ADVANCED CONTROL OF WAVE ENERGY CONVERTERS

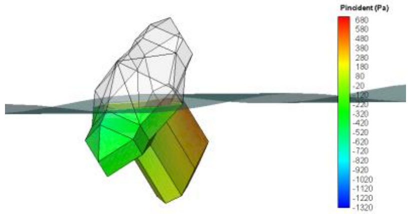
IFPEN’S APPROACH

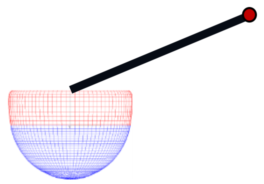
OUTLINE

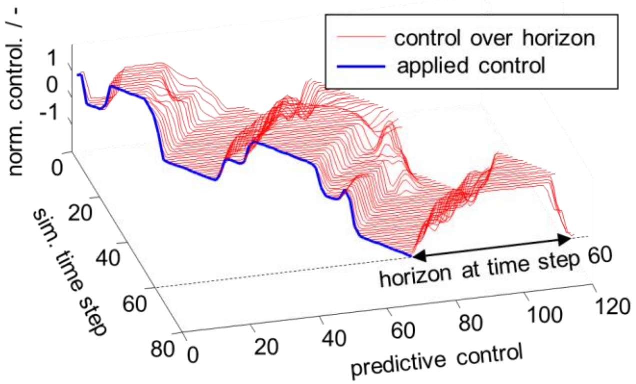
- WEC control development at IFPEN
- Model predictive versus conventional control
- IFPEN's control solution
  - Wave excitation force estimation
  - Wave excitation force prediction
  - Real-time compatible “efficiency-aware” model predictive control
- Preliminary experimental assessment of MPC
- Current work and perspectives

WEC CONTROL DEVELOPMENT AT IFPEN

- IFPEN has been studying WECs for several years
  - Based on the expertise in design and simulation of floating structures
  - Control identified as a key factor for its role in LCOE reduction after a few preliminary studies
    - SEAREV, Wavestar
- Dedicated project started in 2013, with a focus on
  - Point-absorbers
  - Model predictive control (MPC) solutions
- Milestones:
  - Development of a nonlinear MPC algorithm taking into account PTO efficiency for point absorbers capable of reactive control [2014]
  - Development and validation of a complete MPC system able to run in real-time [2015]



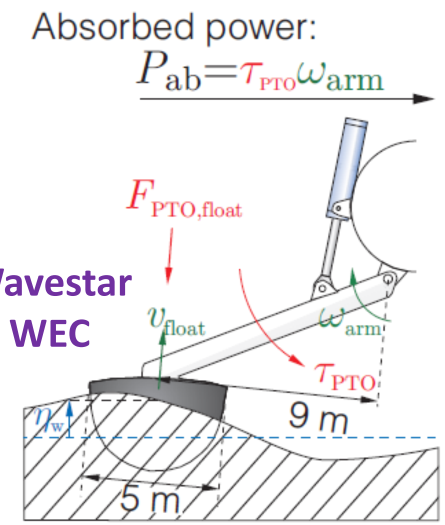


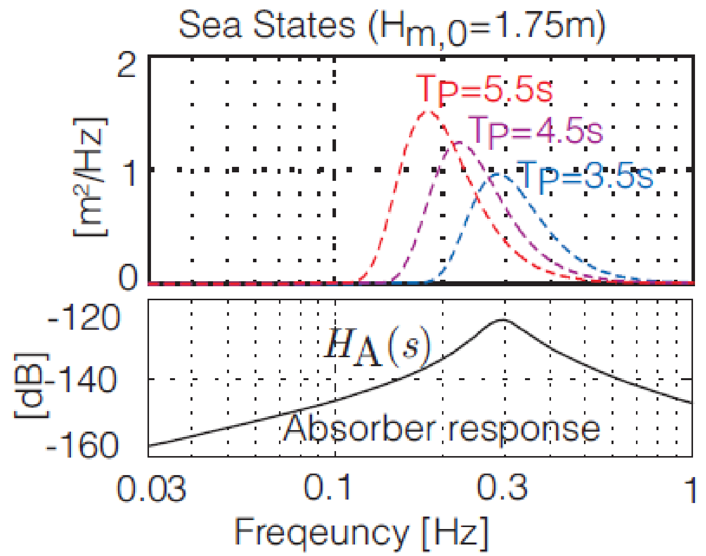


MODEL PREDICTIVE VS. CONVENTIONAL CONTROL [1]

- The narrower the band of its frequency response, the less adaptable a WEC is to sea state changes

