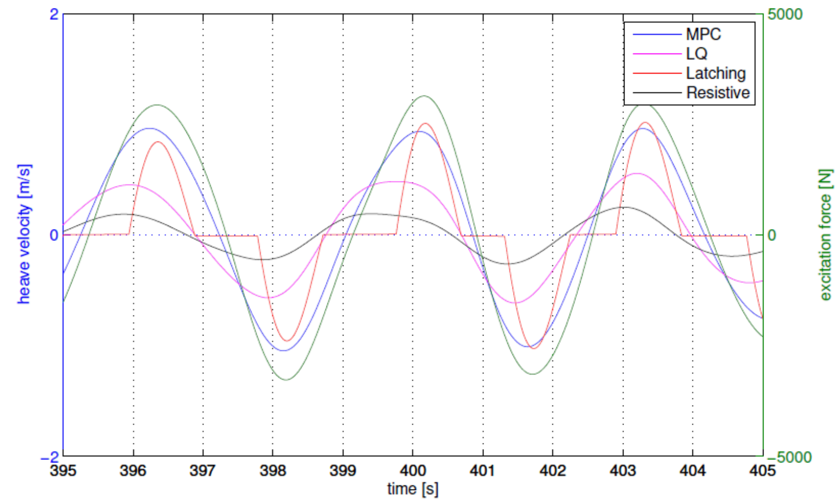
Summary of results

	Bounding cases		TP	TAP-FB		TAP-FF		
	Resistive	CCC	Latching	LQG	PDC3	Linear MPC	DP	SB
Power production characteristics								
Average power-in	0	279	0	46.5	45.8	98.8	374.8	39.0
Average power-net	15.5	52.5	28.8	39.8	25.5	46.1	38.4	22.6
Average energy-stored	0	251	0	27.5	42.9	76.4	332.9	23.8
Power-in, peak/RMS	0.0	5.8	0.0	5.6	5.1	5.6	5.4	4.3
Power-net, peak/RMS	7.3	38.8	6.2	14.3	17.3	20.2	60.1	16.2
Total absolute power flow	15.5	313.3	28.8	76.0	91.5	131.8	384.9	54.5
PCC requirements								
PCC force, peak	739	4312	2099	1970	1854	2653	5850	2500
Slew rate requirements	2.8 E+3	1.1 E+3	1.5 E+6	5.9 E+3	4.5 E+3	7.0 E+3	1.2 E+3	5.5 E+3
PCC force, RMS	315	2367	923	915	1086	1401	2730	1010
PCC Force, peak/RMS	2.35	1.82	2.27	2.15	1.71	1.89	2.14	2.49
Mechanical loading								
Oscillation amplitude, peak	0.06	0.25	0.10	0.14	0.11	0.17	0.28	0.12
Oscillation amplitude, peak/RMS	2.52	1.97	2.05	2.27	1.89	2.09	1.99	2.52
Oscillation velocity, peak	0.14	0.47	0.30	0.31	0.22	0.35	0.50	0.22
Oscillation velocity, peak/RMS	2.63	2.20	2.77	2.43	2.30	2.33	2.17	2.6
Oscillation acceleration, peak	0.39	1.02	0.45	0.78	0.22	0.46	1.27	0.64
Oscillation acceleration, peak/RMS	2.70	2.39	1.21	2.58	2.30	1.95	2.36	2.56

