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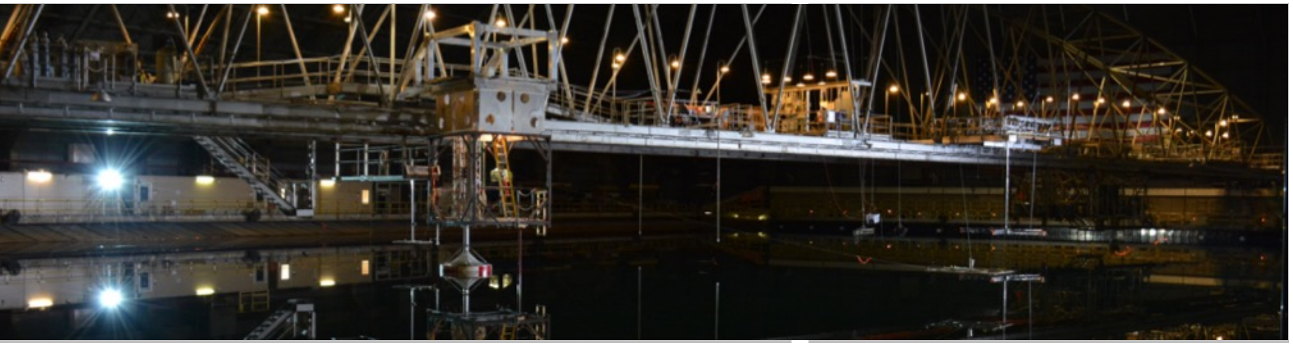


State estimation

Advanced WEC Dynamics and Controls

Giorgio Bacelli, Ryan Coe

April 12 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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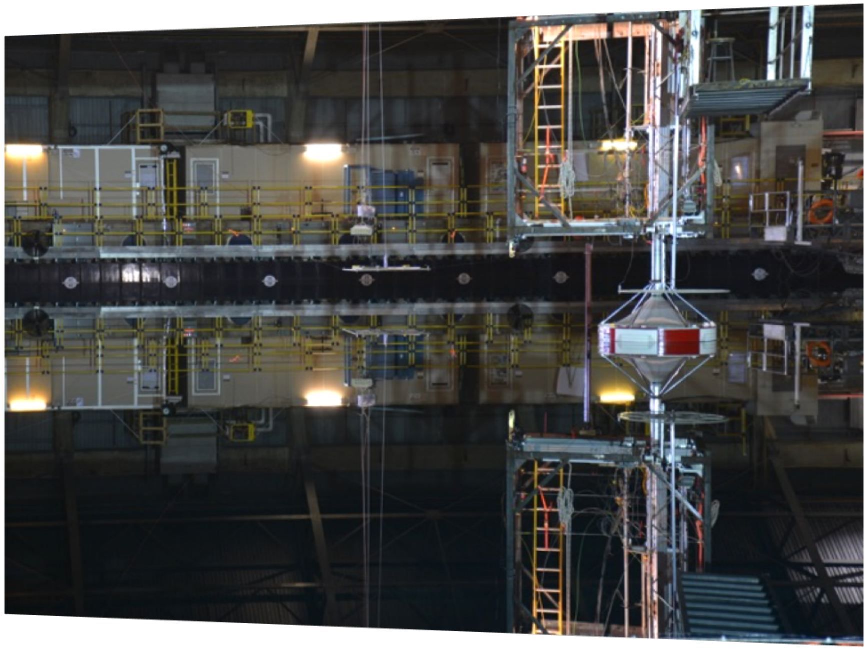
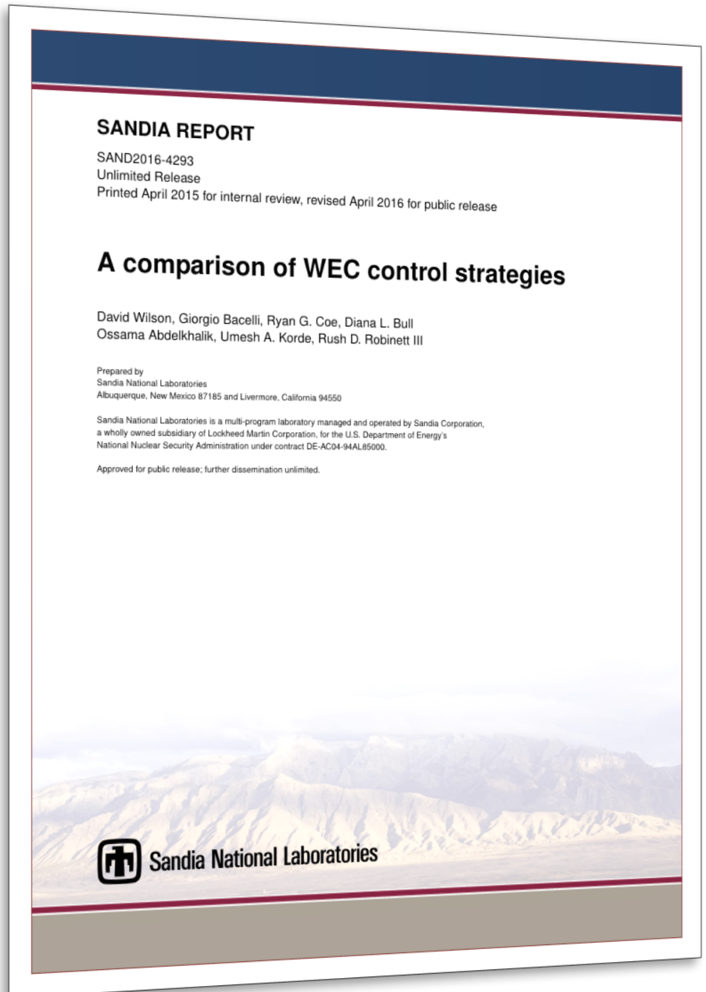
Project motivation

- Numerous studies have shown large benefits of more advanced control of WECs (e.g., Hals et al. showed 330% absorption increase)
- Most studies rely on significant simplifications and assumptions
  - Availability of incoming wave foreknowledge
  - 1-DOF motion
  - Linear or perfectly know hydrodynamics
  - No sensor noise
  - Unlimited actuator (PTO) performance



Project goal: accelerate/support usage of advanced WEC control by developers

Control strategy comparison


SANDIA REPORT

SAND2016-4293
Unlimited Release
Printed April 2015 for internal review, revised April 2016 for public release

A comparison of WEC control strategies

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

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Initial comparison completed and published (METS and SAND report)

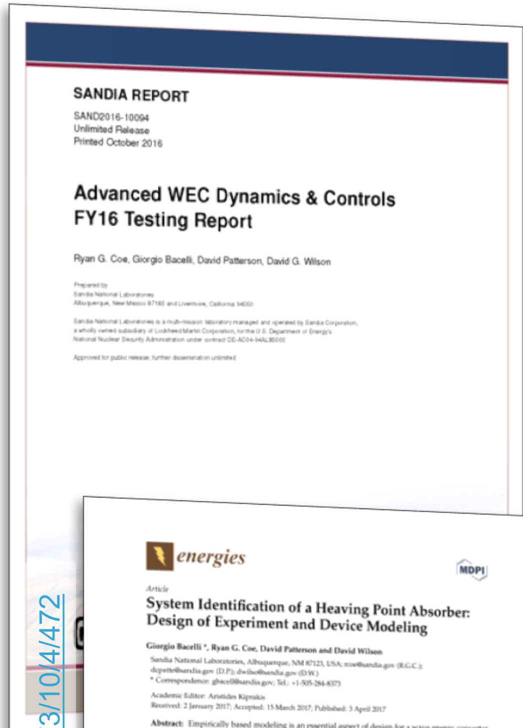
- Multiple **novel strategies** applied to WECs
- Relative power improvement offered by 8 control strategies
- **"Cost-to-implement" metrics**
- **Roadmap to WEC control** w/ in-depth discussion/instructions for implementation

http://energy.sandia.gov/wordpress/../wp-content/uploads/dlm_uploads/2016/06/SAND2016-4293.pdf

Testing and system identification

https://mhkdr.openei.org/submissions/151

http://www.mdpi.com/1996-1073/10/4/472



SANDIA REPORT

SAND2016-10094
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Printed October 2016

Advanced WEC Dynamics & Controls FY16 Testing Report

Ryan G. Coe, Giorgio Bacelli, David Patterson, David G. Wilson

Prepared by
Sandia National Laboratories
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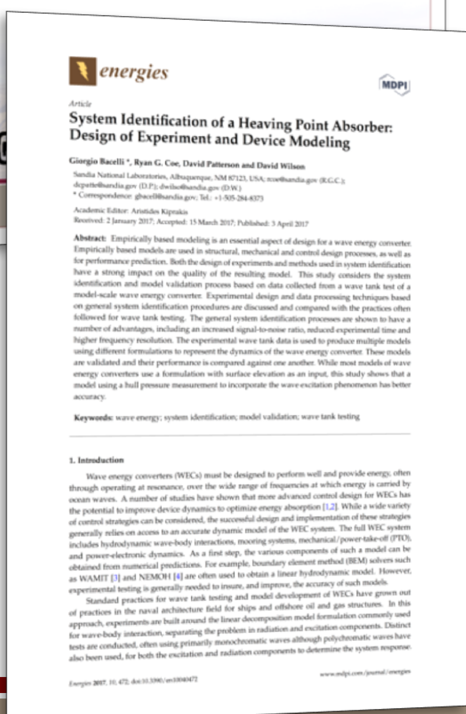

energies

MDPI

Article

System Identification of a Heaving Point Absorber: Design of Experiment and Device Modeling

Giorgio Bacelli *, Ryan G. Coe, David Patterson and David Wilson

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Abstract: Empirically based modeling is an essential aspect of design for a wave energy converter. Empirically based models are used in structural, mechanical and control design processes, as well as for performance prediction. Both the design of experiments and methods used in system identification have a strong impact on the quality of the resulting model. This study considers the system identification and model validation process based on data collected from a wave tank test of a model-scale wave energy converter. Experimental design and data processing techniques based on general system identification procedures are discussed and compared with the practices often followed for wave tank testing. The general system identification processes are shown to have a number of advantages, including an increased signal-to-noise ratio, reduced experimental time and higher frequency resolution. The experimental wave tank data is used to produce multiple models using different formulations to represent the dynamics of the wave energy converter. These models are validated and their performance is compared against one another. While most models of wave energy converters use a formulation with surface elevation as an input, this study shows that a model using a hull pressure measurement to incorporate the wave excitation phenomenon has better accuracy.