Wavestar WEC





Different sea-state spectra

WEC velocity frequency response

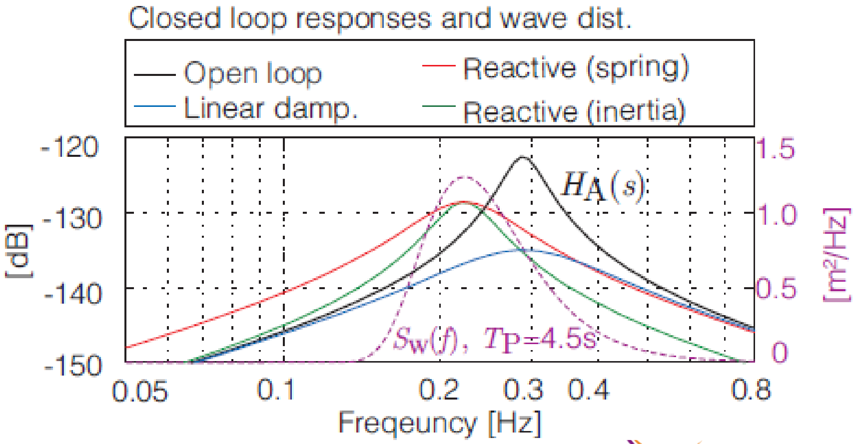
- Open-loop response can be reshaped modulating the applied PTO force, via a feedback on float motion
  - **1.** is the most common strategy
  - Other strategies (i.e. **2.** and **3.**) can harvest more energy, but require drawing power from the grid
    - Reactive vs. resistive control
    - PTO capable to work both in generator and in motor modes

1. $\tau_{PTO} = B_{PTO}\omega_{arm}$ **P**

2. $\tau_{PTO} = B_{PTO}\omega_{arm} + J_{PTO}\dot{\omega}_{arm}$ **PD**

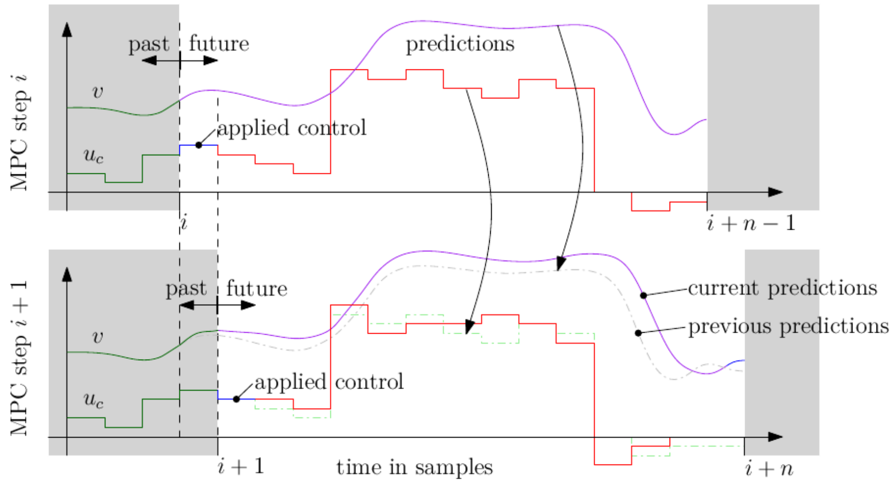
3. $\tau_{PTO} = B_{PTO}\omega_{arm} + k_{PTO}\theta_{arm}$ **PI**

Examples of control laws



MODEL PREDICTIVE VS. CONVENTIONAL CONTROL [2]

- MPC principle
  1. Predict system state over a short future horizon
  2. Compute the optimal control sequence maximising (or minimising) an objective function over this limited horizon
  3. Apply only the first step of computed control sequence during one period
  4. Start over at the next sample time



- Like a chess player
  - MPC « looks ahead » to find the winning strategy
  - applies one move at time
  - changes strategy depending on the reaction

- In the WEC context, the optimal control can be computed so as to maximise the energy harvested over the prediction horizon
- Thanks to the receding horizon principle, this a way of approaching the maximisation of energy (or mean power) over a long(er) time horizon

