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Fault tolerant control in marine energy systems: A wave energy perspective

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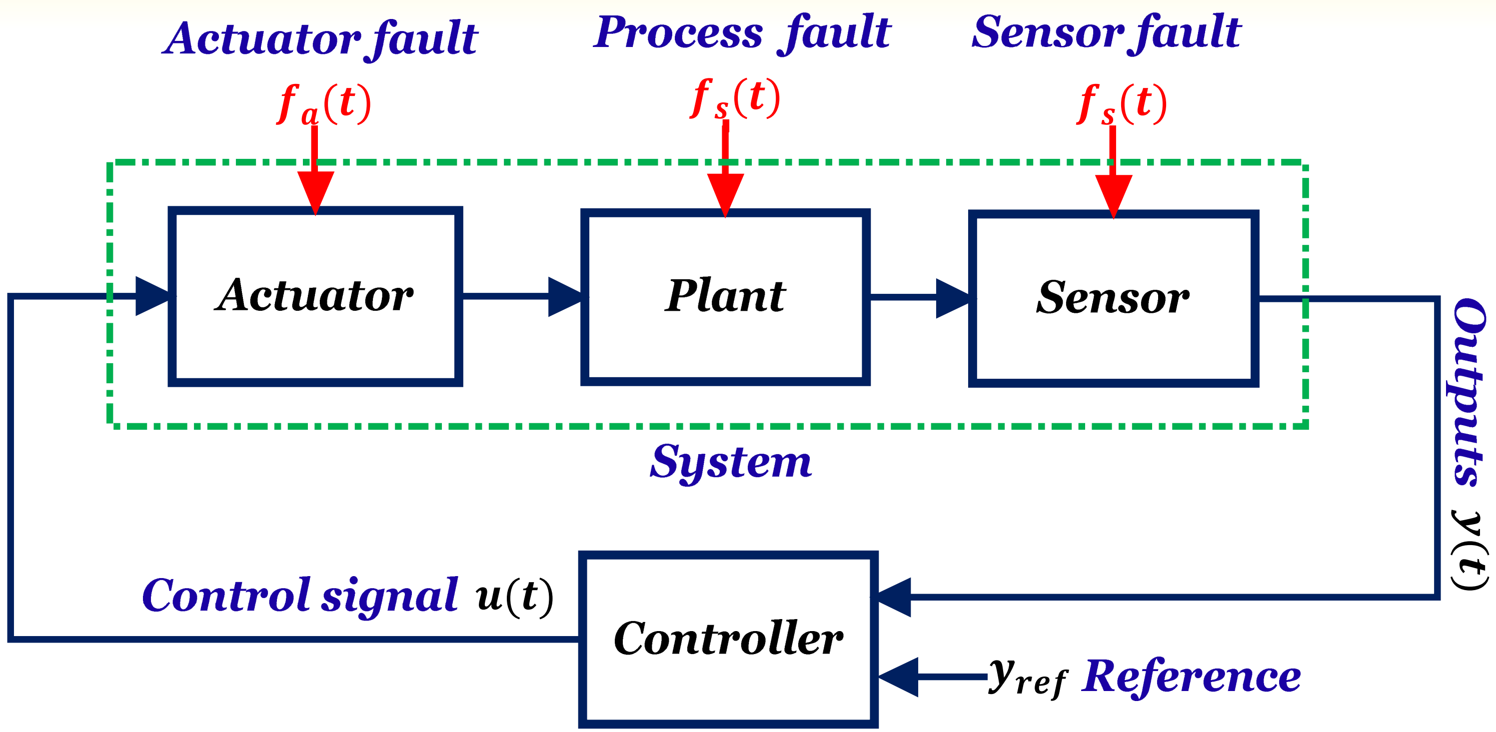
Thanks to Bingyong Guo for great help & advice

Fault Tolerant Control



Aim

Joint optimization of stability and *admissible* performance
Subject to bounded faults, complexity and modelling uncertainty!

Topic with increasing interest at major international conferences of IFAC, IEEE, etc (CDC, ACC, IFAC *Safeprocess (1991-2015)*, IEEE *Systol (2010, 2013, 2016)*, IFAC World Congress (1999, 2002, 2005, 2008, 2011, 2014, 2017), *MED* 01-16, Asian Control Conference, etc…………

Valuable for industrial applications, e.g. Marine Energy Systems…….

MAIN STRUCTURE OF FTC

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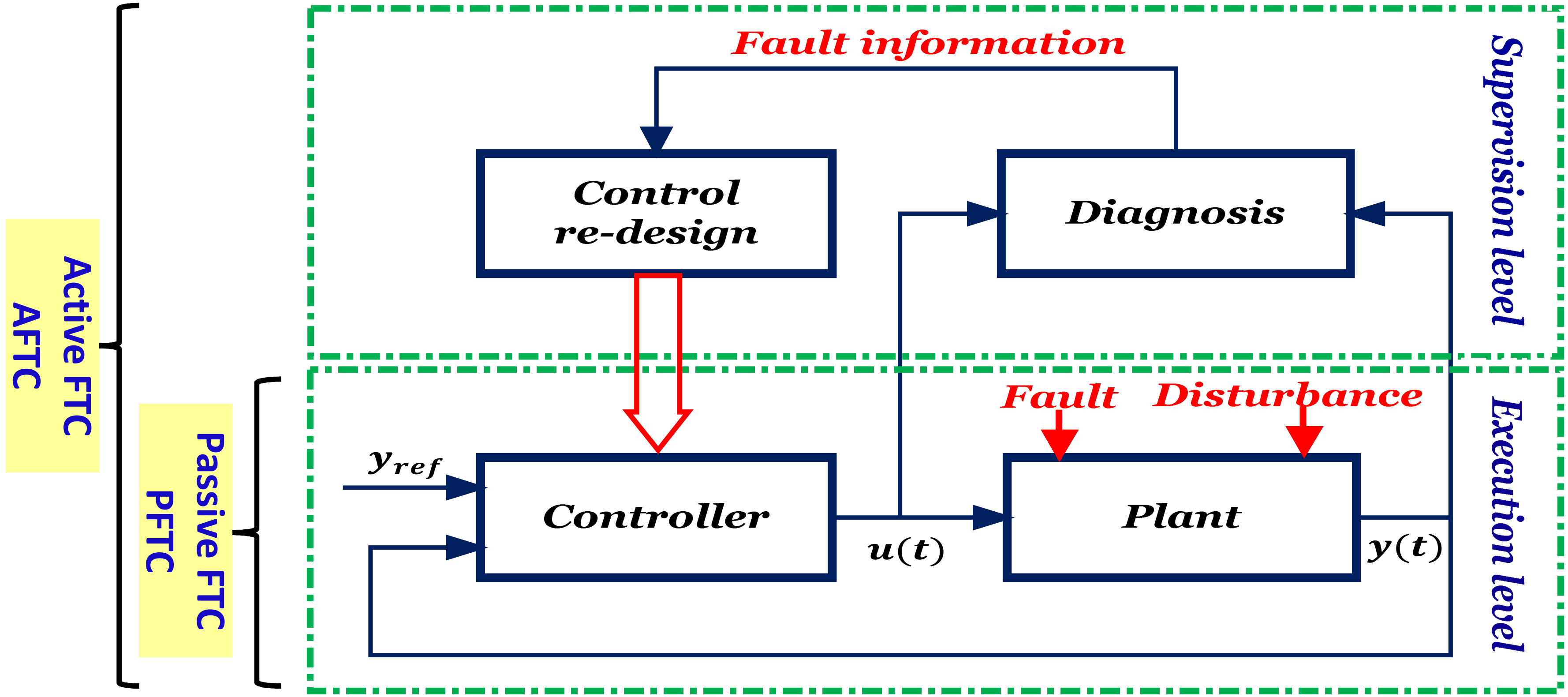
Generally, two levels included to make system able to Tolerate Faults:

- **Supervision level.**
- **Control reconfiguration level.**



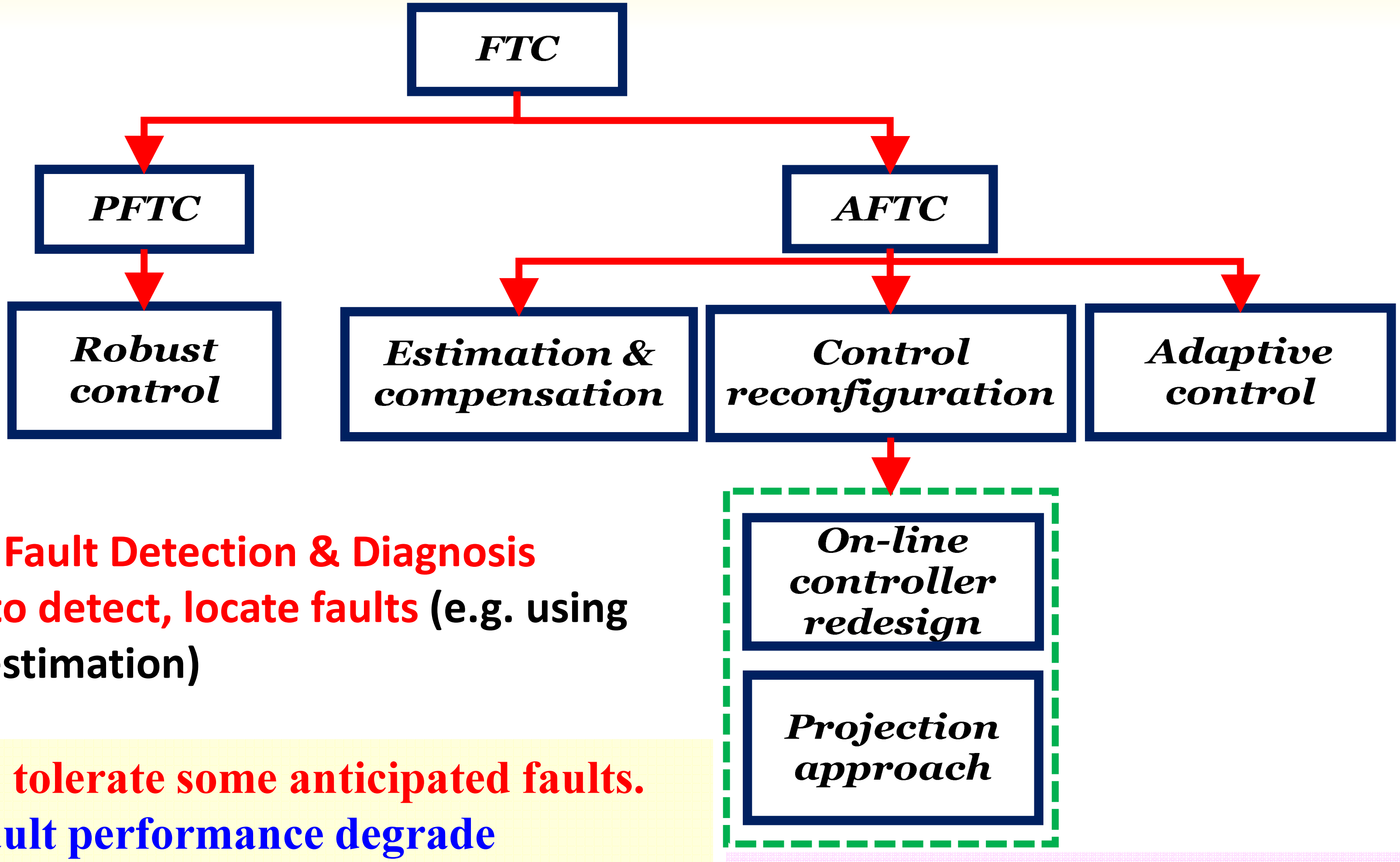
PFTC:

- **Robust fixed structure controller**
- **Faults anticipated at the controller design stage**

AFTC:

- **Explicit fault supervision scheme**
- **Real time decision-making and controller reconfiguration**

GENERAL CLASSIFICATION OF FTC METHODS



FDD – Fault Detection & Diagnosis
Used to detect, locate faults (e.g. using fault estimation)

PFTC tolerate some anticipated faults.
Pre-fault performance degrade
Remove need for FDD

Avoid reconfiguration time delays
PFTC doesn't handle sensor faults with tracking control framework

AFTC systems are designed to handle the occurrence of system faults on-line
No pre-fault performance degradation

Sensors, actuators and reliability

SENSOR FAULTS

- **Generator speed (scaling), Rotor speed (scaling), Torque (offset), Low speed shaft position encoder (bit error), Yaw misalignment (stuck drive, wind vane [nacelle/hub, along blade / Lidar]), Accelerometer (offsets), Loads & Deflections (blade root bending moment scaling), Wind speed (anemometer [nacelle/hub] / along blade / Lidar), Pitch angle sensors (stuck), Blade root bending moments (scaling)**

ACTUATOR FAULTS

- **Pitch actuators (leakage, air content, stuck actuation), Generator/power converter, Yaw motor.**

Faults may result in power reduction, down-time, increased O&M cost

FAULT CONSEQUENCES

Pitch actuator fault - Pitch feathering vital for safety; "Pitch runaway" often drives extreme loads.

Torque actuator fault - Loss of load, turbine shut down using pitch; power surge; gearbox overload

Yaw actuator failure:

- **Turbine shuts down – not urgent, could even wait until yaw misalignment is excessive.**

Consequences of actuator failure

Pitch actuator failure:

- Pitch feathering is vital for safety.
- "Pitch runaway" often drives extreme loads – but is it realistic? Actual cause of failure is unspecified - really requires a proper FMEA (failure mode and effects analysis).