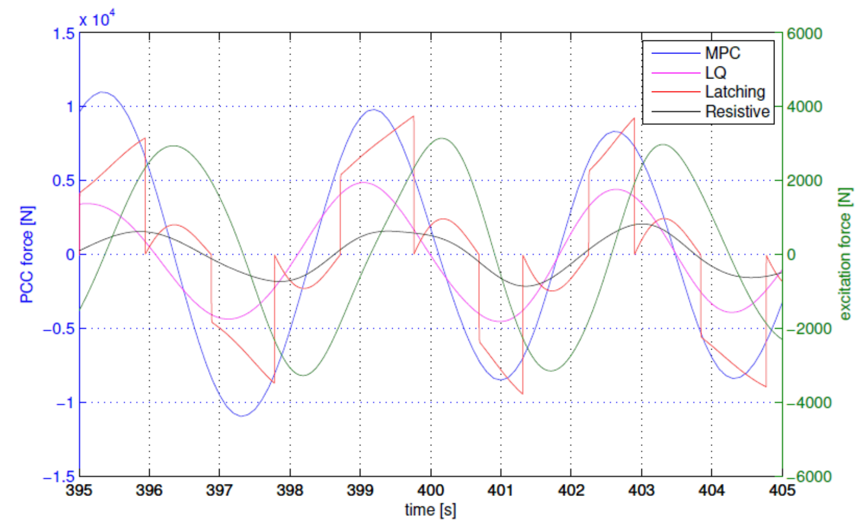
Summary of results

Sample time-series

Velocity vs Excitation force

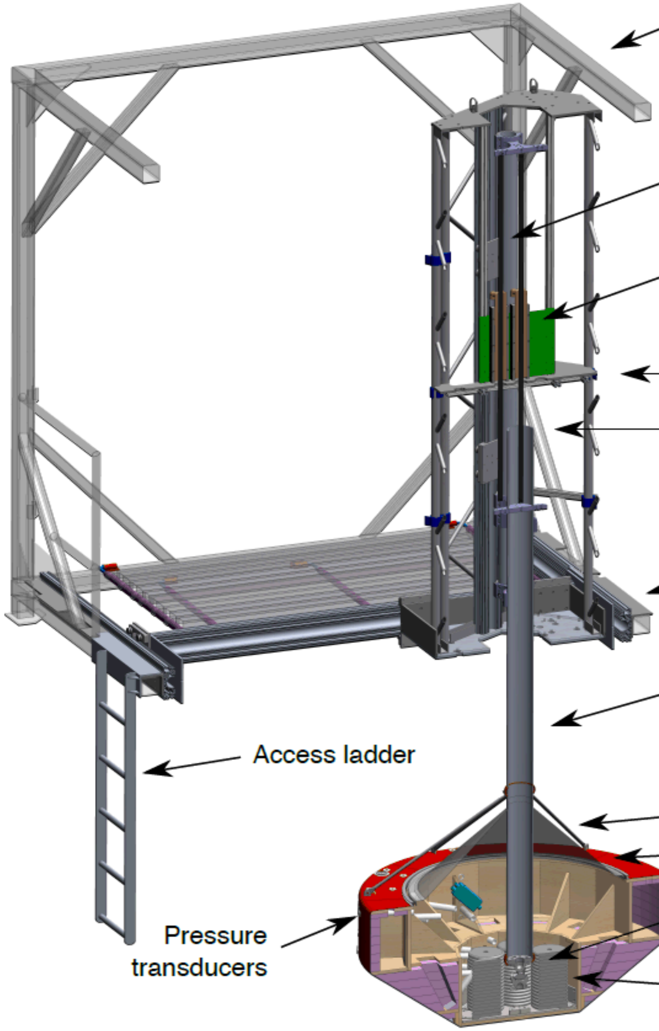


Actuator force vs Excitation force



NEXT STEPS

Wave tank testing: completed



Wave tank testing: completed

Buoy

Maneuvering and Sea Keeping (MASK) Basin
NSWCCD - Bethesda MD

Next steps

- System identification:
  - Dynamic model of the device from experimental data

↓

- Re-evaluate/tune control strategies with new model

↓

- Test control strategies in wave tank

Thank you.

This research was made possible by support from the Department of Energy's Energy Efficiency and Renewable Energy Office's Wind and Water Power Program. The research was in support of the Resilient Nonlinear Controls (RNLC) Program.

Sandia National Laboratories is a multiprogram laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.