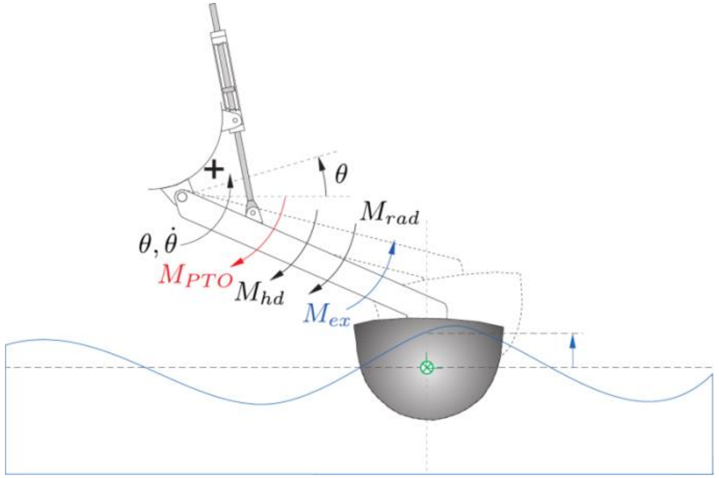
$$\frac{1}{T}\int_0^T P\mathrm{d}t$$

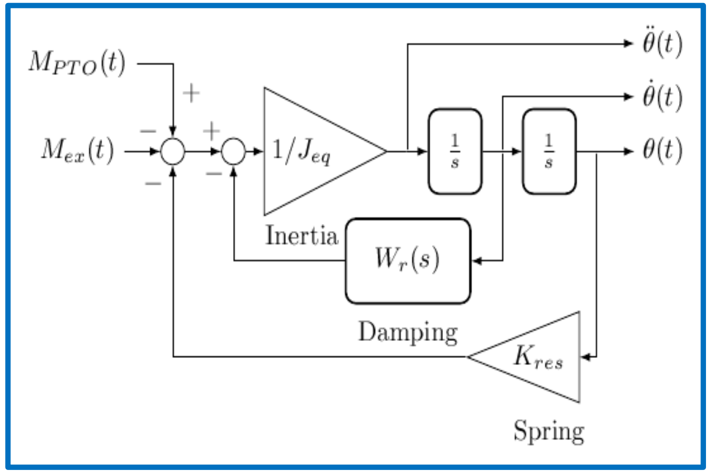
MODEL PREDICTIVE VS. CONVENTIONAL CONTROL [3]

- In the WEC context, the optimal control can be computed so as to maximise the energy harvested over the prediction horizon

- This requires a model of WEC dynamics, such as an Equation-of-Motion model derived from standard linear wave theory
  - $J_{eq}s^2\theta(s) + W_r(s)s\theta(s) + K_{res}\theta(s) = M_{ex}(s) - M_{PTO}(s)$
- $M_{PTO}(t)$ is the variable that allows controlling WEC dynamics
  - Force or torque applied by the PTO
- $M_{ex}(t)$, the incident wave excitation force, is an exogenous variable affecting WEC dynamics

MPC requires the knowledge (forecast) of future values of incident wave excitation force M_{ex} over the prediction horizon





- J_{eq}, K_{res} and $W_r(s)$ can be derived from BEM (boundary element methods) computations, estimated via dedicated experiments or both

IFPEN'S CONTROL SOLUTION

- The MPC algorithm (in IFPEN's approach) is designed to maximise, over a given time horizon T, the harvested electrical power (not the hydrodynamic power)

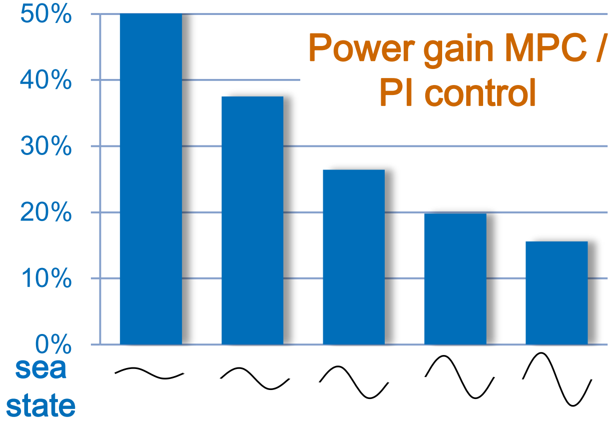
$$\overline{P}_e = \frac{1}{T}\int_0^T P_e \mathrm{d}t \qquad \begin{cases} P_e = \eta P_a \\ \quad = \eta M_{PTO}\omega \end{cases}$$

- With PTO efficiency $\boldsymbol{\eta}$<1
  - $P_e < P_a$ when generating (to grid)
  - $P_e > P_a$ when motoring (from grid)

MPC must "know" that realistic PTO efficiencies make power taken from the grid more expensive and reduce the value of generated electric power

- IFPEN has shown in simulation [1], that this solution can improve energy harvesting of up to 50% compared to the standard solution [B]
  - $M_{PTO} = B_{PTO}\omega + k_{PTO}\theta$,
  - with B_{PTO}, k_{PTO} computed off-line for each sea state

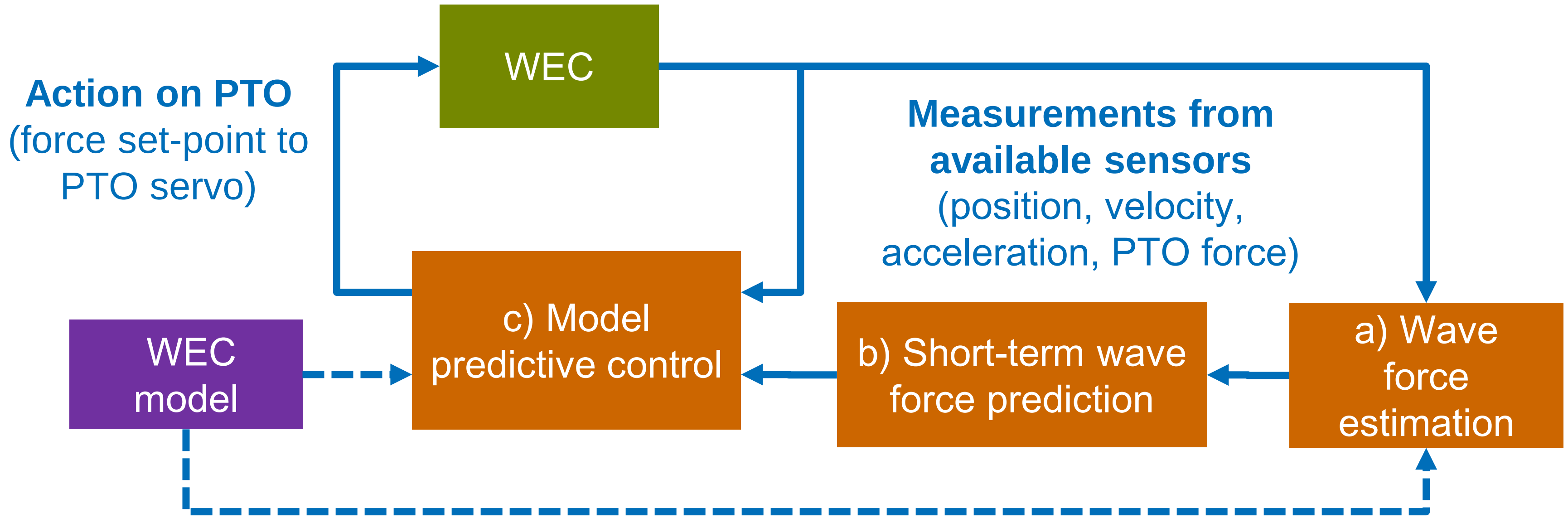
  and that the MPC solution is very close to the off-line optimal solution