Keywords: wave energy; system identification; model validation; wave tank testing

1. Introduction

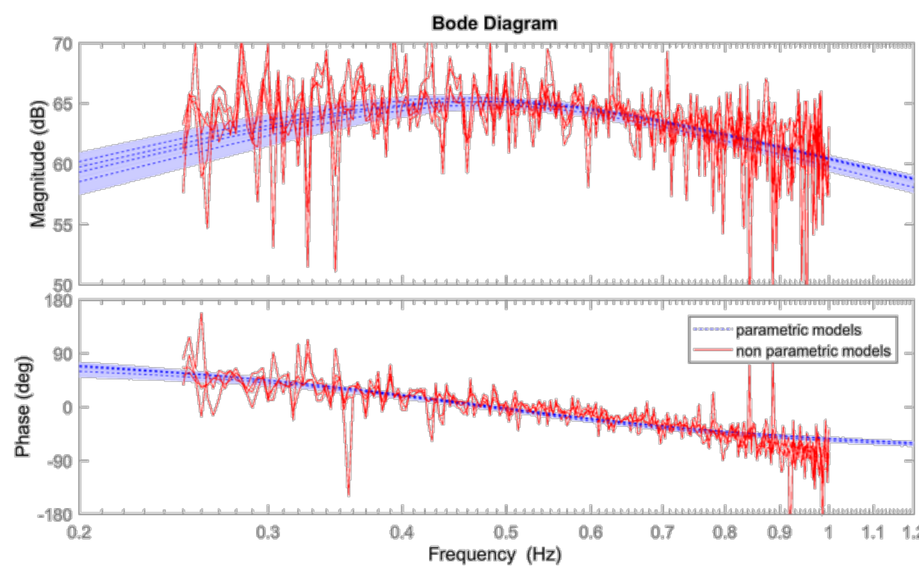
Wave energy converters (WECs) must be designed to perform well and provide energy, often through operating at resonance, over the wide range of frequencies at which energy is carried by ocean waves. A number of studies have shown that more advanced control design for WECs has the potential to improve device dynamics to optimize energy absorption [1,2]. While a wide variety of control strategies can be considered, the successful design and implementation of these strategies generally relies on access to an accurate dynamic model of the WEC system. The full WEC system includes hydrodynamic wave-body interactions, mooring systems, mechanical/power-take-off (PTO), and power-electronic dynamics. As a first step, the various components of such a model can be obtained from numerical predictions. For example, boundary element method (BEM) solvers such as WAMIT [3] and NEMOH [4] are often used to obtain a linear hydrodynamic model. However, experimental testing is generally needed to insure, and improve, the accuracy of such models.

Standard practices for wave tank testing and model development of WECs have grown out of practices in the naval architecture field for ships and offshore oil and gas structures. In this approach, experiments are built around the linear decomposition model formulation commonly used for wave-body interaction, separating the problem in radiation and excitation components. Distinct tests are conducted, often using primarily monochromatic waves although polychromatic waves have also been used, for both the excitation and radiation components to determine the system response.

Energies 2017, 10, 472; doi:10.3390/en10040472 www.mdpi.com/journal/energies

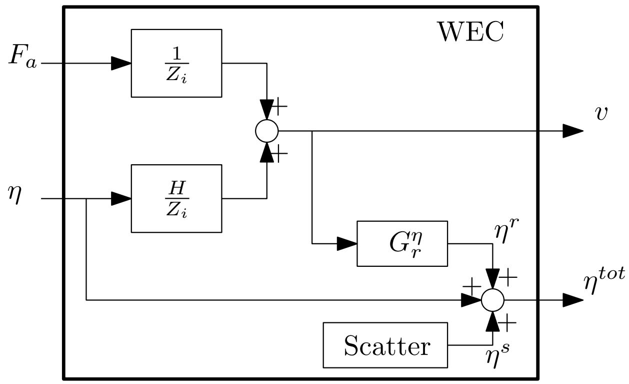
Wave tank testing results and analysis

- Raw data available for download (MHK-DR)
- Experimental design for wave tank testing of WECs
- System identification methods
- Model formulation and validation
- Pressure-based model for excitation



System identification

Dual SISO



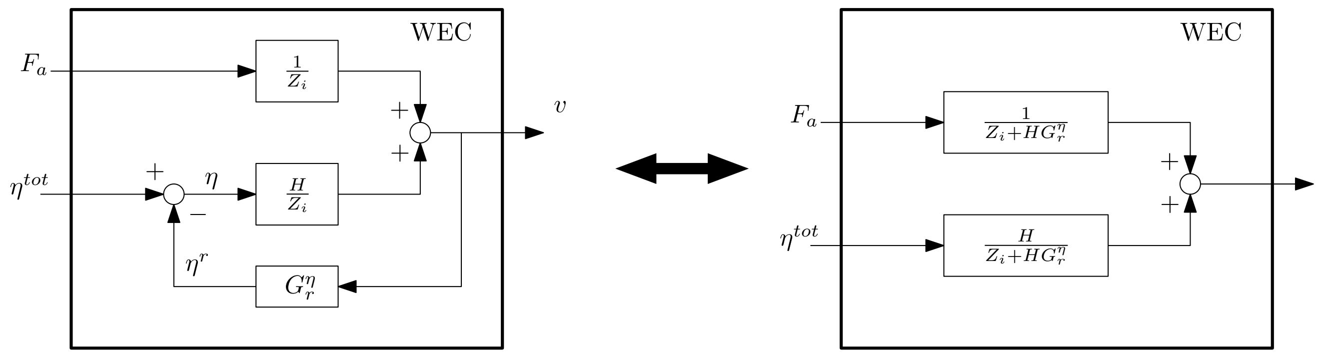
$$\left(B(\omega) + B_f + i\left(\omega\left(M + A(\omega)\right) - \frac{K}{\omega}\right)\right)\hat{V} = H(\omega)\,\hat{\eta} + \hat{F}_a$$

$$\hat{F}_e = H(\omega)\,\hat{\eta}$$

$$Z_i(\omega) = B(\omega) + B_f + i\left(\omega\left(M + A(\omega)\right) - K/\omega\right)$$

$$\hat{V} = \frac{H(\omega)}{Z_i(\omega)}\,\hat{\eta} + \frac{1}{Z_i(\omega)}\hat{F}_a.$$

$$\begin{aligned} v &= \frac{1}{Z_i}F_a + \frac{H}{Z_i}\eta \\ &= \frac{1}{Z_i}F_a + \frac{H}{Z_i}(\eta^{tot} - \eta^r) \\ &= \frac{1}{Z_i}F_a + \frac{H}{Z_i}(\eta^{tot} - G_r^\eta v) \end{aligned}$$



$$v = \frac{1}{Z_i + HG_r^\eta}F_a + \frac{H}{Z_i + HG_r^\eta}\eta^{tot}\Bigg|_{G_r^\eta \to 0} \approx \frac{1}{Z_i}F_a + \frac{H}{Z_i}\eta^{tot}$$

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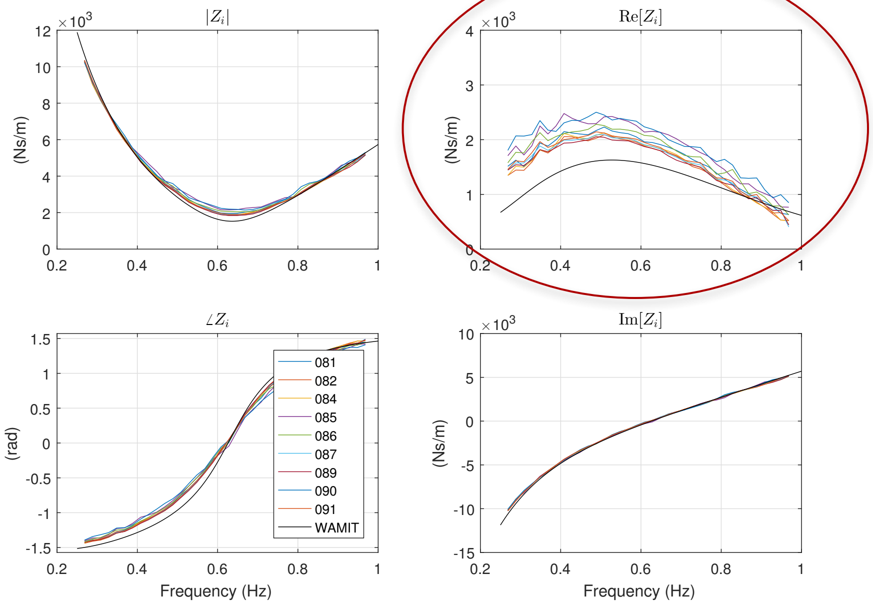
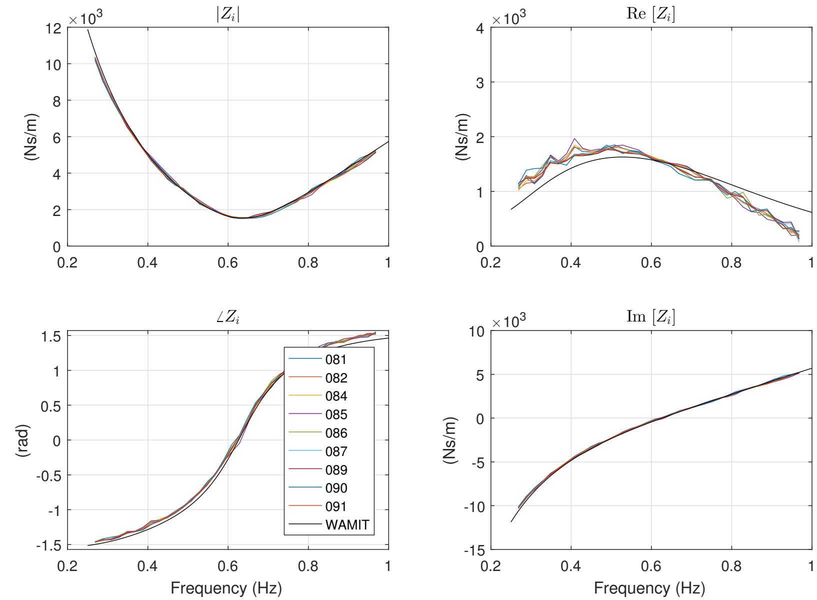
System identification

Local linear models

Results depend on test amplitude, nonlinear?





