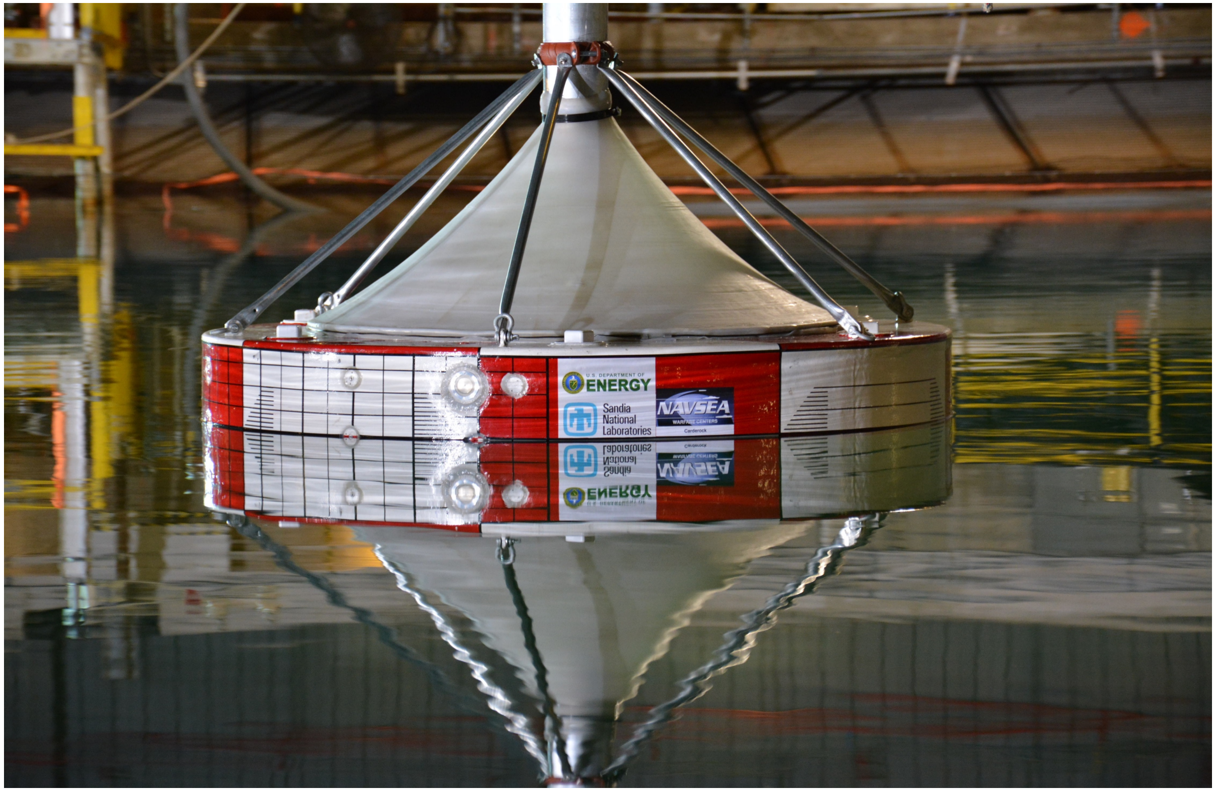
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Advanced WEC Controls

Ryan Coe
Sandia National Labs
phone: 505-845-9064; email: ryan.coe@sandia.gov
February 2017

Project Overview

Advanced WEC Controls: WEC control system is essential. Advanced control has the potential to greatly increase (200%+) energy absorption and improve overall performance. The current project will strongly support control design for current and future devices, and will impact design of future devices.

The Challenge: The gap between the impressive results reported in paper studies and open-ocean deployments comprises many non-trivial engineering problems, including state-estimation, nonlinear dynamics and hardware limitations.

Partners: Naval Surface Warfare Center, Carderock Division (tank testing); Michigan Technical University (controls and optimization); ATA engineering (structural dynamics)

Sandia National Laboratories

NAVSEA WARFARE CENTERS Carderock

Michigan Technological University 1885

ATA ENGINEERING, INC.