- Unfortunately, the real-time implementation of this solution is difficult
  - High computational costs associated to a nonlinear MPC formulation (non-convex objective function)
  - Online estimation of wave excitation force
  - Accuracy and robustness of wave excitation force predictions

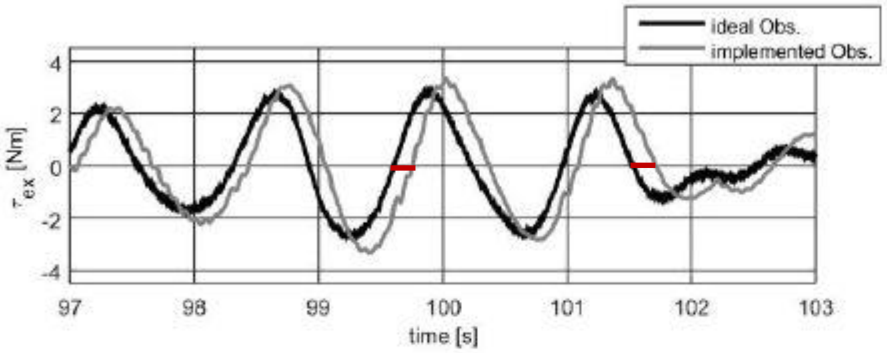
IFPEN'S CONTROL SOLUTION: THE BUILDING BLOCKS

- These issues were dealt with in the new generation of IFPEN's control solution, comprising
  a) An online estimation algorithm, with no need of additional sensors, for wave excitation force (not directly measurable)
  b) An accurate and robust algorithm for short-term wave force prediction (1-5 s) from wave force estimation time series
  c) Real-time compatible nonlinear model predictive control algorithm using wave force prediction, taking into account PTO efficiency



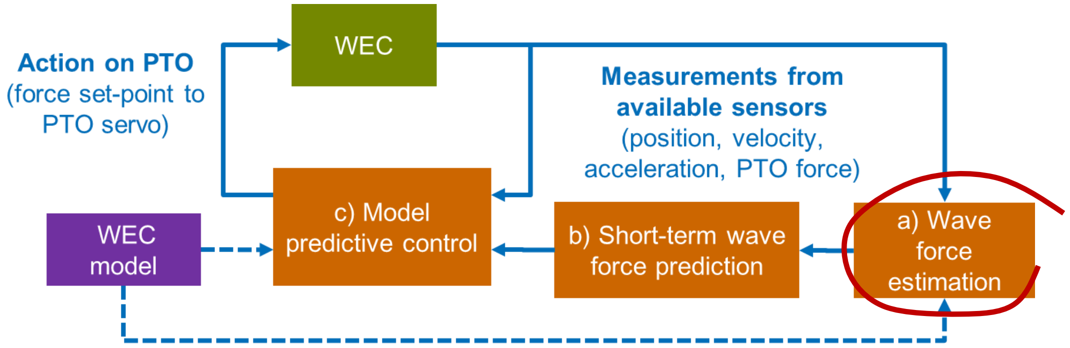
WAVE EXCITATION FORCE ESTIMATION

- Wave excitation force/moment is measured offline in a dedicated experiment where the float is blocked a force/torque sensor measures the effect of the wave on the WEC
- During normal WEC operation, this is an unknown quantity that must be estimated online

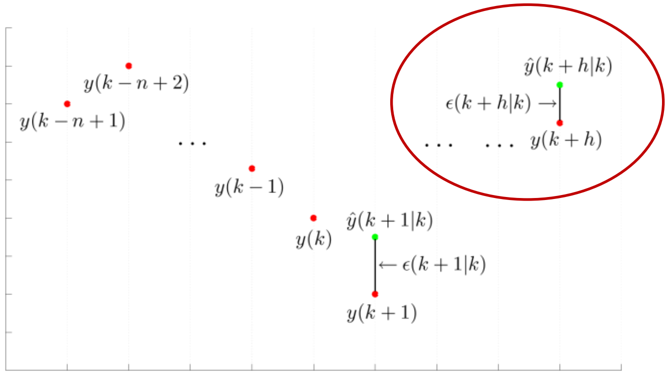


- Few solutions proposed in literature and even fewer tested on a real system
  - E.g., bank of independent harmonic oscillators [C]
  - Unexploitable in practice, in particular because of a lag in the estimation larger than the control sampling period

