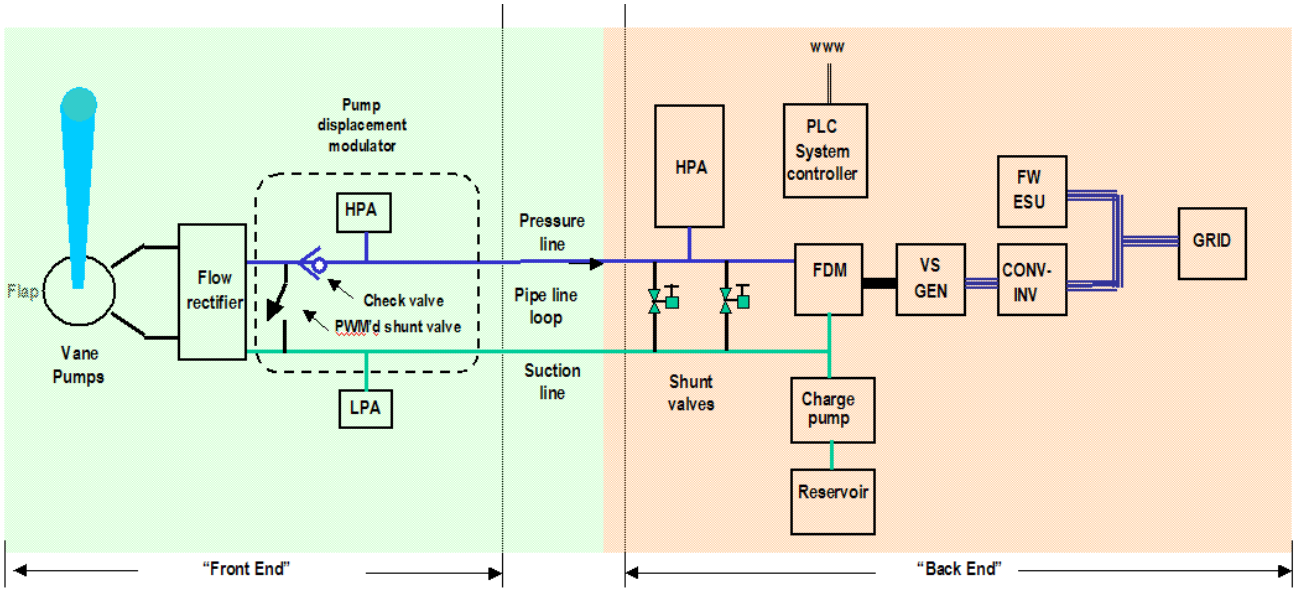

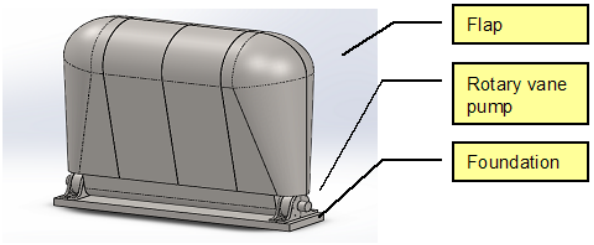

Optimal Control of a Surge-Mode WEC in Random Waves

William Staby/Mirko Previsic

Resolute Marine Energy/Re Vision
wstaby@resolutemarine.com – 917.626.6790

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Project Overview

- Optimal Control of a Surge-Mode WEC in Random Waves
  - Increase energy capture efficiency of surge-mode wave energy converter (WEC) (“flap”)
  - Via causal or non-causal *real-time* control of power take-off (PTO) reaction torque vs slowly adjusted Coulomb damping (baseline)
  - Reduce levelized cost of electricity (LCOE)
- Challenges
  - Create *PTO loss* model and link to existing flap model to form a *plant* model
  - Create causal and non-causal controllers
  - Determine how to modulate hydraulic PTO reaction torque in real-time
  - Evaluate flap performance improvement
  - Assess added component capital expenditures (CAPEX)/ operational expenditures (OPEX) and LCOE impact
- Partners
  - University of Michigan – Dr. Jeffrey Scruggs – causal controllers
  - Re Vision Consulting – Mr. Mirko Previsic – non-causal controllers
  - University of Minnesota – Dr. James Van de Ven – switch-mode PTO control

Program Strategic Priorities

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

Technology Maturity

- Test and demonstrate prototypes
- Develop cost effective approaches for installation, grid integration, operations and maintenance
- **Conduct R&D for innovative MHK systems & 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

Technology Maturity

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

The Impact

- The primary figure of merit (metric) for this project is the LCOE associated with the implementation of causal and non-causal control systems versus baseline Coulomb damping, which RME has used in past experiments.
- The impact this research may have on the industry is to reduce LCOE by a significant amount.
- This project's endpoint/output product is a theoretical estimate of the improvement in LCOE achieved by advanced control. A more realistic LCOE was not achieved due to a cut-back in funding at the Go/No-Go midpoint of the project.