Torque actuator failure:

- Loss of load: no worse than grid dropout. Turbine shuts down using pitch.
- Short circuit → large transient gearbox loading

Yaw actuator failure:

- Turbine shuts down – not urgent, could even wait until yaw misalignment is excessive.

OFFSHORE WIND TURBINE MAINTENANCE

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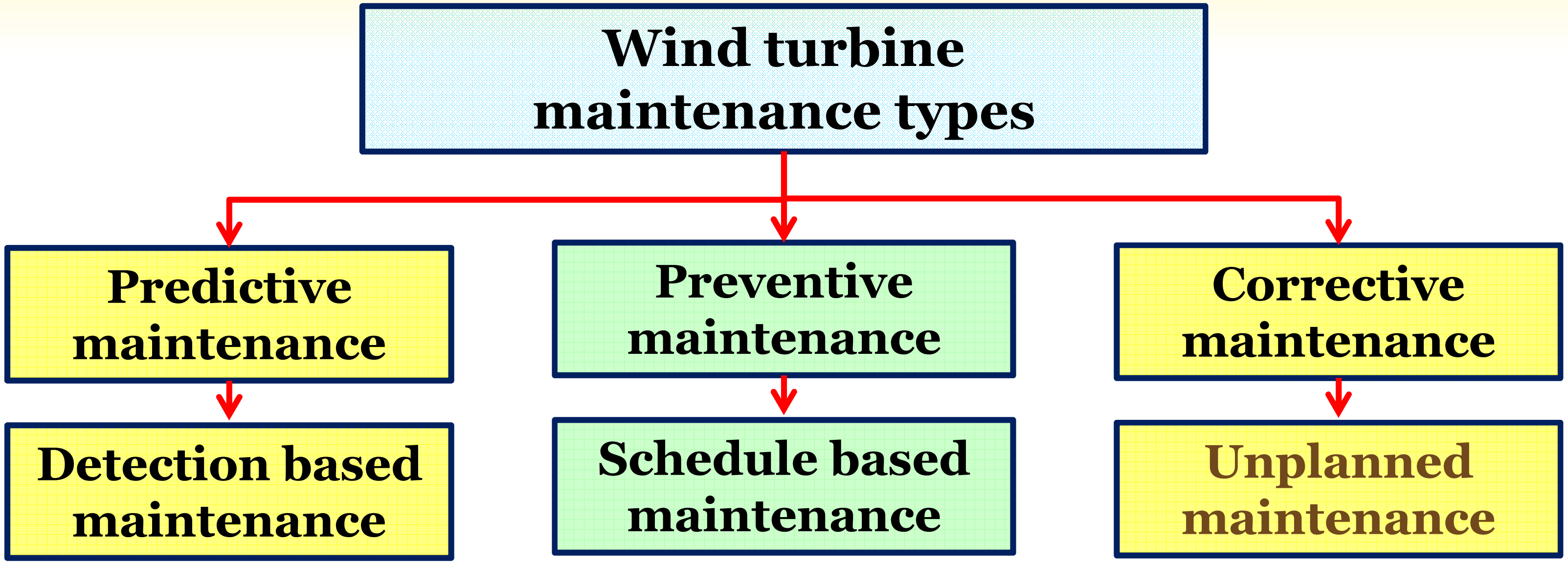

- Offshore work between 5-10 times more expensive than work on land.
- Predictive maintenance preferable. Technical reports (Verbruggen, 2003) show that signal based monitoring techniques not suitable for wind turbine applications because of stochastic nature of wind affecting fault decision-making.
- Site inaccessibility.

Reduction of maintenance effort is essential when locating wind turbines offshore

Verbruggen, T. W. 2003. Wind turbine operation and maintenance based on condition monitoring. Petten, the Netherlands: Energy Research Center of the Netherlands.

Van Bussel, G. J. W. & Zaaijer, M. B. Year. Reliability, Availability and Maintenance Aspects of Large-Scale Offshore Wind Farms, a Concepts Study. *In: MAREC 2001 Marine Renewable Energies Conference Newcastle 119-126.*

"SUSTAINABLE WIND TURBINE"

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Aim:
Increase multi MWatt wind turbine reliability

Existing problem:
Trade-off the annual power production with lifetime and cost

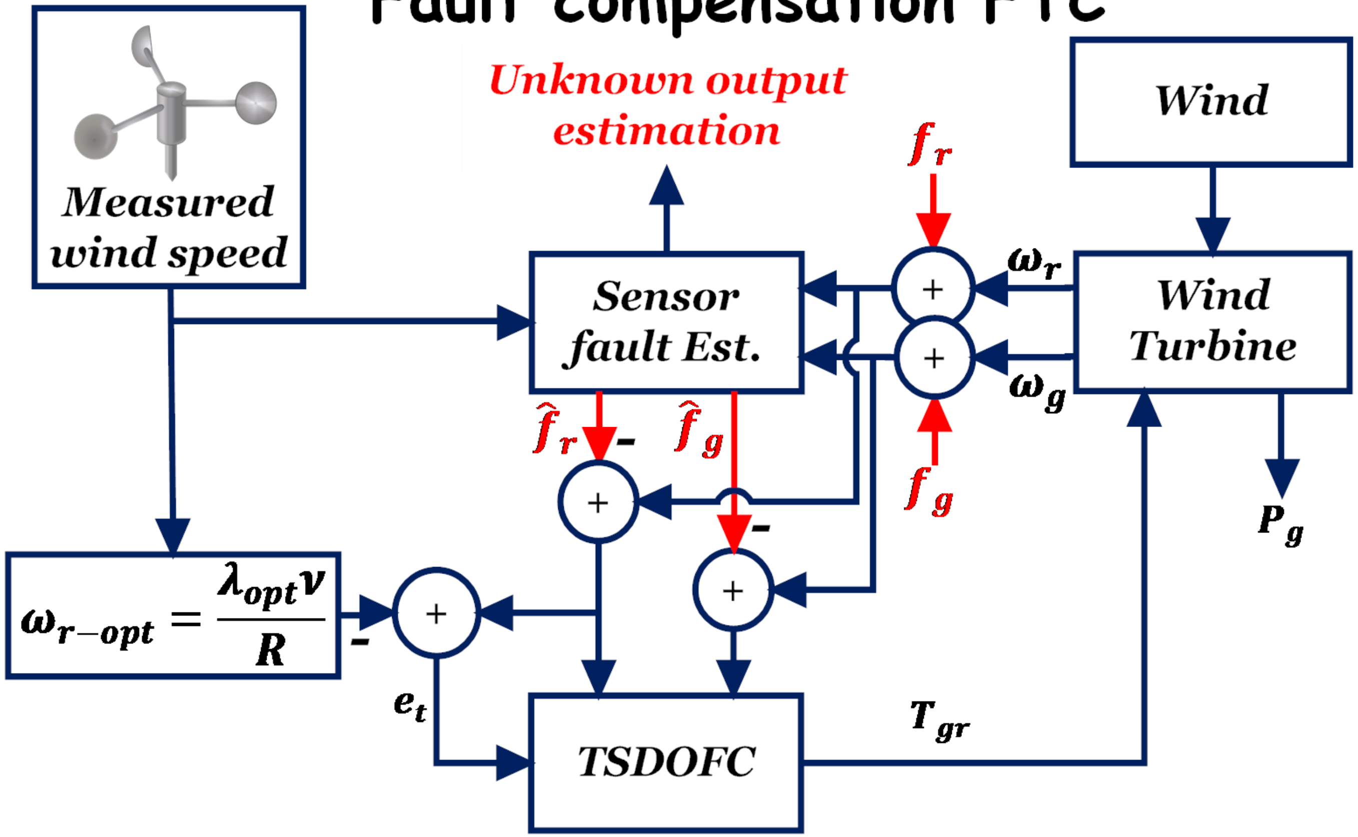
Suggestions

- Build monitoring systems using model based techniques
- Fault Tolerant Control system