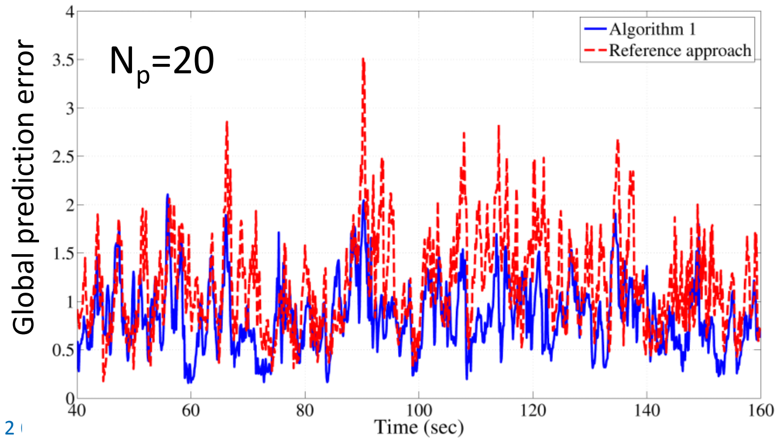
- IFPEN's approach is based on a Kalman filter coupled with a random walk model:
  - Only float position and velocity measurements are used together with PTO force/torque
  - No significant lag in the estimation
  - Time-varying model of sea state



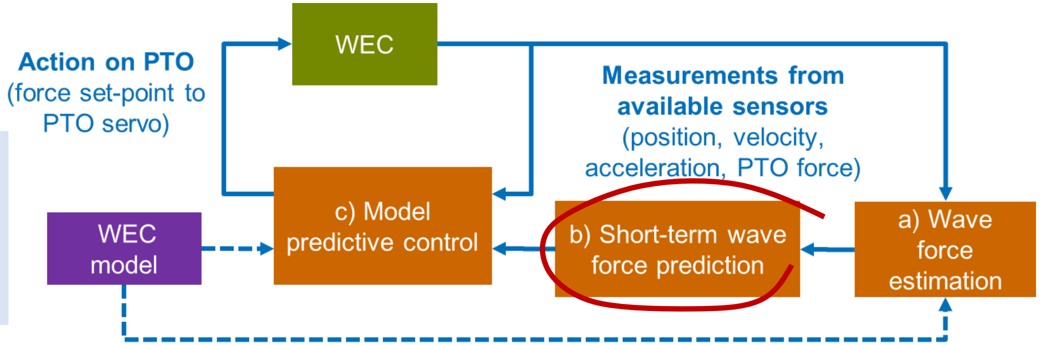
WAVE EXCITATION FORCE PREDICTION



- The most popular method to forecast future values of wave excitation force (or wave elevation) from time series of past measurements is Fusco and Ringwood's [D]
  - An autoregressive (AR) model is used, with parameters re-identified off-line in a batch procedure by minimising a multi-step least-square prediction error criterion
- IFPEN's approach is based on a Kalman filter bank used for online prediction with AR models
  - Low computational complexity
  - No supervisory layer to trigger AR model parameters identification (sea state changes)
  - Wide range of sampling periods allowed



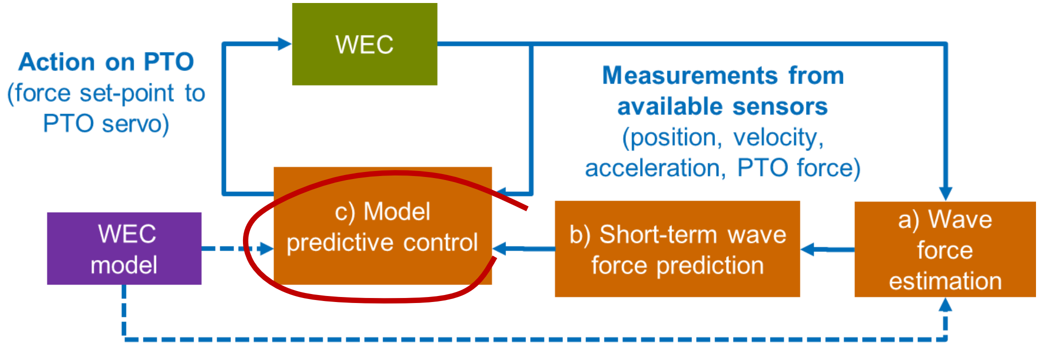
Fully implementable and more accurate, w.r.t. [D]