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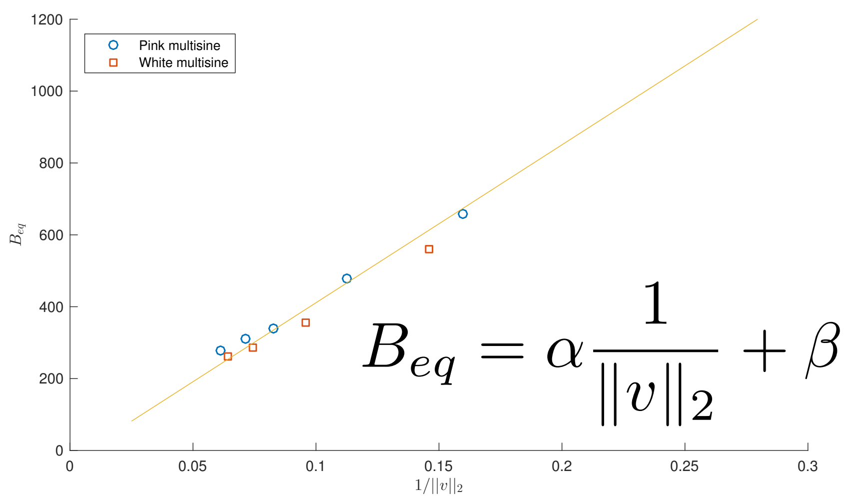
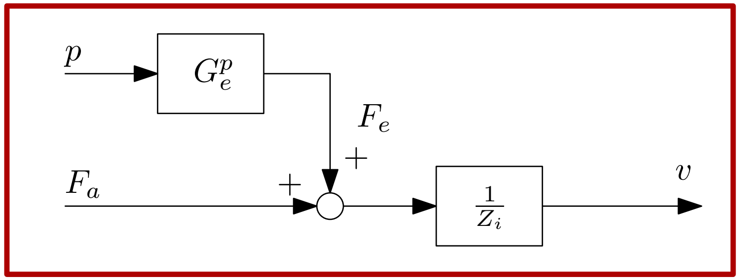


$$B_{eq} = \alpha \frac{1}{\|v\|_2} + \beta$$

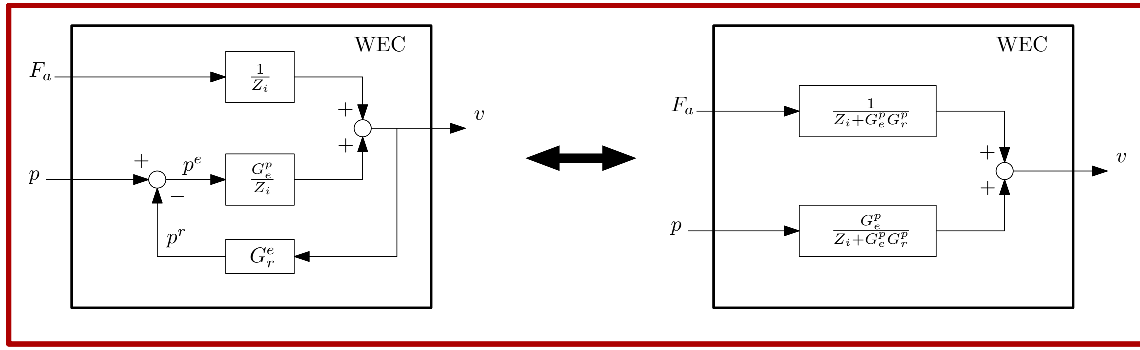
System identification

Pressure based models

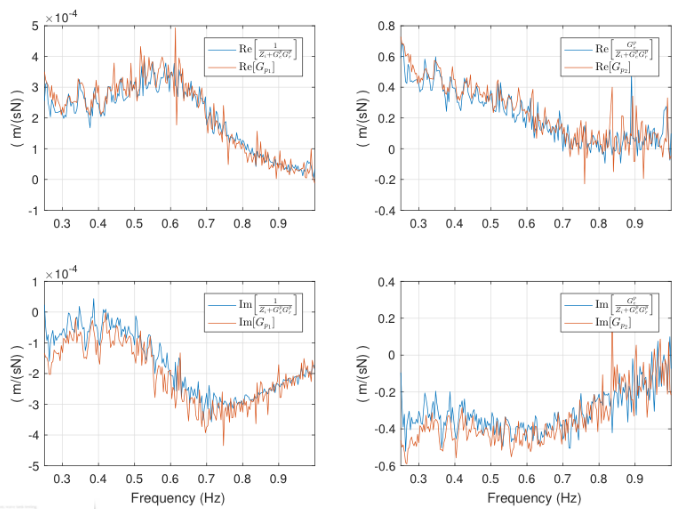
Dual SISO



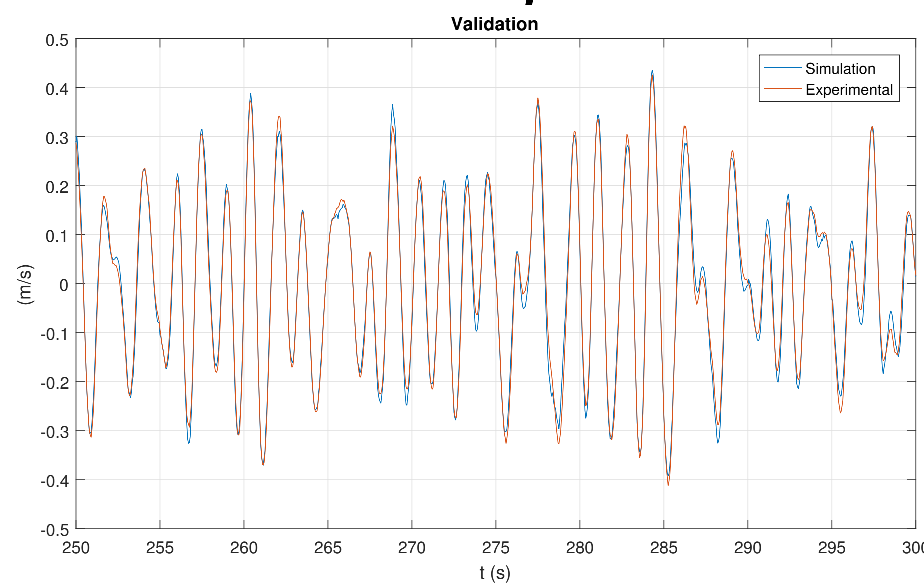
MISO



Dual SISO vs. MISO



MISO vs. experiment



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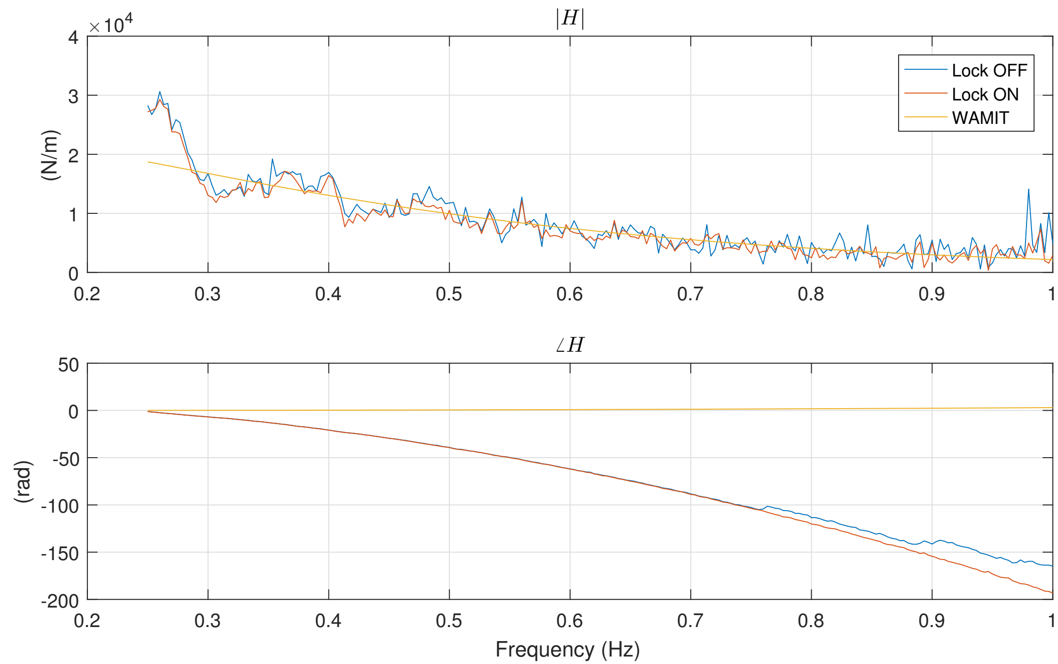
System identification

At-sea modeling

1. Execute forced oscillation experiments in calm water to obtain a model of the intrinsic impedance and obtain either a parametric or nonparametric model for Zi.
2. Execute the forced oscillation experiment in presence of waves. In this case, the available measurements are the actuator force (Fa), the buoy velocity (v) and the surface elevation (η). By using the frequency-domain equation of motion it is possible to write the excitation FRF as function of the known quantities as:

$$\hat{F}_e(\omega) + \hat{F}_a(\omega) = Z_i(\omega)\,\hat{V}(\omega), \qquad \text{with} \qquad \hat{F}_e(\omega) = H(\omega)\hat{\eta}(\omega)$$

$$H(\omega) = \frac{Z_i(\omega)\,\hat{V}(\omega) - \hat{F}_a(\omega)}{\hat{\eta}(\omega)}$$



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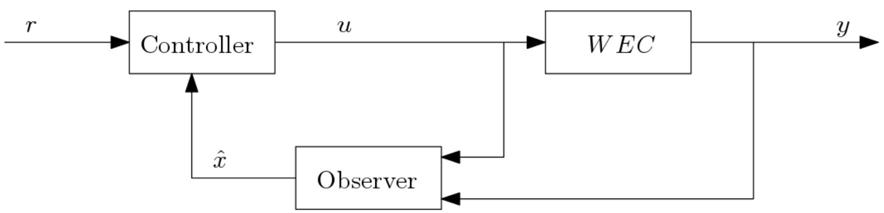
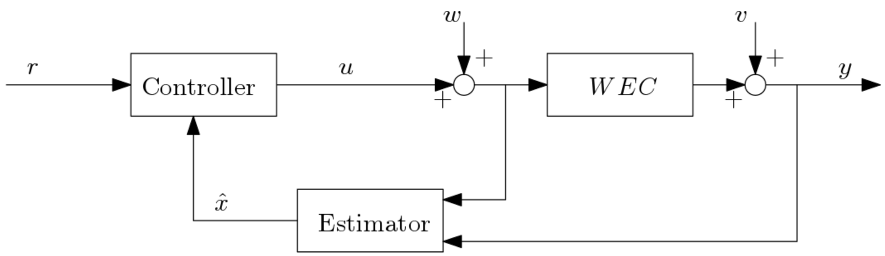
State observers and state estimators

Observer



Estimator



WEC model

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

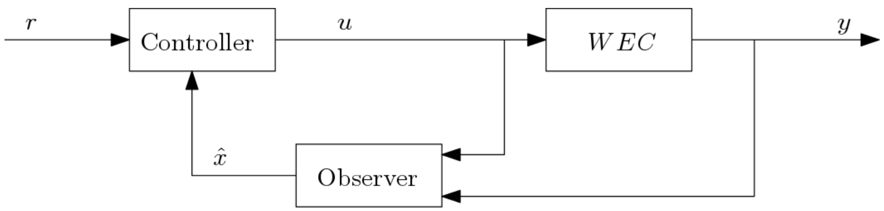
WEC model

$$\dot{x} = Ax + Bu + w$$
$$y = Cx + Du + v$$

u = control signal (e.g. reference for PTO force)
$\hat{x}$ = estimated state (e.g. velocity, radiation)
y = output measured quantities (e.g. position, acceleration, force, pressure)
w = process noise
v = measurement noise
r = reference (e.g. Reference PTO force, reference optimal velocity)

- WHY?
  - Control system designed to make use of state information have generally better performance

Observers



Discrete time observer

$$\hat{x}_{k+1} = A\hat{x}_k + L[y_k - \hat{y}_k] + Bu_k$$
$$\hat{y}_k = C\hat{x}_k + Du_k$$