Increases lifetime & decreases cost

Reliable multi MWatt wind turbine

Fault compensation FTC



Takagi-Sugeno Dynamic Output feedback Controller (TSDOFC) uses “fault hiding” sensor fault compensation to provide Fault tolerant Generator Torque reference to sustain optimal power maximization in presence of rotation sensor faults.

Sensor fault estimation & compensation with wind speed estimation

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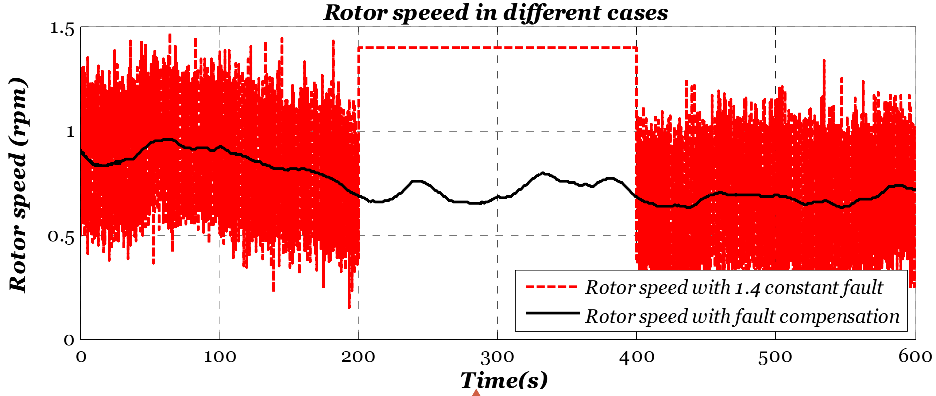
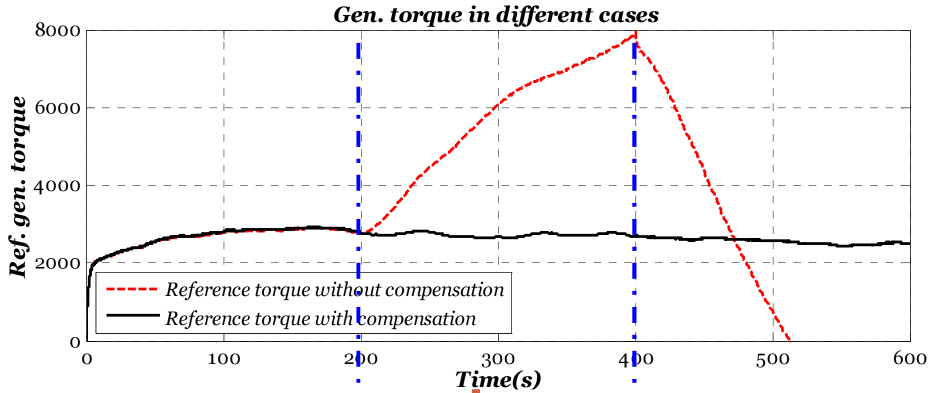


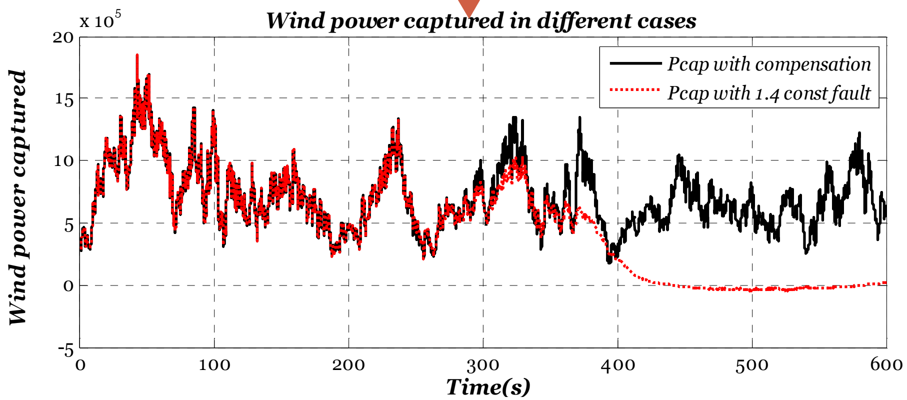
A T-S PMIO is designed for rotor speed sensor fault estimation

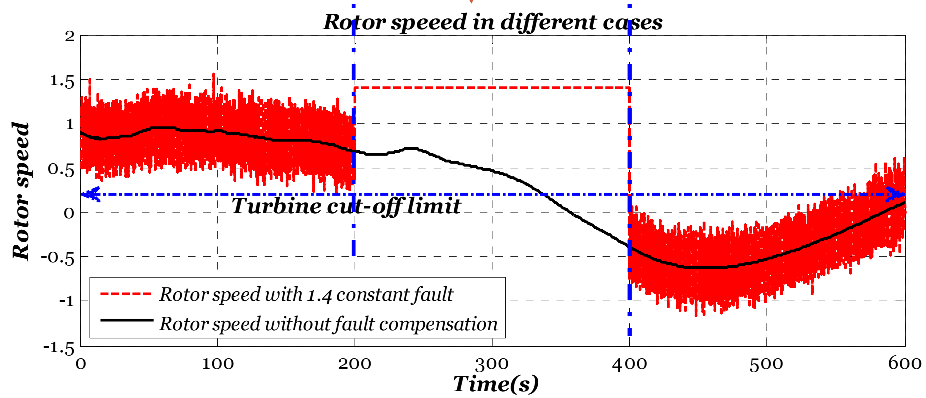
The controller forces the turbine to slow down



Measured rotational speed exceeds optimal rotational speed

Power captured with and without compensation





WHAT ABOUT "SUSTAINABLE WEC"?