REAL-TIME COMPATIBLE “EFFICIENCY-AWARE” MODEL PREDICTIVE CONTROL

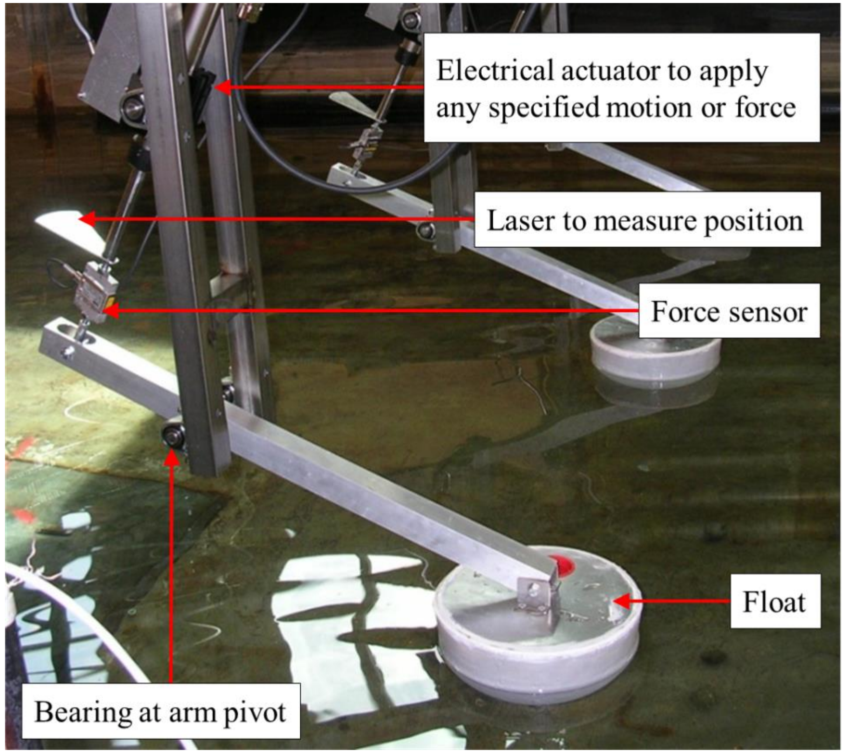
- Solving the original nonlinear MPC problem with imperfect power conversion in the PTO taken into account is currently too computationally expensive
  - Sampling period $T_s < 100ms$ needed in a small-scale set-up could only be handled with special hardware
  - Same issues for other approaches in the literature with realistic power maximisation criteria
- New formulation developed
  - Imperfect power conversion in the PTO still taken into account
  - Objective function convexified with minimal loss of optimality

Computational load can be hugely reduced with a convex objective function (10^3-10^5 times less is a reasonable figure)

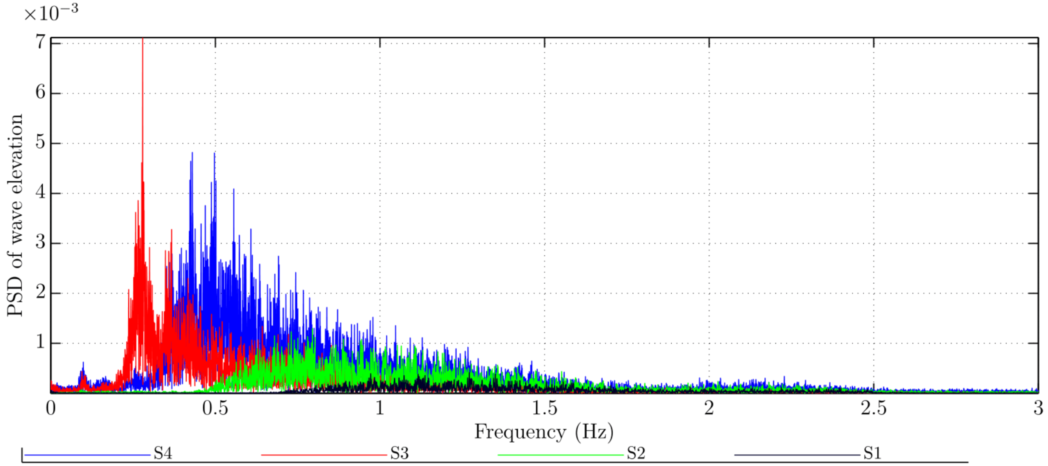


FIRST EXPERIMENTAL ASSESSMENT OF MPC: TEST FACILITY AND SETUP

- Tests in Aalborg University basin in June 2015 on a pivoting-buoy point absorber



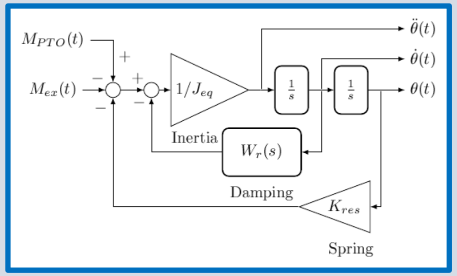
- 1:20 scaled version of WaveStar Hanstholm prototype [A]
- float attached to an arm, connected to an electric PTO
- position & acceleration sensors (velocity via Kalman filter)
- 4 different sea states plus a transition (S2 ⇒ S3)