WEC model

$$x_{k+1} = Ax_k + Bu_k$$
$$y = Cx_k + Du_k$$

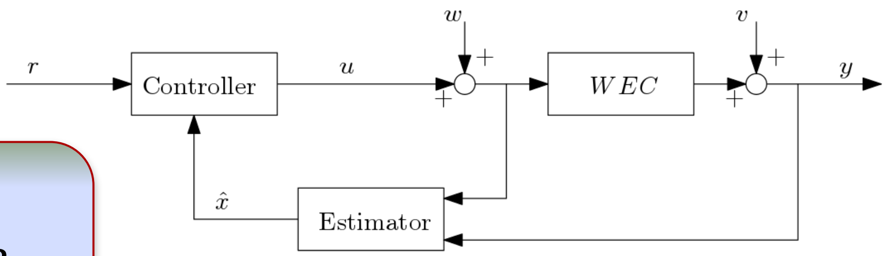
$e_k = \hat{x}_k - x_k$ (observer error)

$e_{k+1} = (A - LC)e_k$ (observer error dynamic)

If stable $\Rightarrow$ $e_k \to 0$ and $\hat{x}_k \to x_k$

- Basic state observer (Luenberger observer)
- The design of an observer is the design of a stable control system: choose L so that (A-LC) is stable

Kalman filter (Estimator)



Discrete time KF

$$\hat{x}_{k+1|k} = A\hat{x}_{k|k-1} + AK_k\left(y_k - C\hat{x}_{k|k-1}\right) + Bu_k$$

Similar structure to the observer but gain K_k is optimized

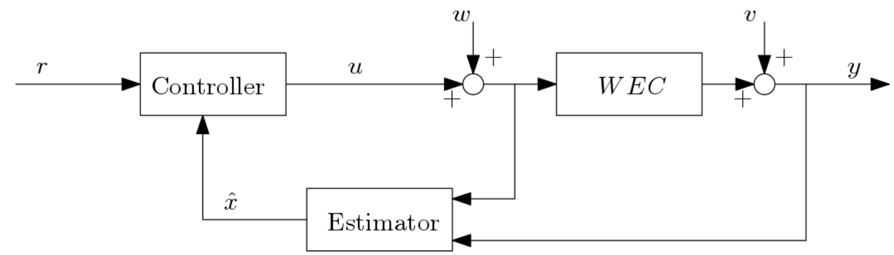
WEC model

$$x_{k+1} = Ax_k + Bu_k + w_k$$
$$y = Cx_k + Du_k + w_k$$

$$P_{k+1|k} = AP_{k|k}A^T + Q$$
$$K_k = P_{k|k-1}C^T\left(CP_{k|k-1}C^T + R\right)^{-1}$$
$$P_{k|k} = (I - K_kC)P_{k|k-1}$$

- Optimal estimator: minimize the covariance matrix of the error on the state (under certain conditions)
- The design of an observer is the design of a stable control system

Kalman filter (Estimator)



Steady state Kalman filter

$$\hat{x}_{k+1|k} = A\hat{x}_{k|k-1} + Bu_k + K_\infty\left(y_k - C\hat{x}_{k|k-1}\right)$$

$$K_\infty = \lim_{k\to\infty} K_k$$

Measurements at time step *k*

Input at time step *k*

WEC model

$$x_{k+1} = Ax_k + Bu_k + w_k$$
$$y = Cx_k + Du_k + w_k$$

- Much simpler implementation
- Much faster computation
- K_∞ and P_∞ can be precomputed using MATLAB “dare” function

$$P_\infty = AP_\infty A^T - AP_\infty C^T\left(CP_\infty C^T + R\right)^{-1} CP_\infty A^T$$
$$K_\infty = P_\infty C^T\left(CP_\infty C^T + R\right)^{-1}$$

Estimation for WECs: objectives

- Limited number of measurements are available when at sea
- For control purposes, it is useful to know:
  - states of the WEC that cannot be measured directly, e.g. velocity and loads on the structure
  - Forces due to the waves, e.g. excitation force (excitation force is an external force)

Estimation for WECs: literature

- Some good literature is available, but strong assumptions on available measurements. E.g. estimation of excitation force when full state is available (Position, velocity,…)
- These measurements are not available for a floating device.
- Velocity difficult to measure directly. If differentiated from position it can be noisy, and noise is not independent from position.
- Excitation is assumed to be part of the state and the state vector is augmented. It works well, however there is a lag in the estimation and model does not reflect the actual physics

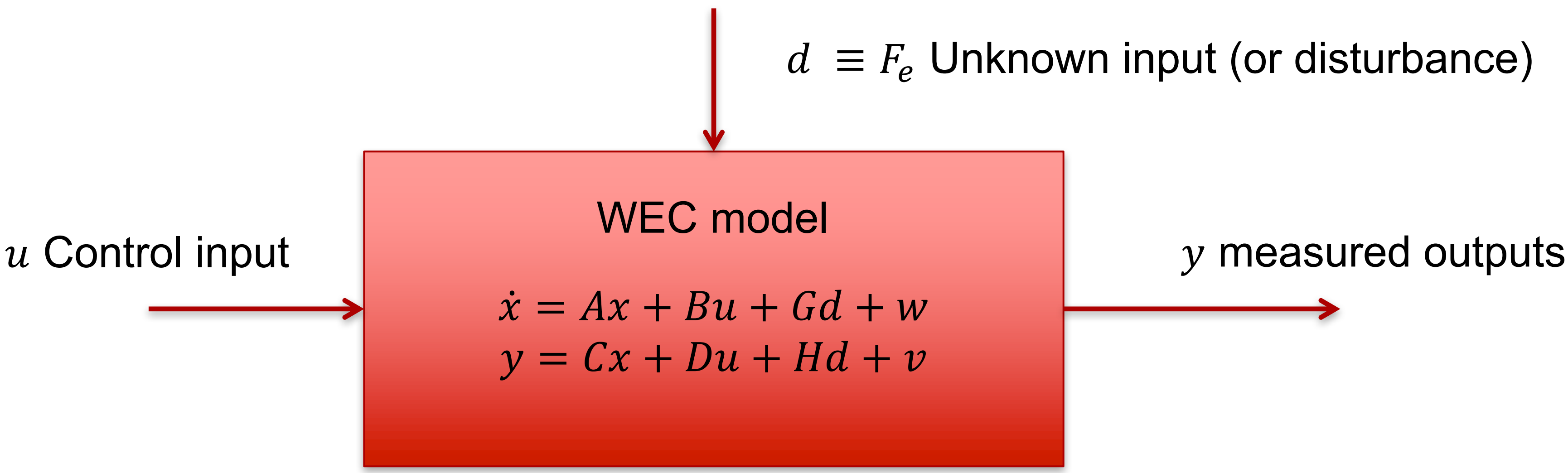
- B. A. Ling and B. A. Batten, "Real Time Estimation and Prediction of Wave Excitation Forces on a Heaving Body," in *Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2015)*, St. Johnś, Newfoundland, 2015.
- P. Kracht, S. Perez-Becker, J. B. Richard, and B. Fischer, "Performance Improvement of a Point Absorber Wave Energy Converter by Application of an Observer-Based Control: Results From Wave Tank Testing," *IEEE Transactions on Industry Applications*, vol. 51, no. 4, pp. 3426–3434, Jul. 2015.
- M. Abdelrahman, R. Patton, B. Guo, and J. Lan, "Estimation of wave excitation force for wave energy converters," in *2016 3rd Conference on Control and Fault-Tolerant Systems (SysTol)*, 2016, pp. 654–659.
- …

Realistic scenarios

- WEC connected to fixed reference
  - Measurements: Position and acceleration
- Floating WEC:
  - Pressure and acceleration (no information on position on a floating body)

Framework

- Simultaneous estimation of state and unknown inputs
  - Excitation force is considered an unknown input
  - It is a generalization of the Kalman filter

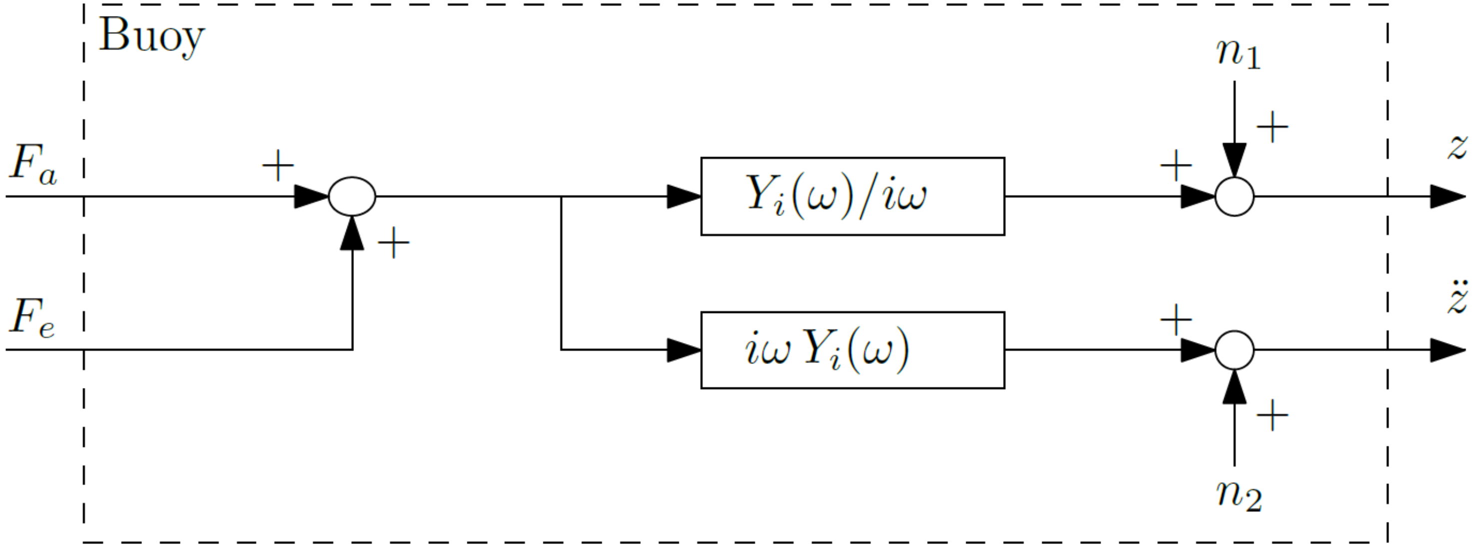


[1] S. Z. Yong, M. Zhu, and E. Frazzoli, "A unified filter for simultaneous input and state estimation of linear discrete-time stochastic systems," *Automatica*, vol. 63, pp. 321–329, 2016.