Increase MHK deployment in opportune markets

Technology Maturity

- Test and demonstrate prototypes
- Develop cost effective approaches for installation, grid integration, operations and maintenance
- Conduct R&D for Innovative MHK Systems and Components
- **Develop tools to optimize device and array performance and reliability**
- Develop and apply quantitative metrics to advance MHK technologies

Deployment Barriers

- Identify potential improvements to regulatory processes and requirements
- Support research focused on retiring or mitigating environmental risks and reducing costs
- Build awareness of MHK technologies
- Ensure MHK interests are considered in coastal and marine planning processes
- Evaluate deployment infrastructure needs and possible approaches to bridge gaps

Market Development

- Support project demonstrations to reduce risk and build investor confidence
- Assess and communicate potential MHK market opportunities, including off-grid and non-electric
- Inform incentives and policy measures
- Develop, maintain and communicate our national strategy
- Support development of standards
- Expand MHK technical and research community

Crosscutting Approaches

- Enable access to testing facilities that help accelerate the pace of technology development
- Improve resource characterization to optimize technologies, reduce deployment risks and identify promising markets
- Exchange of data information and expertise

Project Strategic Alignment

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Increase MHK deployment in opportune markets

Technology Maturity

- Test and demonstrate prototypes
- Develop cost effective approaches for installation, grid integration, operations and maintenance
- Conduct R&D for Innovative MHK Systems and Components
- **Develop tools to optimize device and array performance and reliability**
- Develop and apply quantitative metrics to advance MHK technologies

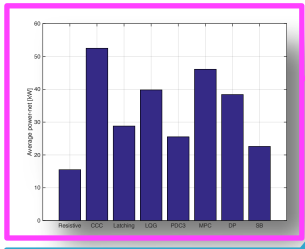
The Impact

- Control design, implementation, and testing for energy absorption increase:
  - 200% (numerical - complete)
  - 50% (closed loop tank test, planned FY17)
- Direct reduction in LCOE through
  - a) increased energy generation
  - b) reduce structural loads
- Empowering developers with key knowledge and proven methodologies to design and implement advanced control strategies for their devices (and therefore improve device design)

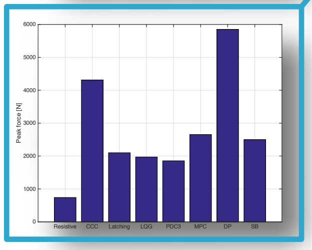
Technical Approach

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Power



PTO force



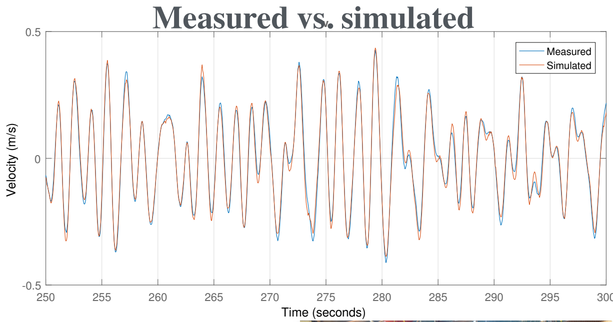
	Resistive	CCC	Latching	LQG	PDC3	Linear MPC	DP	SB
Power production characteristics								
Average power-in	0	279	0	46.5	45.8	98.8	374.8	39.0
Average power-net	15.5	52.5	28.8	39.8	25.5	46.1	38.4	22.6
Average energy-stored	0	251	0	27.5	42.9	76.4	332.9	23.8
Power-in, peak/RMS	0.0	5.8	0.0	5.6	5.1	5.6	5.4	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

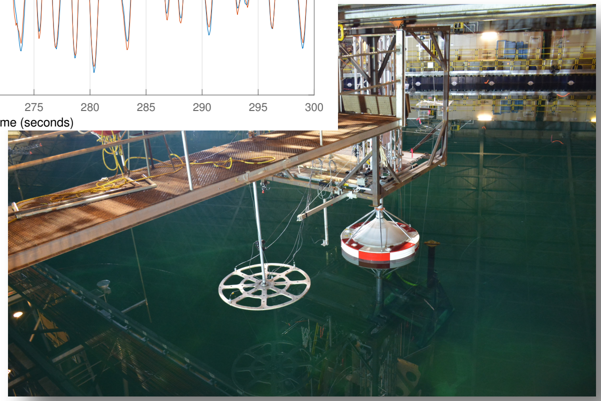
Wide ranges of WEC devices and control strategies