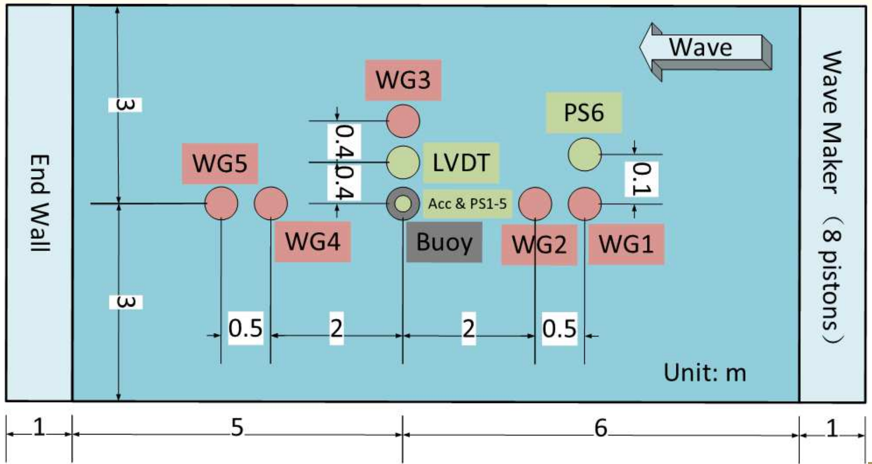
Different actuators, sensors, components, WEC devices

- But similar problems of reliability, sustainability, O & M Cost Reduction .....

A common feature between wind & wave energy problems is absence of repeated (hardware) redundancy. Signals can be estimated in different ways using Analytical Redundancy , this provides a way to estimate fault effects.

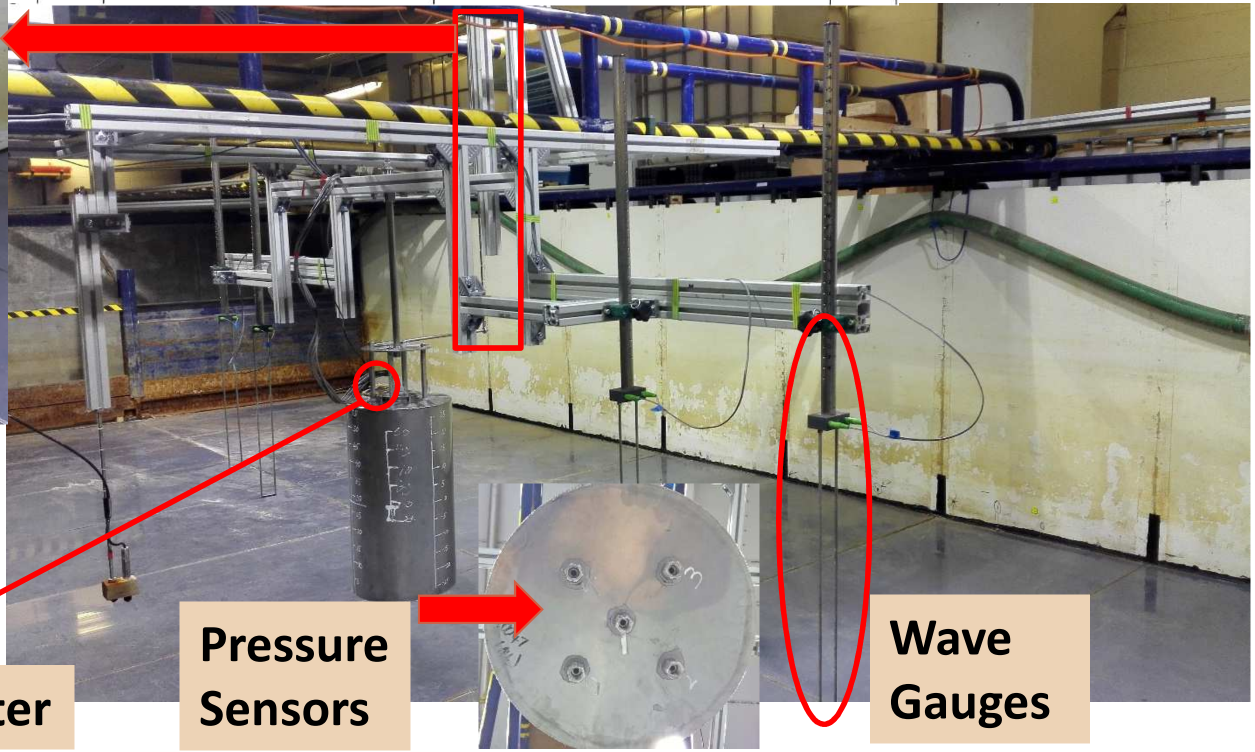
Research shows that the "fault estimation & compensation" strategy can even be used to tune the power conversion efficiency – compensate for non-linearity as well as faults!

1/50 Scale Prototype & Tank Tests



Tank: 13m long, 6m wide, 2m height with 1m water depth.