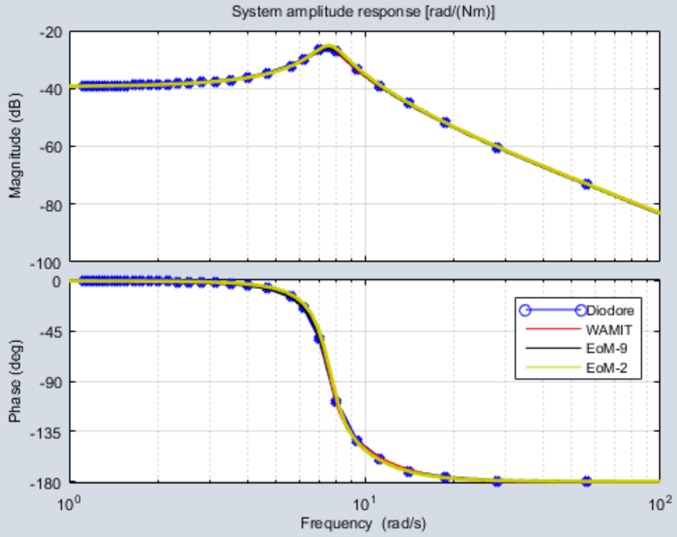


FIRST EXPERIMENTAL ASSESSMENT OF MPC: CONTROL DESIGN AND IMPLEMENTATION

NEW ENERGIES

Control model and design parameters



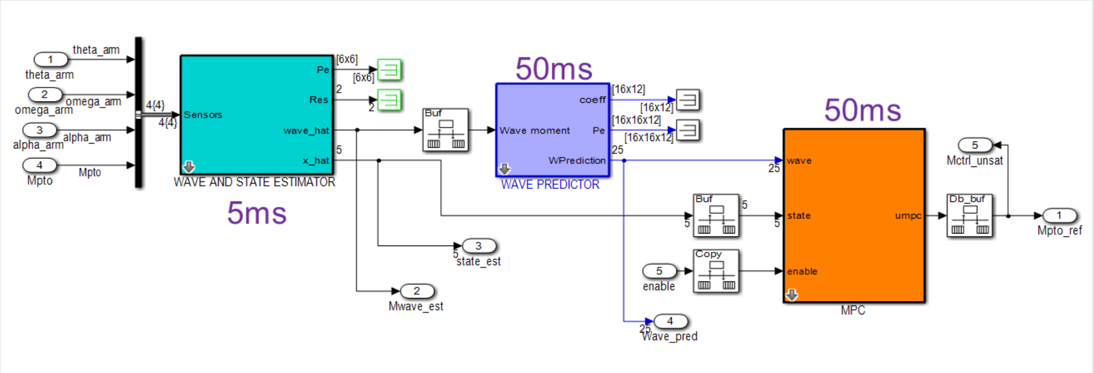


Model EoM-9

- $J_{mech} = 1.004\ kg\ m^2, J_{add,\infty} = 0.461\ kg\ m^2$, $K_{res} = 93\ N\ m\ rad^{-1}$
- $W_r(s) = \frac{38.02\ s^2 + 25.59\ s}{s^3 + 14.07\ s^2 + 97.5\ s + 32.65}$

- $\eta = 0.7$, 25-steps prediction horizon

Implementation



- Running in real-time with $T_s = 50\text{ms}$,
- Task Execution Time $T_{TE} = 145\mu\text{s} \ll 1\text{ms}$

Reference control

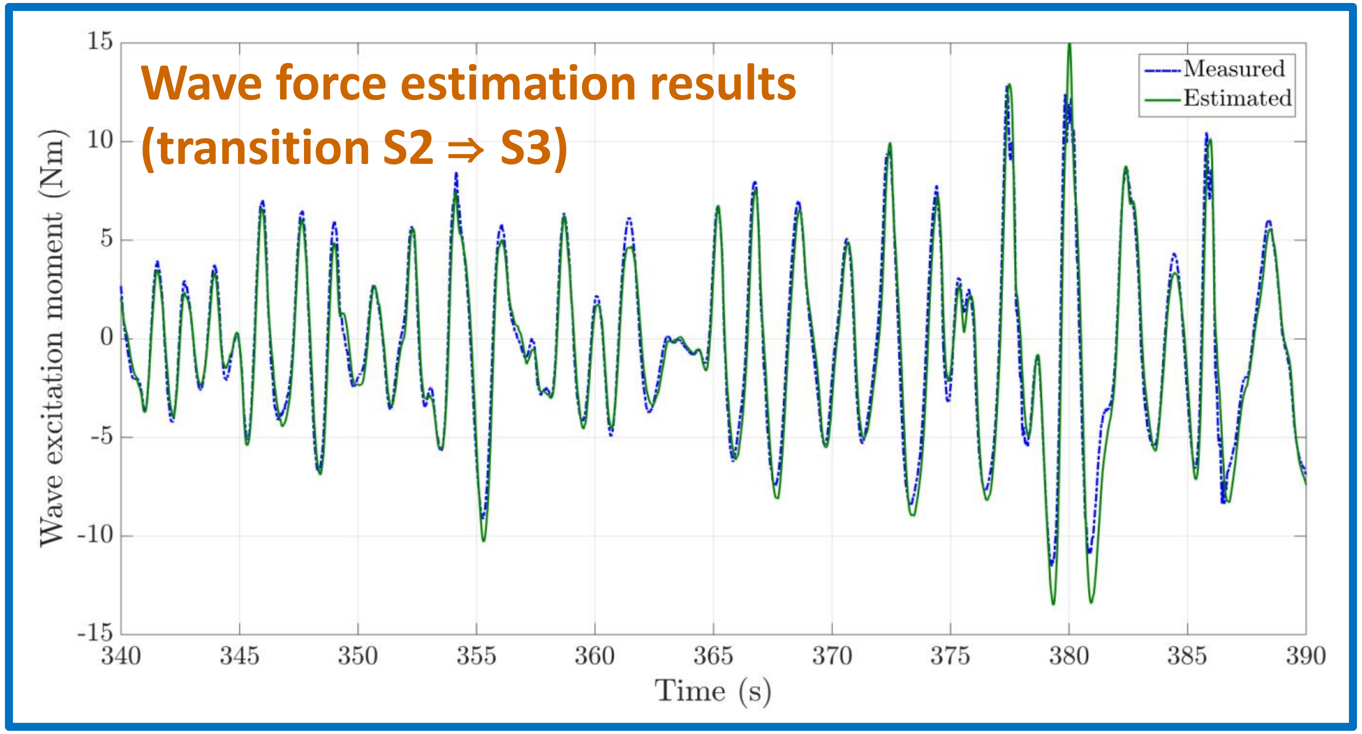
- PI velocity feedback $M_{PTO} = B_{PTO}\omega + k_{PTO}\theta$,
- with gains provided by Wavestar