Case 1: position and acceleration

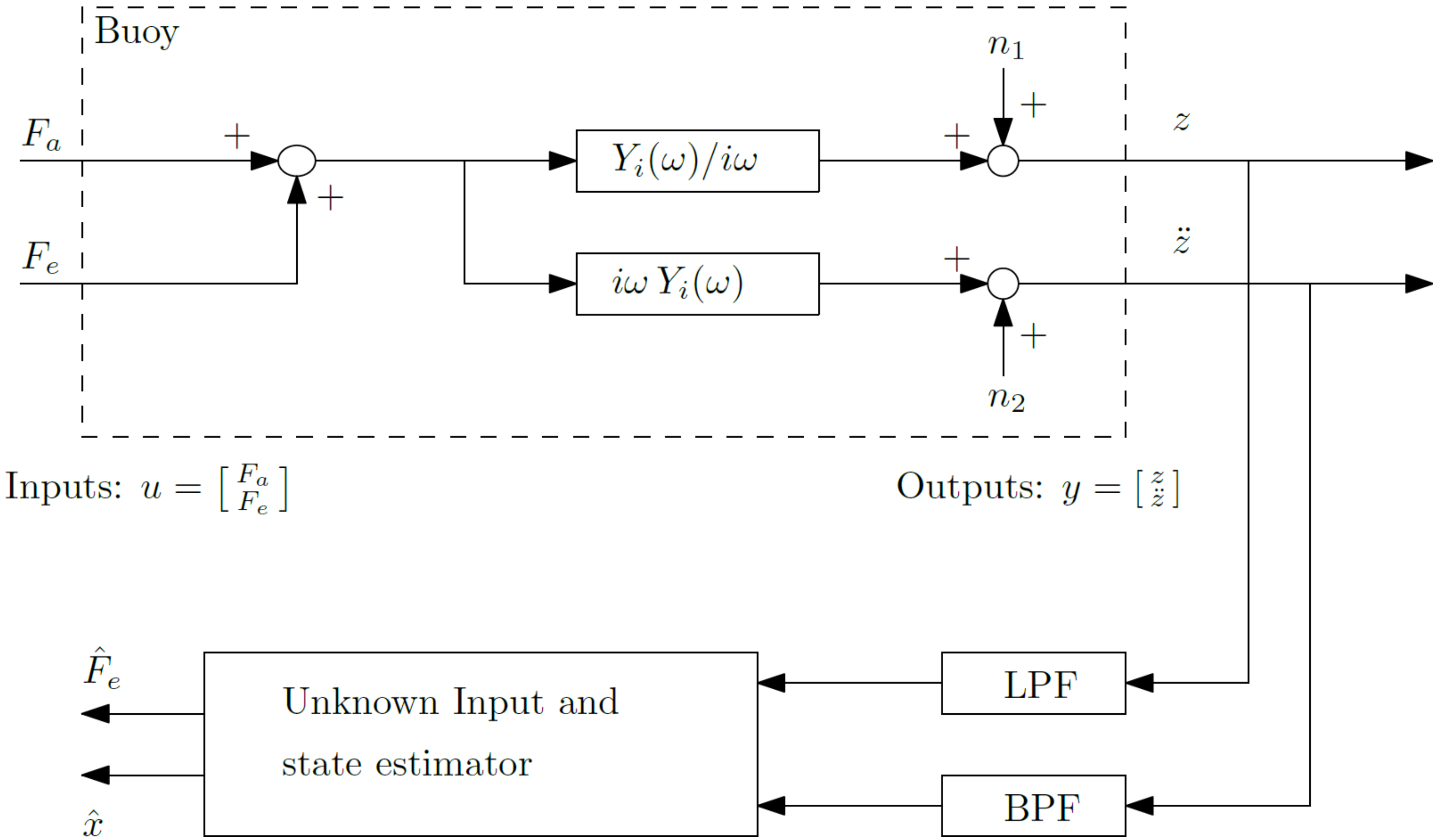
- Measurements
  - Position (encoder, potentiometer..)
  - acceleration (accelerometer)

Models have been identified from experimental data



Inputs: $u = \begin{bmatrix} F_a \\ F_e \end{bmatrix}$ Outputs: $y = \begin{bmatrix} z \\ \ddot{z} \end{bmatrix}$

Case 1: position and acceleration

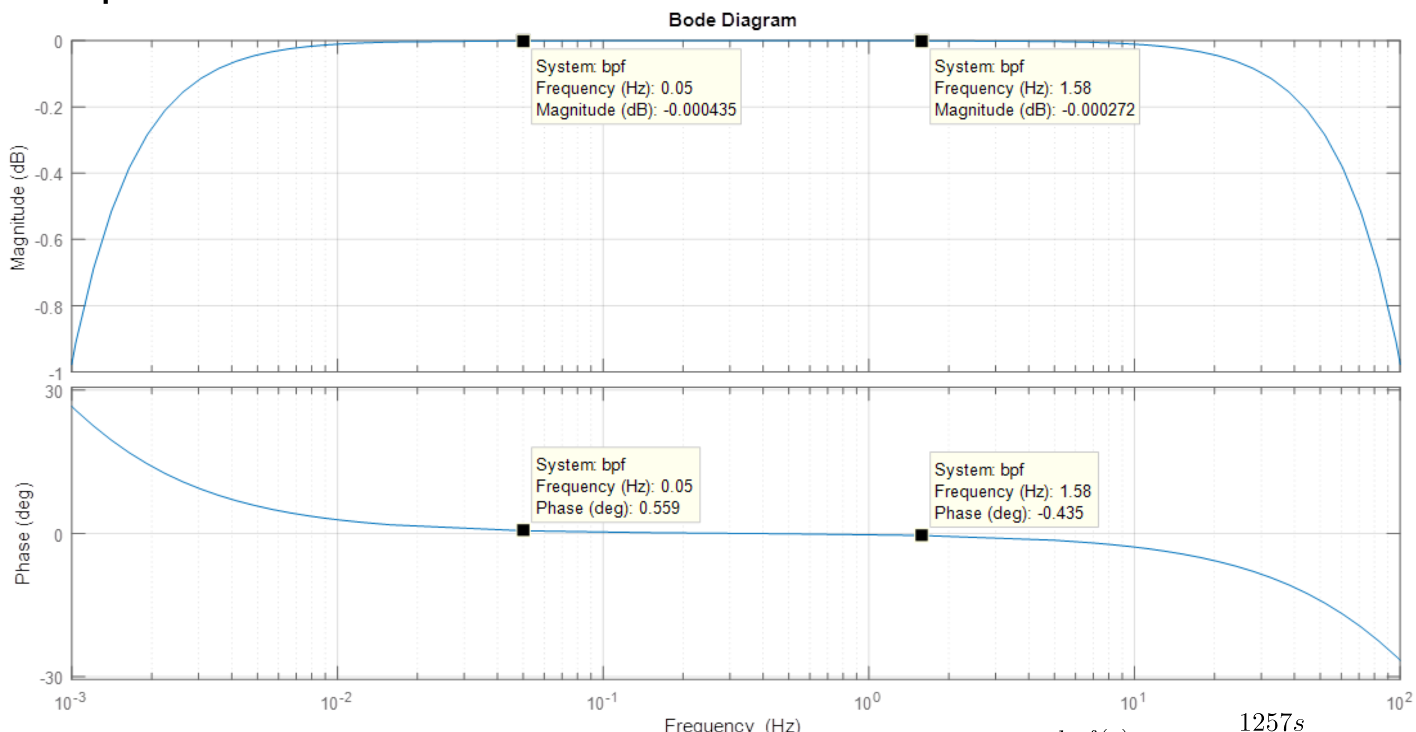


Case 1: position and acceleration

A short note on filters:

Accelerometers are affected by drift, but power in waves is band limited

Band pass filter for accelerometer

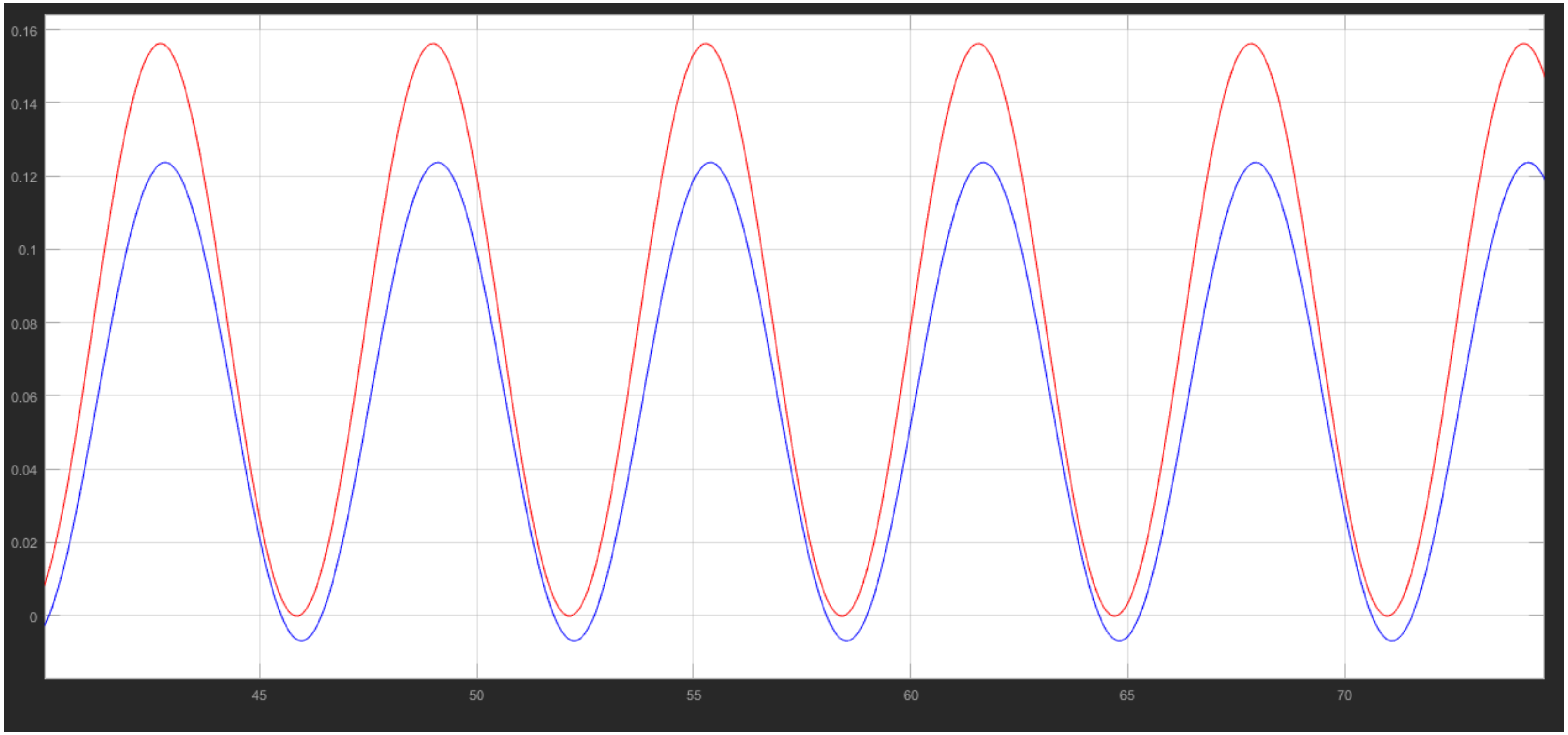


$$bpf(s) = \frac{1257s}{s^2 + 1257 + 3.948}$$

Case 1: position and acceleration

Cutoff frequency should be at least 10x max frequency of the waves

Absorbed power with linear damper and velocity filtered trough a LPF



Cutoff frequency > 10x excitation frequency

Cutoff frequency = 2x excitation frequency

Case 1: position and acceleration

Algorithm: steady state

$$\hat{x}_{k|k-1} = A\hat{x}_{k|k} + Bu_k + G\hat{d}_{k-1}$$

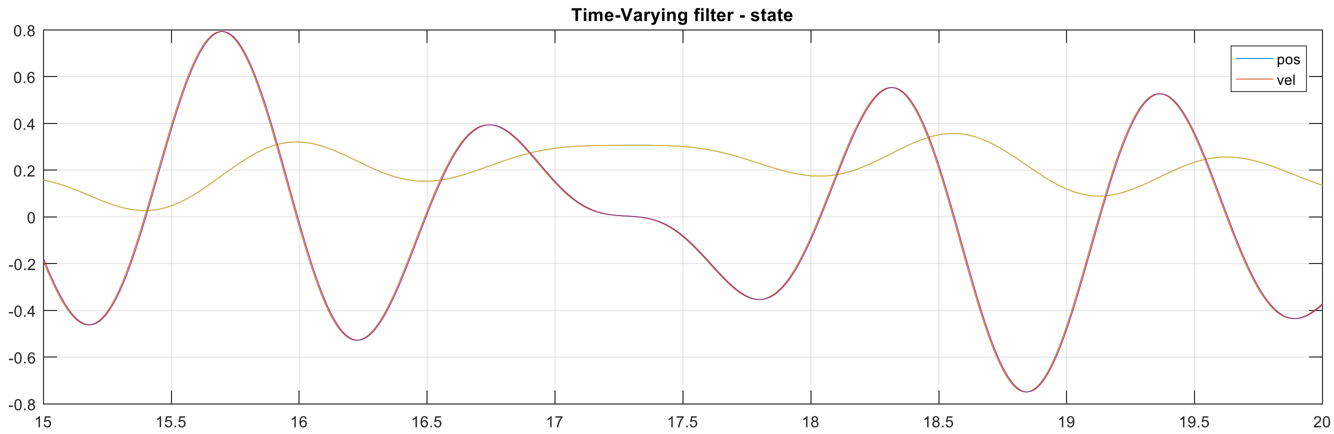
$$\hat{x}_{k|k} = A\hat{x}_{k|k-1} + L_\infty\left(y_k - C\hat{x}_{k|k-1} - Du_k\right)$$

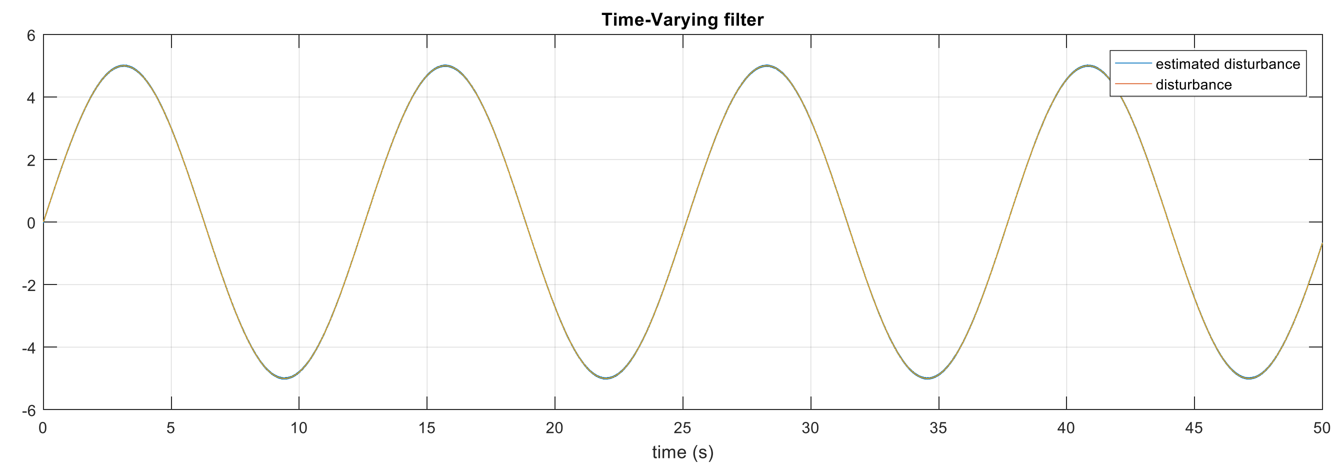
$$\hat{d}_{k-1} = M_\infty\left(y_k - C\hat{x}_{k|k} - Du_k\right)$$

Similar structure to Kalman fiter

Much simpler and 10x faster than time-varying version

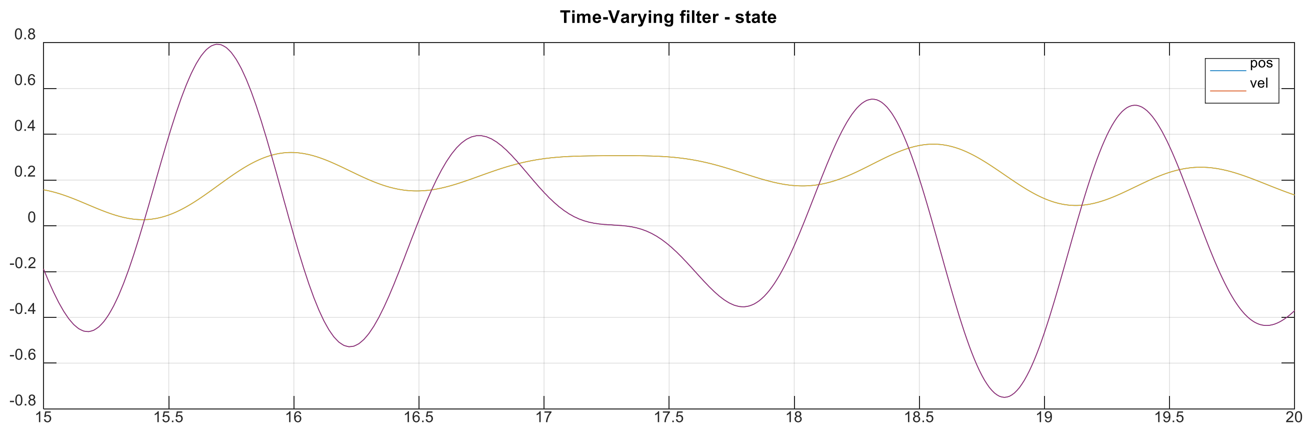
Case 1: position and acceleration

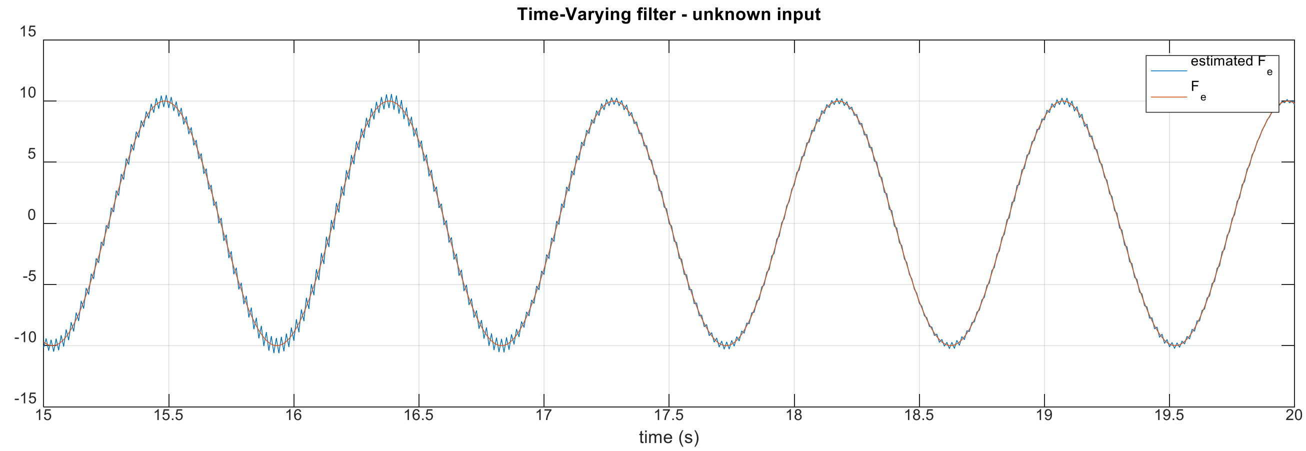




Case 1a: position only

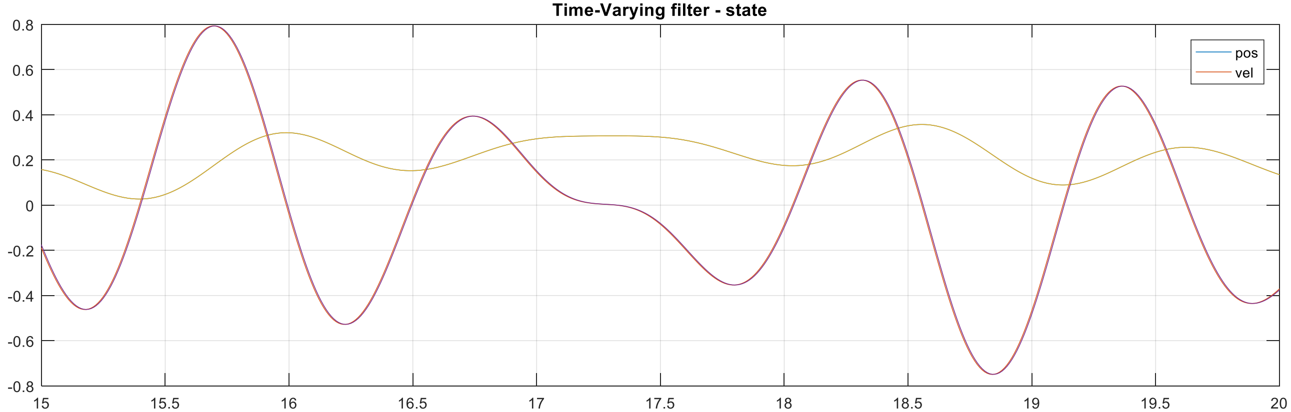
Show sample results: very sensitive to noise