Wave-maker: regular/irregular waves: f=0.4-1.2Hz, A=2-10cm



Buoy:
r=0.15m
h=0.56m
d=0.28m

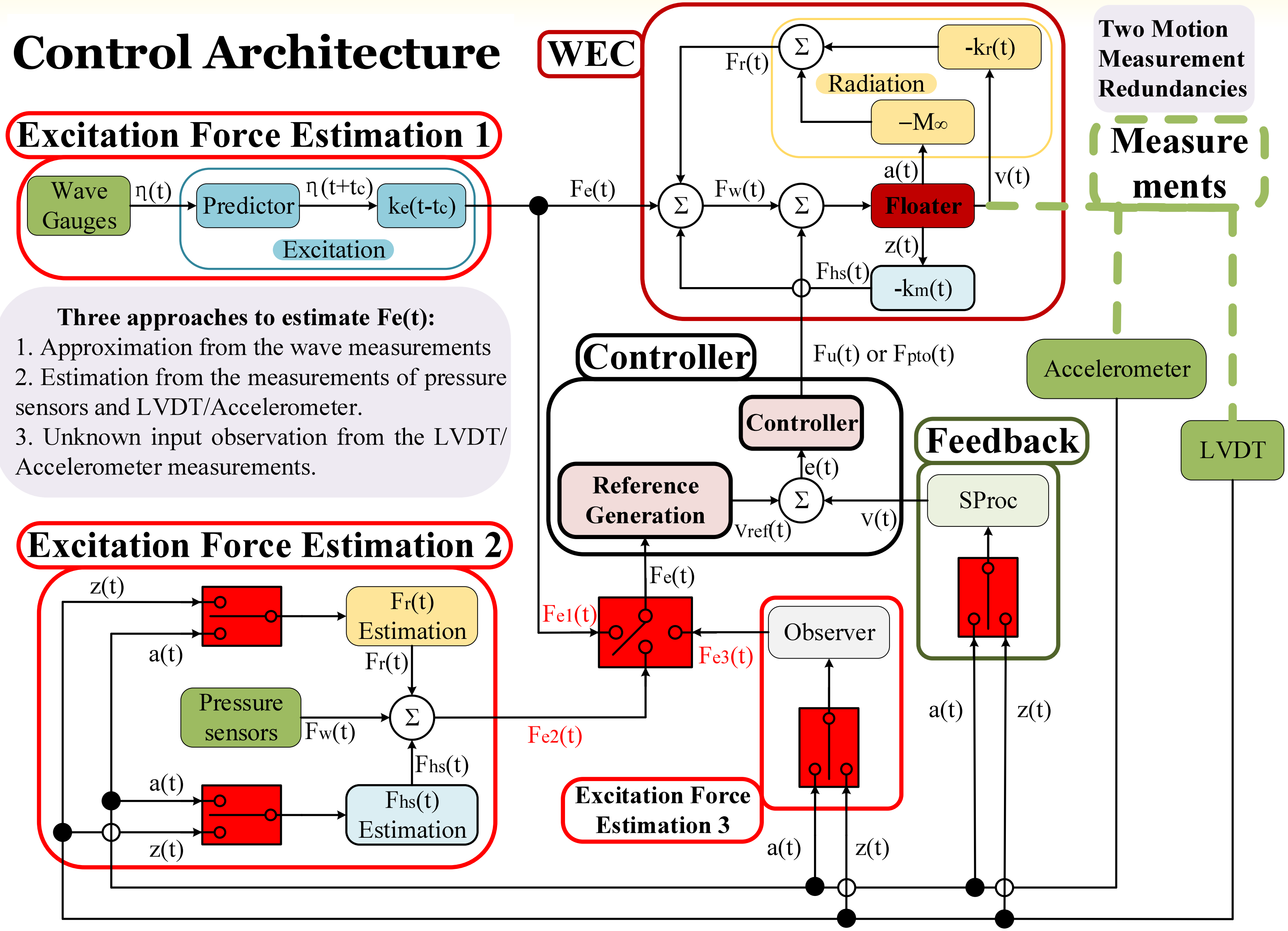
DAQ: NI USB-6210

Data collected via LabView fs=100Hz

Some results shown in [1].

1. Guo, B., et al. *A continuous control approach to point absorber wave energy conversion*. in *Control (CONTROL), 2016 UKACC 11th International Conference on*. 2016. IEEE.

Control Architecture



Three approaches to estimate Fe(t):

1. Approximation from the wave measurements
2. Estimation from the measurements of pressure sensors and LVDT/Accelerometer.
3. Unknown input observation from the LVDT/ Accelerometer measurements.

Three Excitation Force Methods

To estimate the wave excitation force:

(1) From wave measurement and its prediction via AR model (to overcome the non-causality of the excitation problem).

(2) From measurements of pressure sensors, LVDT/accelerometer. Total wave force can be calculated from the pressure sensors fixed at buoy bottom.

- **The radiation force can be approximated from the accelerometer measurements, according to Cummins Equation.**
- **The hydrostatic force is proportional to the displacement measurement.**

Hence, excitation force approximates wave force by subtracting the estimated radiation and hydrostatic forces.

(3) The excitation force can also be observed as an "unknown input" from LVDT and Acc measurements ……..and Estimated…a new approach in control.

These provide "analytical redundancy" for potential FTC application.

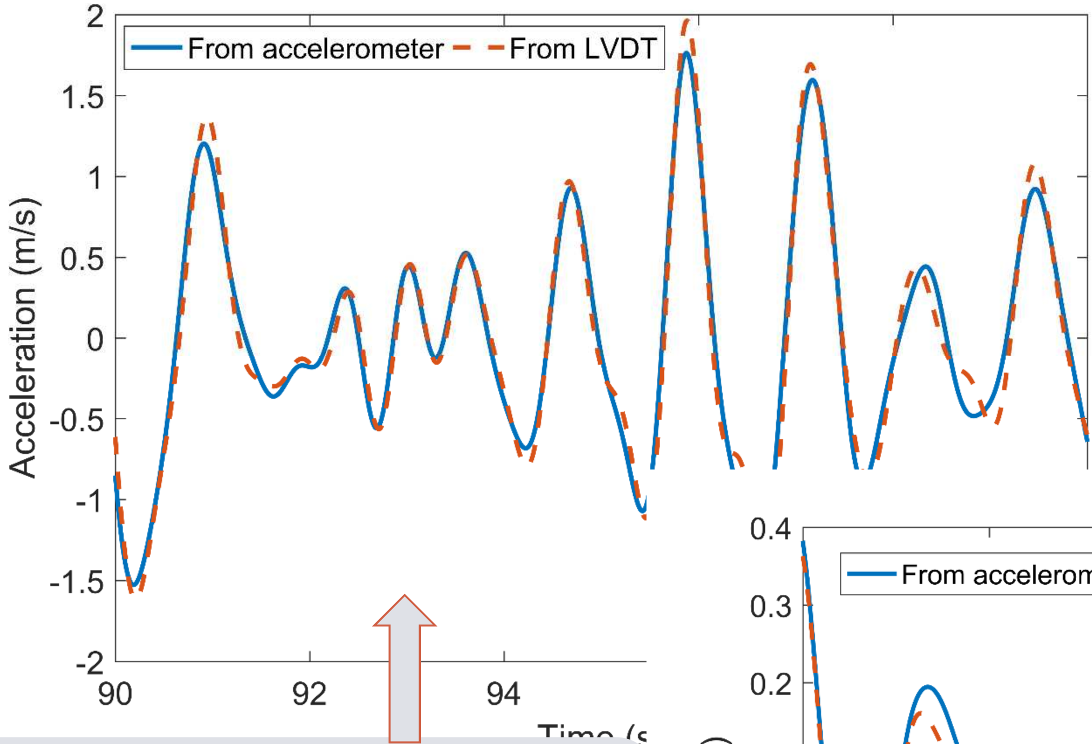
Either scheme can be applied as a feedback signal to give Fault Tolerant Control.

Redundancy also exists in motion measurements, displacement and acceleration.