In-depth implementation and performance comparisons provide a roadmap for developers, informing future research paths

Current WEC dynamic models are insufficient for control

More accurate and efficient testing/data processing methodologies, allowing developers to produce better models and therefore better device performance

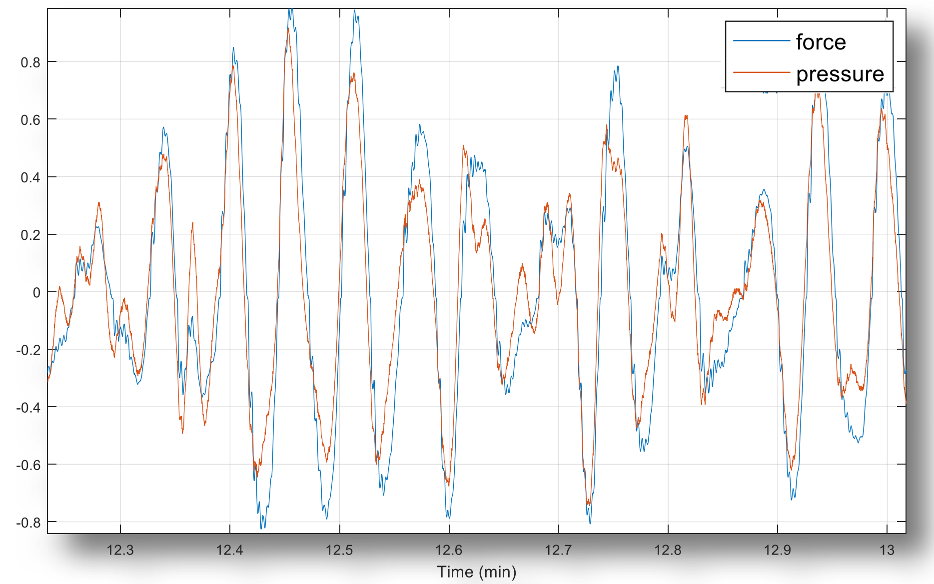




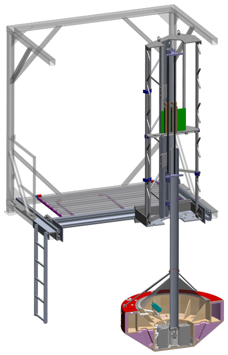
Technical Approach

Dynamics and control expertise
Leveraging extensive institutional dynamics and controls expertise (defense, aerospace) for WEC applications; introducing new WEC control strategies

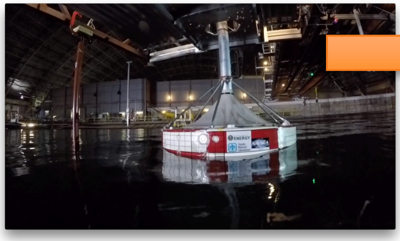
Knowledge in open-ocean deployment is limited
Pressure-based state estimation shows promising results to obviate need for remote wave sensing; advanced testing techniques for open-ocean system ID



Accomplishments and Progress



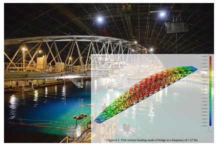
Design of experimental WEC for controls research



Testing, system identification and model validation with 1/20th scale WEC device

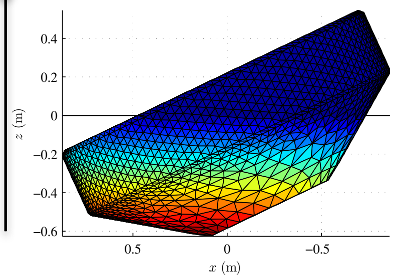
Public dataset and methods for testing/system ID