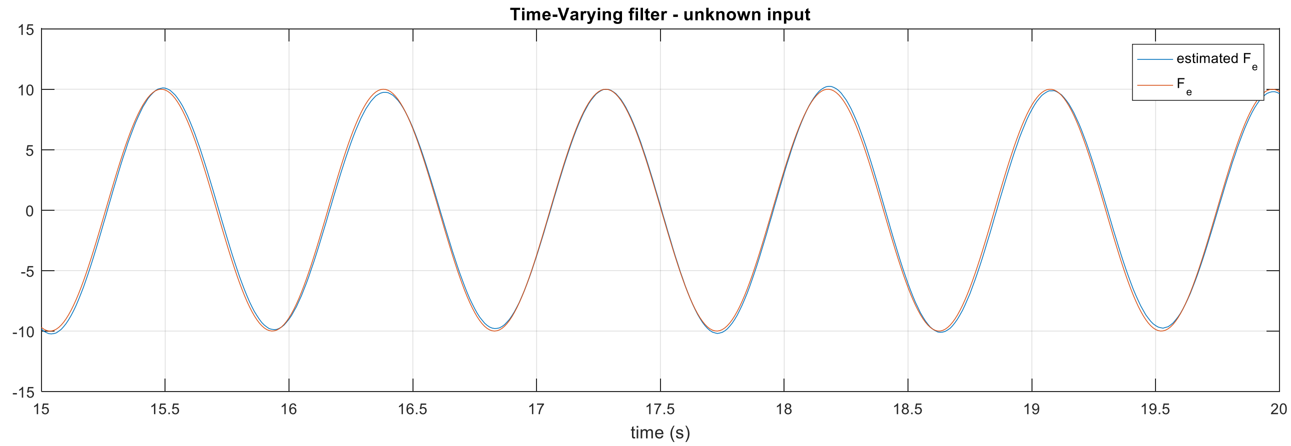




Case 1b: position only

Velocity obtained by differentiating position





Very sensitive to noise, but a bit better than case 1a

Case 1

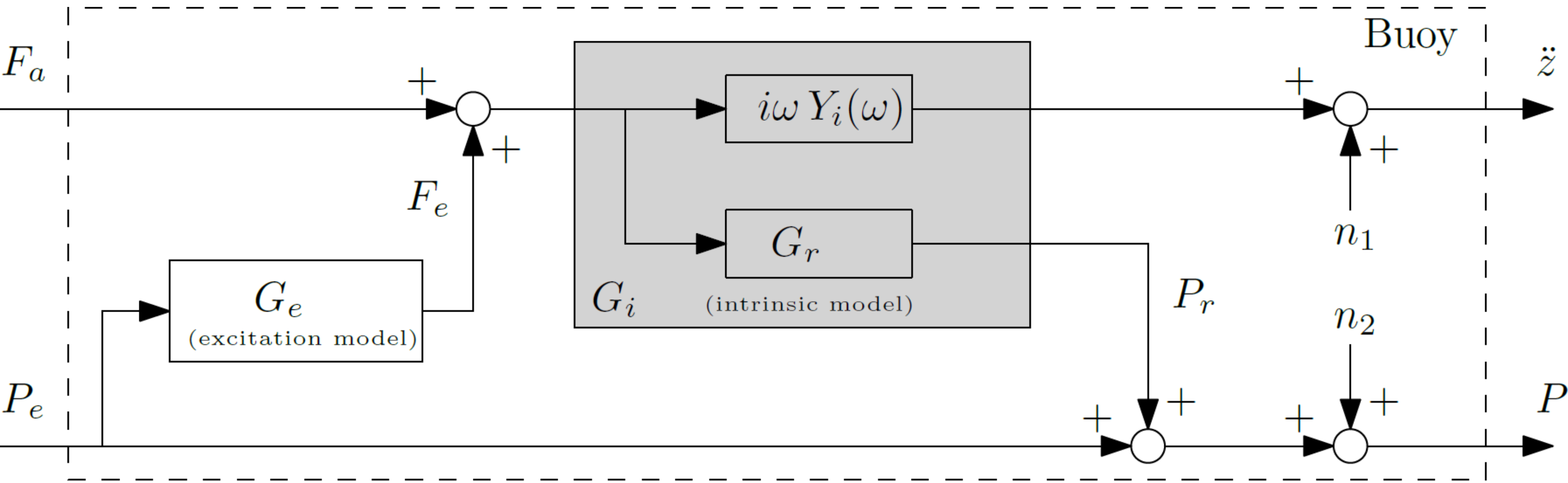
Summary:

- Adding redundant measurement makes the estimation more robust.
- Accelerometers are relatively inexpensive

Case 2: pressure and acceleration

- Measurements
  - Pressure
  - Acceleration (accelerometer)

Models have been identified from experimental data



Inputs: $u = \begin{bmatrix} F_a \\ P_e \end{bmatrix}$

Outputs: $y = \begin{bmatrix} \ddot{z} \\ P \end{bmatrix}$

Case 2: pressure and acceleration

- State space model

Models have been identified from experimental data

$$G_e: \quad \begin{aligned} \dot{x}_e &= A_e x_e + B_e P_e \\ F_e &= C_e x_e + D_e P_e \end{aligned}$$

$$G_i: \quad \begin{aligned} \dot{x}_i &= A_i x_i + B_i F_A + B_i F_e \\ y_i &= C_i x_i + D_i F_a + D_i F_e \end{aligned}$$

Unknown input form

$$\dot{x} = Ax + BF_A + GP_e$$
$$y = Cx + DF_a + GP_e$$

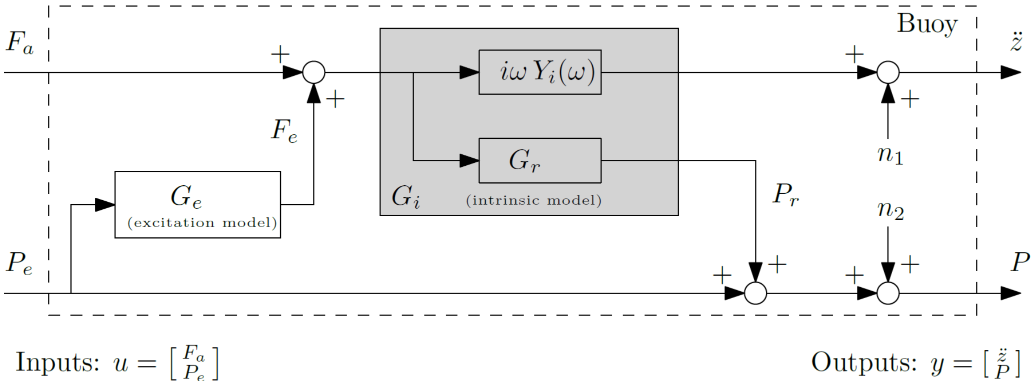
$$A = \begin{bmatrix} A_i & B_i C_e \\ 0 & A_e \end{bmatrix}$$

$$B = \begin{bmatrix} B_i \\ 0 \end{bmatrix} \qquad G = \begin{bmatrix} B_i D_e \\ B_e \end{bmatrix}$$