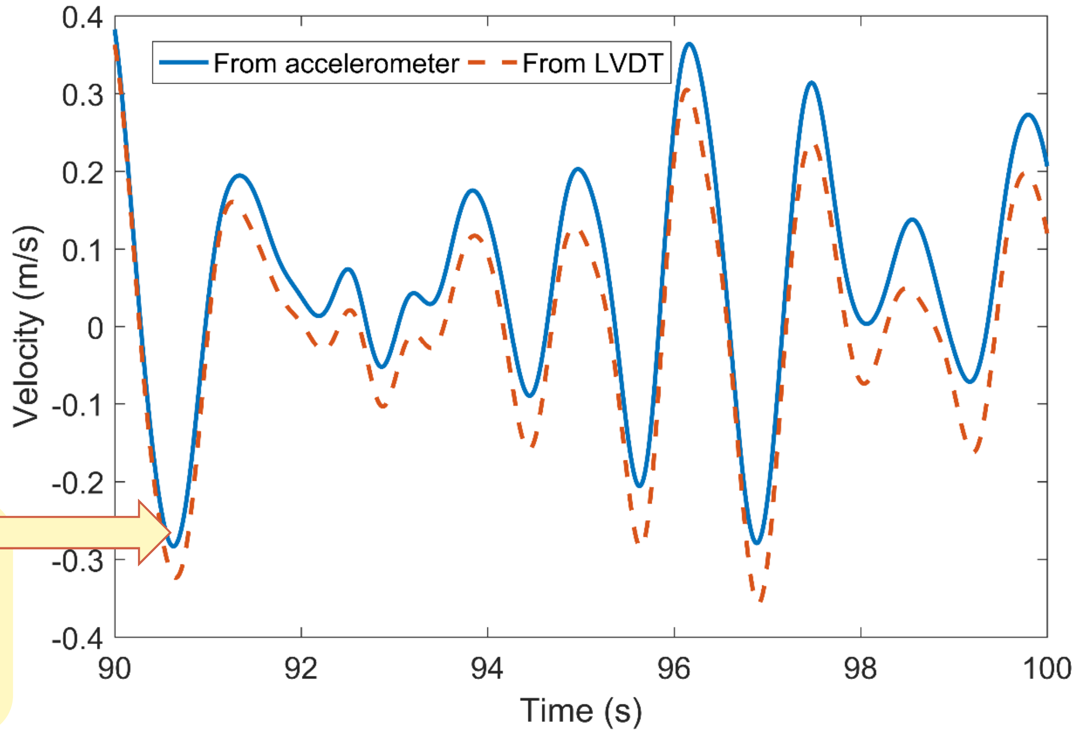
Redundancy in Measurement

Irregular Waves:
Pierson-Moskowitz spectra:

$$f_p = 0.60Hz$$
$$H_s = 0.12m$$



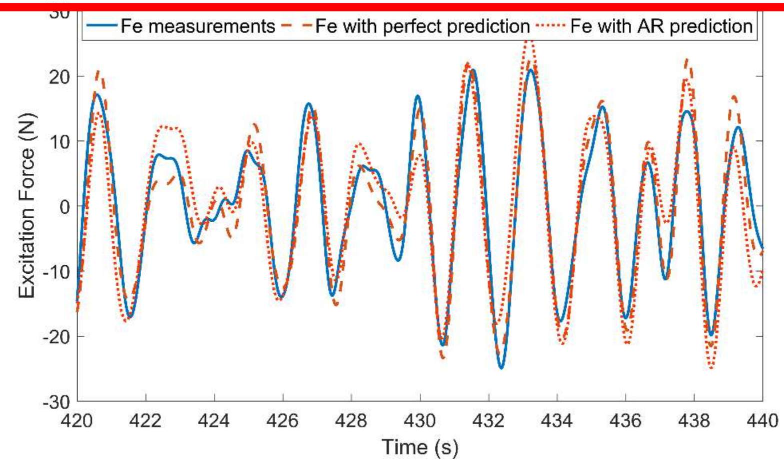
Acceleration comparison from LVDT/Accelerometer measurements.



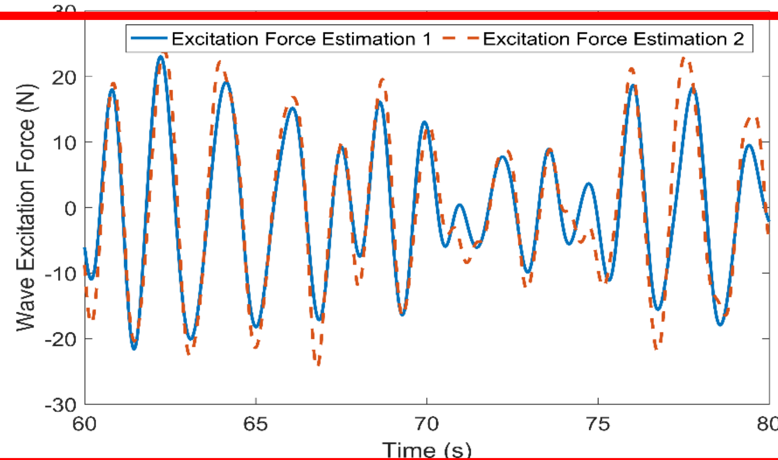
Velocity comparison from LVDT/Accelerometer measurements.

Redundancy in Excitation Force

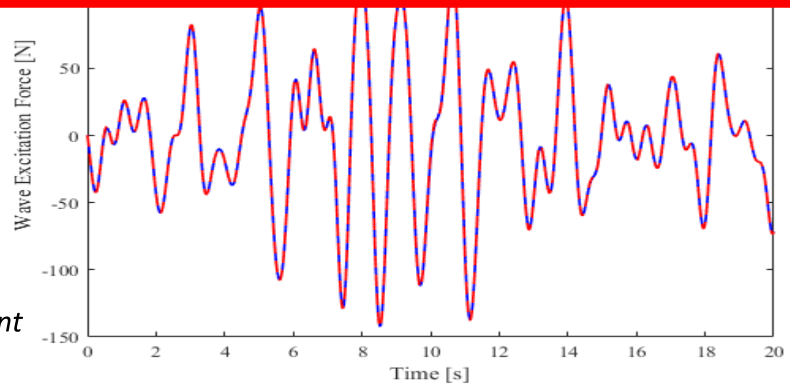
Fe Estimation 1: Using the wave gauge measurements to identify the excitation force with wave prediction, experimental results for irregular waves of PM spectra with $f_p = 0.6Hz, H_s = 0.12m$.



Fe Estimation 2: Using measurements of pressure sensors, LVDT/accelerometer to estimate the excitation force, experimental results for irregular waves of PM spectra with $f_p = 0.6Hz, H_s = 0.12m$.



Fe Estimation 3: Unknown input observed from buoy motion, simulation results [3] for irregular waves of PM spectra with $f_p = 0.67Hz, H_s = 0.4m$.



3. Abdelrahman, M., et al. *Estimation of wave excitation force for wave energy converters*. in *SysTol16: 3rd International Conference on Control and Fault-Tolerant Systems*. 2016. Barcelona, Spain: IEEE.