Increase MHK deployment in opportune markets

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**

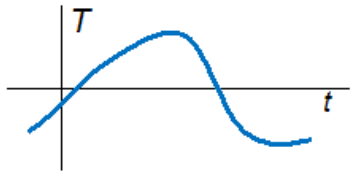
The Impact

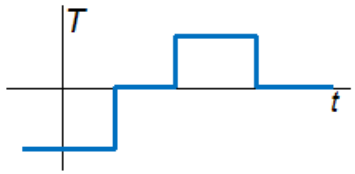
- This project has already generated a scholarly paper on the subject of causal control systems (Scruggs: University of Michigan) and project sub-contractor Re Vision Consulting may publish the results of its research into non-causal control systems at the conclusion of its System Performance Advancement (SPA)-2 Controls project.
- RME shared its LCOE model with the National Renewable Energy Laboratory (NREL), and it would be fair to say that several deficiencies in the NREL model were identified.

Technical Approach

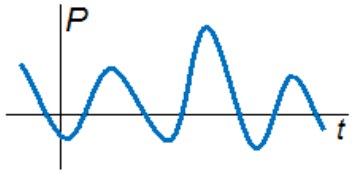
- Evaluate four causal and four non-causal controller configurations
  - Continuous or Bi-Polar PTO pump torque control
    - Uni-directional power from flap pump to on-shore hydraulic motor-generator
    - Bi-directional power to and from shore terminal (improve flap power factor)

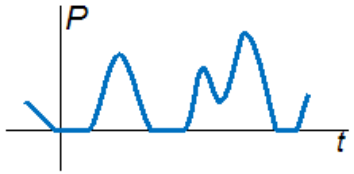
Continuous or Bi-Polar flap load torque





Uni or bi-directional power flow capability





Option 4	Option 3
Option 2	Option 1

Technical Approach

- Key issues to be addressed
  - Refine hydraulic PTO model – especially pipe line loss and dynamics
    - Resolute Marine Energy (RME) as subcontractor to Re Vision for SPA2
    - Allan Chertok PI
    - Assisted by Dr. James Van de Ven and associate
  - Validate RME numerical flap model – especially viscous damping coefficient
    - Re Vision SPA2 tank testing with simulated PTO load
  - Validate Re Vision wave forecasting model for non-causal controllers
    - Re Vision SPA2 ocean trials with seaward wave forecasting sensor array
- Novel RME switch-mode control of flap pump torque
  - Apply established power electronic control methods to hydraulics
  - Enable real-time modulation of flap pump reaction torque – i.e., flap load
- LCOE Analysis
  - Follow NREL methodology with adjustments for deep water reference site
  - Proposal anticipated reduction of LCOE from 0.44 to 0.26 $/kWh
  - Achieved 0.39 and 0.36 $/kWh for least and most complex solutions respectively

Accomplishments and Progress

- Identified potential flap capture efficiency gains over Coulomb damping for four real-time causal and four real-time non-causal controllers

  Assumptions

  - Cutoff wave height H_c = 3.75m (inclusive)
  - PTO rating P_{rat} varied between 25 and 200 kW
  - Option 3 & 1 results reflect optimization of T_0 over all possible values

  Performance metrics independent of P_{rat}

Information option	Power train option	E_{inc} (GWh)	E_{abs} (GWh)	Q	Q_B
Causal	4	1.84	0.68	0.37	145%
	2	1.84	0.64	0.35	137%
	3	1.84	0.61	0.33	131%
	1	1.84	0.62	0.34	134%
Non-causal	4	1.84	0.88	0.48	188%
	2	1.84	0.75	0.41	161%
	3	1.84	0.83	0.45	177%
	1	1.84	0.73	0.40	157%
Baseline		1.84	0.47	0.25	100%

- RME SPA1 proposal anticipated improvement of 163%

Project Plan & Schedule

- RME SPA1 project original initiation date and completion date
  - February 1, 2014
  - August 31, 2016

- Explanation for slipped milestones and slips in schedule
  - Renegotiation of Statement of Project Objectives (three times)
  - Hardware-in-the-loop test of advanced controls not funded

Project Budget

Budget History					
FY2014		FY2015		FY2016	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$402.449k	$121.311k (30%)	$808.749k	$202.913k (25%)	$808.749k	$202.913k (25%)

- Federal share of the total budget was exhausted 100% in December 2015 due to confusion with respect to budget reductions applied over the course of three contract modifications
- RME's budget increase request (April 2016) was denied
- RME self-funded eight-month gap between full utilization of federal funding share (December 2015) and project conclusion (August 2016)
- Total added RME financial burden approximately $100,000

Research Integration & Collaboration

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

Partners, Subcontractors, and Collaborators:

- University of Michigan – Dr. Jeffrey Scruggs – causal controllers
- Re Vision Consulting – Mr. Mirko Previsic – non-causal controllers
- University of Minnesota – Dr. James Van de Ven – Switch-mode PTO control

Communications and Technology Transfer

European Wave and Tidal Energy Conference 2015 presentation by Prof. Jeffrey Scruggs

- Analytical approximations for design of optimal causal controllers for WECs with nonlinear dynamics and loss models

Next Steps and Future Research

Proposed future research:

Refinement of causal and non-causal, real-time flap load controllers—and switch-mode PTO torque control means to implement them—underway by Re Vision with RME as sub-contractor under SPA2 program

- Refine PTO model
- Integrate with existing RME numerical model of flap hydrodynamic performance
- Wave tank tests to validate flap model
- Ocean trials to validate wave forecasting method for non-causal control