$$C = [C_i \quad D_i C_e]$$

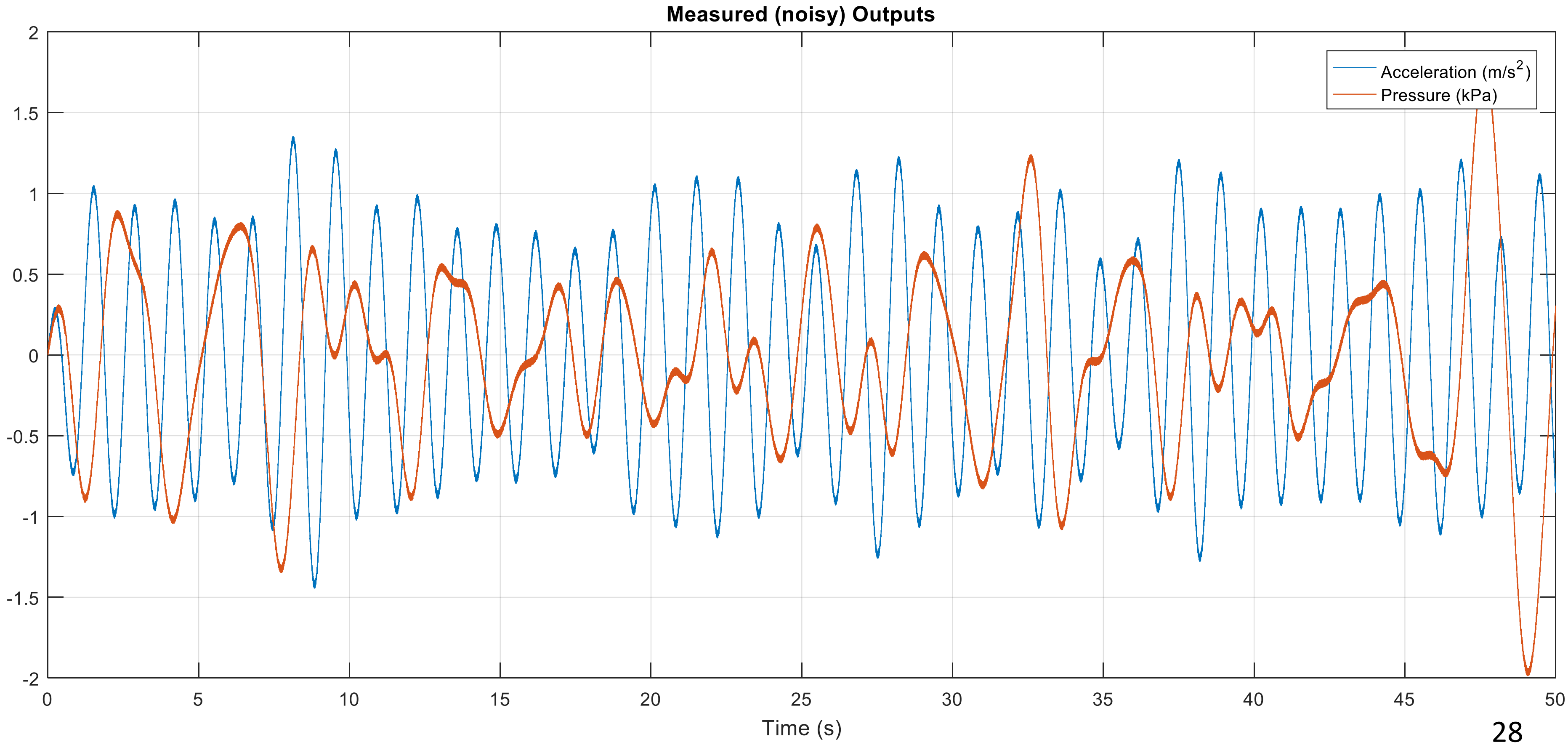
$$D = D_i$$

$$H = D_i D_e + \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$



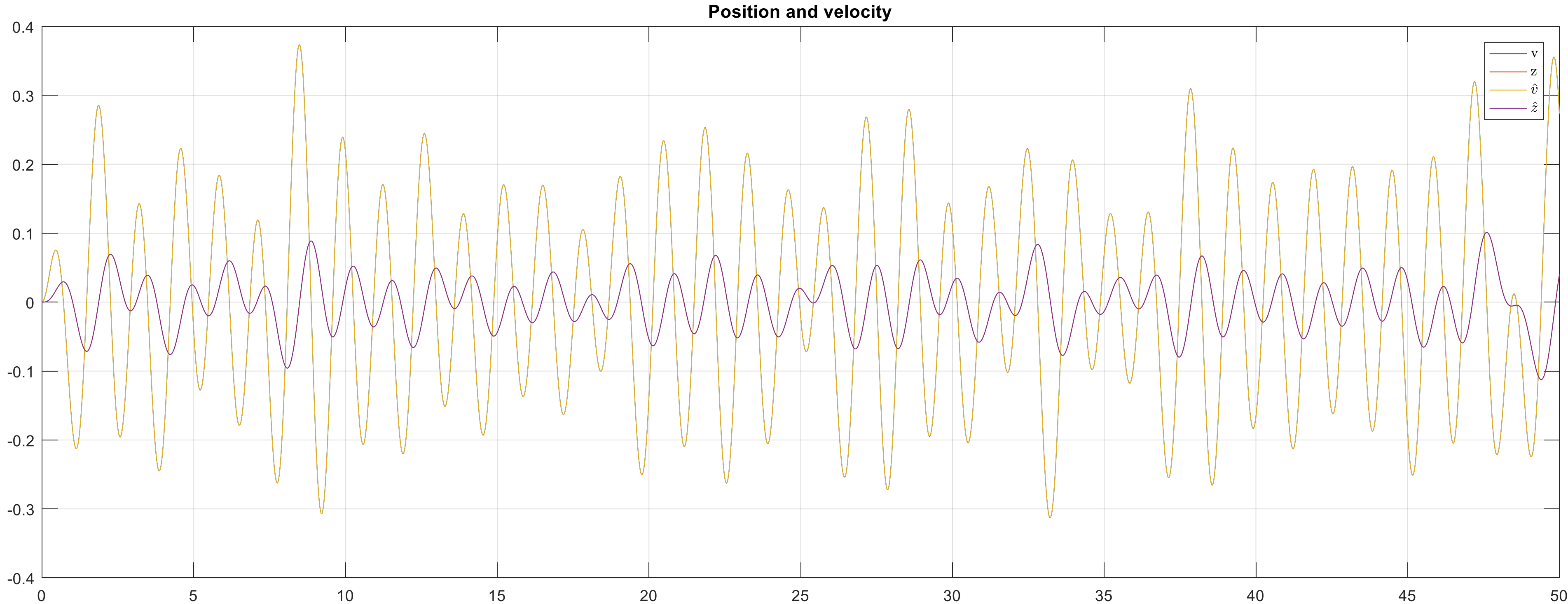
Case 2: pressure and acceleration

- Sample results:



Case 2: pressure and acceleration

- Sample results:
  - System states



Case 2: pressure and acceleration

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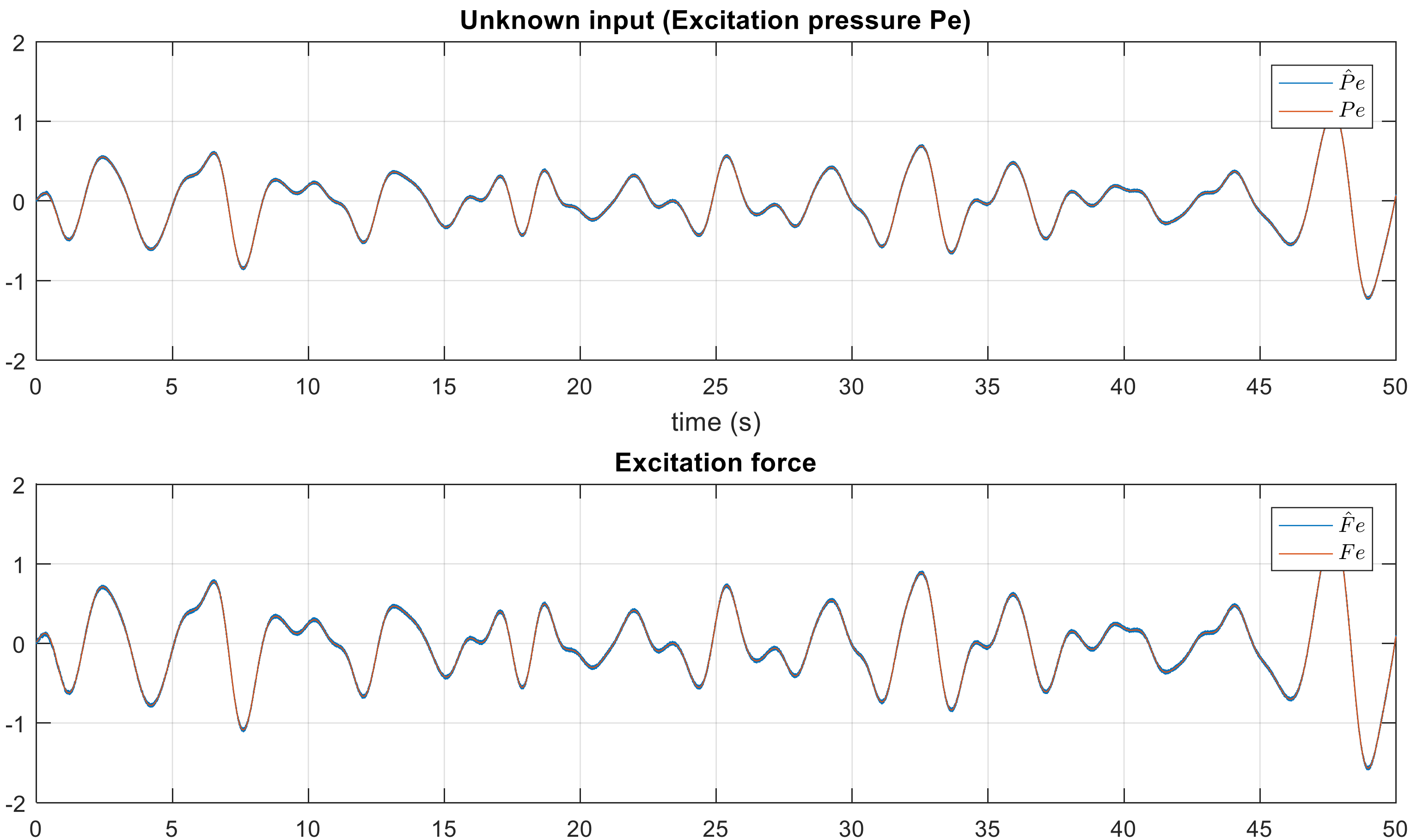
- Sample results:

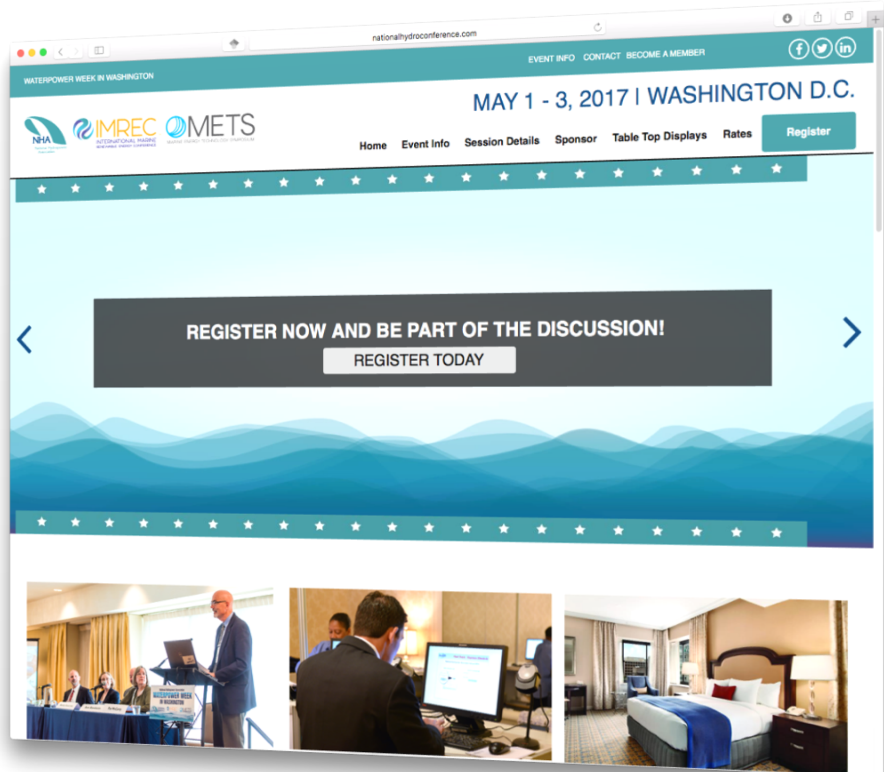


In-progress

- Will release the code shortly on MHKDR website
- Can easily be extended to
  - Multiple degree of freedom/multi-body/multi-device
  - Multi-sensor data fusion to improve estimation

METS Workshop

- May 3rd 1-5 PM (in conjunction with METS in Washington, DC)
- Extended technical presentations
- Invited speakers
- Roundtable discussion
- Networking and collaboration brainstorming



IMREC INTERNATIONAL MARINE RENEWABLE ENERGY CONFERENCE

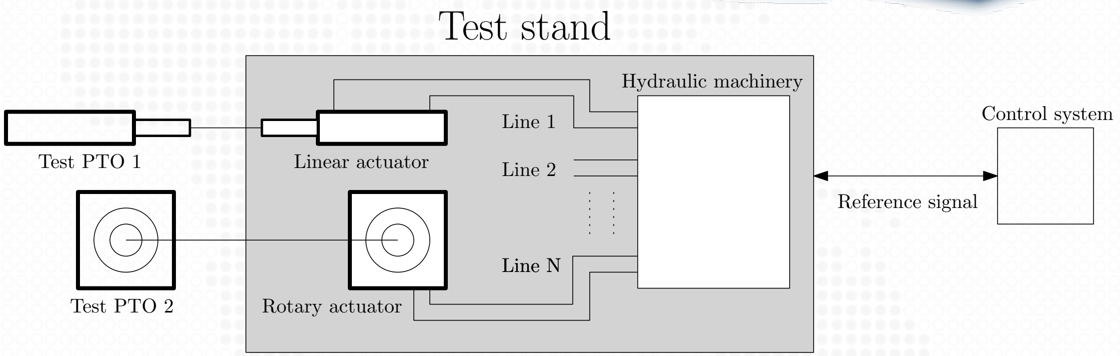
NHA ANNUAL CONFERENCE

METS MARINE ENERGY TECHNOLOGY SYMPOSIUM

http://www.nationalhydroconference.com/index.html

Sandia Power Take-Off Test Stand

- A mobile test lab is being developed by Sandia National Labs for the testing of WEC power take-offs (PTOs)
  - Linear and rotational PTOs
  - Multiple degrees-of-freedom, with independent control
  - Test stand will simulate dynamics (inertia, damping, stiffness) of full scale WEC, as well as input from waves
- This system will allow for PTO studies including
  - System identification
  - Real-time control
  - Reliability
  - Grid interface simulations
- $1.2M of internal (Sandia) funding
- Planned completion: October 2017
- Planned specs.
  - 5 to 500 kW
  - 0 and 2 Hz



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SAND2017-3300 M

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