Control-structure interaction at large-scale

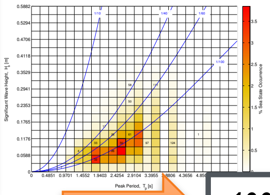


2014 | **2015** | **2016**

Numerical model for control design and assessment

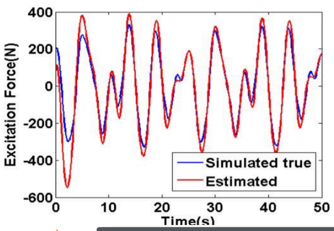


In-depth implementation and numerical comparison of 8 advanced WEC control strategies



100+% power absorption increase

Pressure-based modeling, providing more accurate predictions



Model formulations for increased accuracy

Roadmap to WEC controls and supporting methods, empowering developers for 100%+ energy absorption increase

Project Plan & Schedule

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Fiscal year	Quarter	Milestone/deliverable	Completed
FY14	Q1	Selection of wave tank facility for experimental testing	12/31/13
	Q2	Develop evaluation scheme for advanced control strategies	3/31/14
	Q3	Dynamic model of experimental WEC device.	6/30/14
	Q4	***Complete wave tank test plan***	***9/30/14***
FY15	Q1	Complete scale model build	9/30/2015
	Q2	Develop and assess performance of 3-6 control strategies	4/15/15
	Q3	***Show 100% improvement in absorbed power***	***5/15/15***
	Q4	Complete fabrication of physical model sub-systems (float, PCC tower, and PMT).	
FY16	Q1	PMPA wave tank test 1 test plan complete	12/31/16
	Q2	Public release of WEC controls comparison	3/31/16
		Complete PMPA wave tank test 1	***4/15/16***
	Q3	Industry webinar	6/6/16
	Q4	WEC controls comparison, V2	9/30/16
		Wave tank testing report	9/30/16
		Open publication of wave tank test data	9/30/16
		Develop state-estimation methodology to provide wave excitation for control and thus obviate the need for remote sensing of incoming waves	9/30/16
		Perform experimental testing and validation of nonlinear control models	9/30/16

SMART milestones shown in bold-italic

3 control strategies with 100%+ annual power increase

Improved system identification methods applicable to a wide range of devices

Novel excitation state-estimation modeling proposed and tested

Project Budget

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$500,000		$1,576,800*		$1,000,000	

- $500k of additional funding in FY15 to support model design and fabrication

Sandia's Advanced WEC Controls Project is targeted at reducing risk and cost for developers:

- System identification and tank testing methods increase test efficiency and improve results
- In-depth comparison and assessment of WEC controls provides an R&D roadmap for developers
- Novel sensing and state-estimation reduces sensor costs and complexity

Research Integration & Collaboration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Partners, Subcontractors, and Collaborators:

- **Naval Surface Warfare Center, Carderock Division (NSWCCD)** - Testing capabilities and collaborating to improve knowledge of MASK basin
- **Michigan Technical University (MTU)** – Control design and optimization expertise
- **ATA engineering** – Structural dynamics modeling and testing

Communications and Technology Transfer:

- **Most popular public dataset** on MHK-DR
- 14+ project publications
- 3 webinars
- 5 conference presentations
- Initial experimental and data acquisition design at MASK basin for Wave Energy Prize

Project publications

[1] R. Coe, G. Bacelli, O. Abdelkhalik, and D. Wilson, “An assessment of WEC control performance uncertainty,” in International Conference on Ocean, Offshore and Arctic Engineering (OMAE2017), in prep. Trondheim, Norway: ASME, 2017.

[2] G. Bacelli, R. Coe, O. Abdelkhalik, and D. Wilson, “WEC geometry optimization with advanced control,” in International Conference on Ocean, Offshore and Arctic Engineering (OMAE2017), in prep, Trondheim, Norway. ASME, 2017.

[3] O. Abdelkhalik, R. Robinett, S. Zou, G. Bacelli, R. Coe, D. Bull, D. Wilson, and U. Korde, “On the control design of wave energy converters with wave prediction,” Journal of Ocean Engineering and Marine Energy, pp. 1–11, 2016.