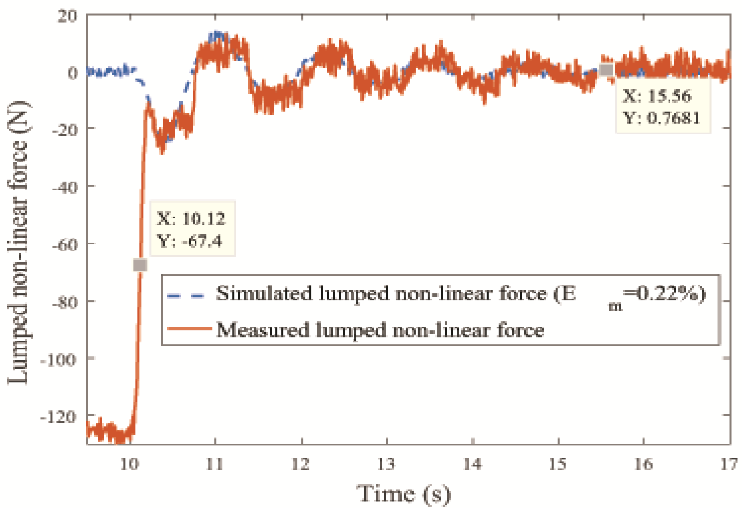
Model Uncertainty

Non-linear Effects: such as viscous and friction forces, cause large uncertainty [2].

$$F_v(t) = -0.5\rho c_d \pi r^2 \left[\dot{z}(t) - \dot{\eta}(t)\right]\left|\dot{z}(t) - \dot{\eta}(t)\right|$$

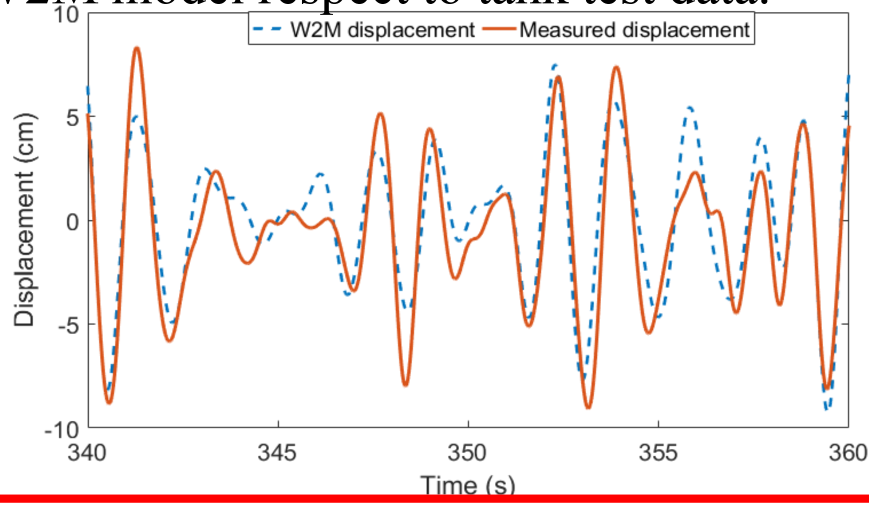
$$F_f(t) = \begin{cases} -s_v(f_c + f_s e^{-c_s|\dot{z}(t)|} + c_f|\dot{z}(t)|), \dot{z}(t) \geq v_{th} \\ -s_v(f_c + f_s e^{-c_s v_{th}} + c_f v_{th})|\dot{z}(t)|/v_{th}, \dot{z}(t) < v_{th} \end{cases}$$

Parameters identified from decay tests.



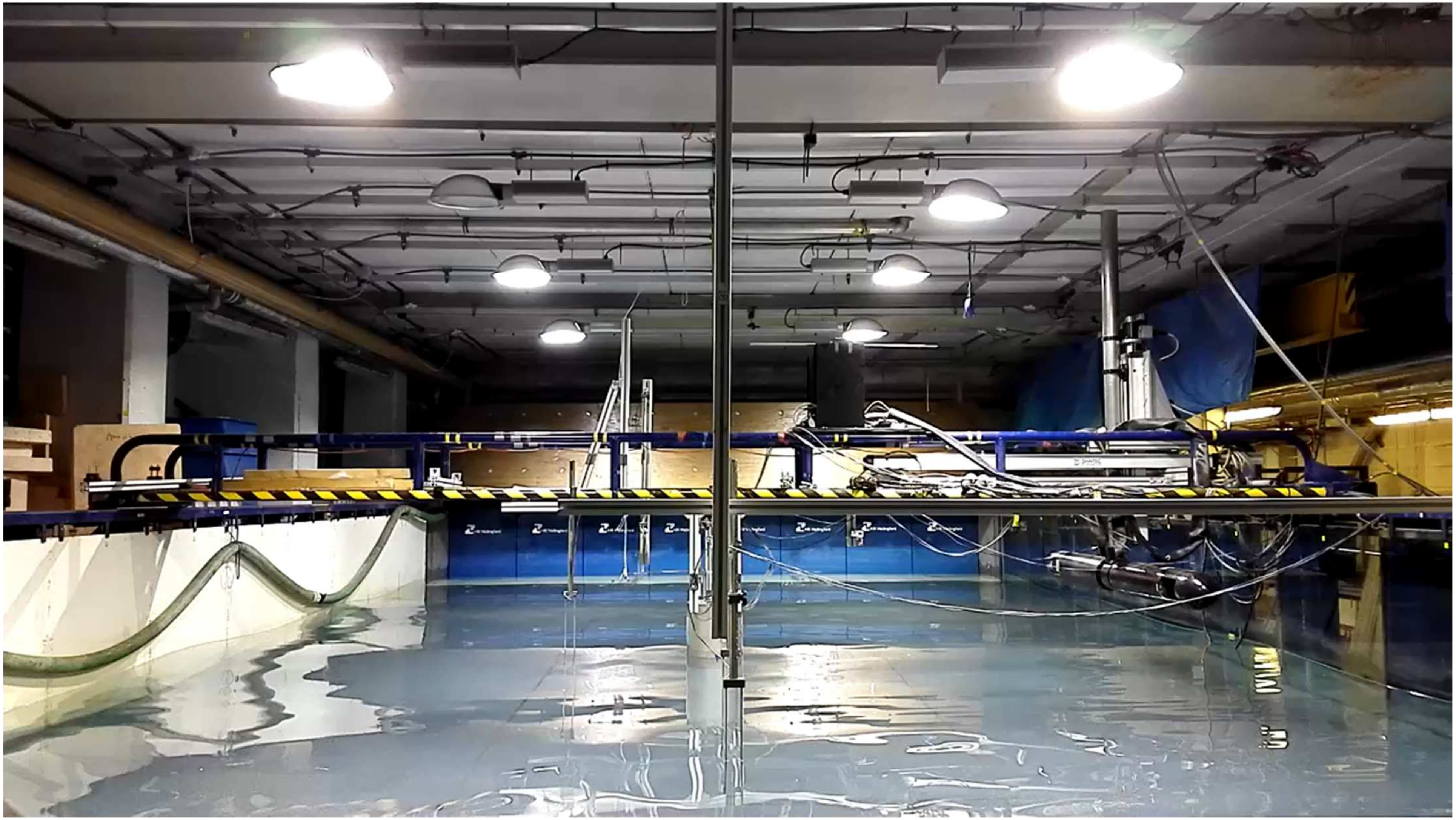
Comparison of non-linear effects between simulated results and experimental data in decay tests.

Uncertainties: (1) radiation and excitation approximations, (2) wave prediction, and (3) WEC system modelling. The following plot shows the displacement error of a W2M model respect to tank test data.



2. Jin, S., et al. *Non-linear analysis of a point absorber wave energy converter*. in *International Conference on Offshore Renewable Energy - CORE 2016*. 2016. Glasgow: ASRANet.

Tests with Regular Waves



Tests with Irregular Waves