[4] O. Abdelkhalik, R. Robinett, S. Zou, G. Bacelli, R. Coe, D. Bull, D. Wilson, and U. Korde, “A dynamic programming approach for control optimization of wave energy converters,” in prep, 2016.

[5] O. Abdelkhalik, S. Zou, G. Bacelli, R. D. Robinett III, D. G. Wilson, and R. G. Coe, “Estimation of excitation force on wave energy converters using pressure measurements for feedback control,” in OCEANS2016. Monterey, CA: IEEE, 2016.

[6] G. Bacelli, R. G. Coe, D. Wilson, O. Abdelkhalik, U. A. Korde, R. D. Robinett III, and D. L. Bull, “A comparison of WEC control strategies for a linear WEC model,” in METS2016, Washington, D.C., April 2016.

[7] R. G. Coe, G. Bacelli, D. Patterson, and D. G. Wilson, “Advanced WEC dynamics & controls FY16 testing report,” Sandia National Labs, Albuquerque, NM, Tech. Rep. SAND2016-10094, October 2016.

[8] D. Wilson, G. Bacelli, R. G. Coe, D. L. Bull, O. Abdelkhalik, U. A. Korde, and R. D. Robinett III, “A comparison of WEC control strategies,” Sandia National Labs, Albuquerque, New Mexico, Tech. Rep. SAND2016-4293, April 2016 2016.

[9] D. Wilson, G. Bacelli, R. G. Coe, R. D. Robinett III, G. Thomas, D. Linehan, D. Newborn, and M. Quintero, “WEC and support bridge control structural dynamic interaction analysis,” in METS2016, Washington, D.C., April 2016.

[10] O. Abdelkhalik, S. Zou, R. Robinett, G. Bacelli, and D. Wilson, “Estimation of excitation forces for wave energy converters control using pressure measurements,” International Journal of Control, pp. 1–13, 2016.

[11] S. Zou, O. Abdelkhalik, R. Robinett, G. Bacelli, and D. Wilson, “Optimal control of wave energy converters,” Renewable Energy, 2016.

[12] J. Song, O. Abdelkhalik, R. Robinett, G. Bacelli, D. Wilson, and U. Korde, “Multi-resonant feedback control of heave wave energy converters,” Ocean Engineering, vol. 127, pp. 269–278, 2016.

[13] O. Abdelkhalik, R. Robinett, G. Bacelli, R. Coe, D. Bull, D. Wilson, and U. Korde, “Control optimization of wave energy converters using a shape-based approach,” in ASME Power & Energy, San Diego, CA, 2015.

[14] D. L. Bull, R. G. Coe, M. Monda, K. Dullea, G. Bacelli, and D. Patterson, “Design of a physical point-absorbing WEC model on which multiple control strategies will be tested at large scale in the MASK basin,” in International Offshore and Polar Engineering Conference (ISOPE2015), Kona, HI, 2015.

[15] R. G. Coe and D. L. Bull, “Sensitivity of a wave energy converter dynamics model to nonlinear hydrostatic models,” in Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2015). St. John’s, Newfoundland: ASME, 2015.

[16] D. Patterson, D. Bull, G. Bacelli, and R. Coe, “Instrumentation of a WEC device for controls testing,” in Proceedings of the 3rd Marine Energy Technology Symposium (METS2015), Washington DC, Apr. 2015.

[17] R. G. Coe and D. L. Bull, “Nonlinear time-domain performance model for a wave energy converter in three dimensions,” in OCEANS2014. St. John’s, Canada: IEEE, 2014.

Next Steps and Future Research

FY17/Current research:

- Implementation of real-time closed-loop control
- Increasingly nonlinear systems
- Transition from 1-DOF to 3-DOF control
- Full wave-to-wire control
- Annual WEC dynamics and controls workshops held in conjunction with METS
- Industry partner collaboration – Apply control design to developer device; layout framework for collaboration in FY17

Proposed future research:

- Verify device-agnostic methods – Apply dynamics modeling, control design and implementation methods to a second device (possibly existing EERE-funded model or developer device)
- Control of arrays