! MPC retuning needed as PTO servo dynamics proved much slower and non-linear than expected

FIRST EXPERIMENTAL ASSESSMENT OF MPC: WAVE EXCITATION FORCE ESTIMATION RESULTS

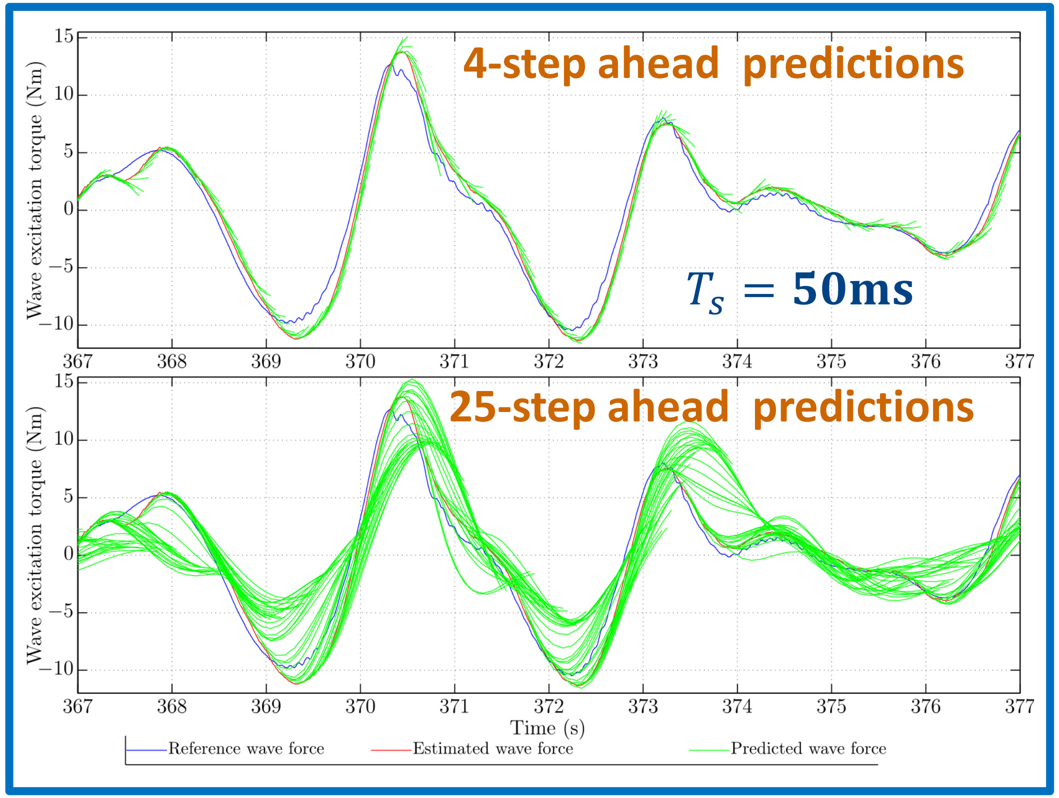
NEW ENERGIES

- Wave excitation force estimation
  - shows excellent fit with no noticeable delay w.r.t. to online measurements
  - works even during sea state transitions



FIRST EXPERIMENTAL ASSESSMENT OF MPC: WAVE EXCITATION FORCE PREDICTION

- Wave excitation force prediction shows
  - Very good fit over short horizons
  - Acceptable fit over longer horizons



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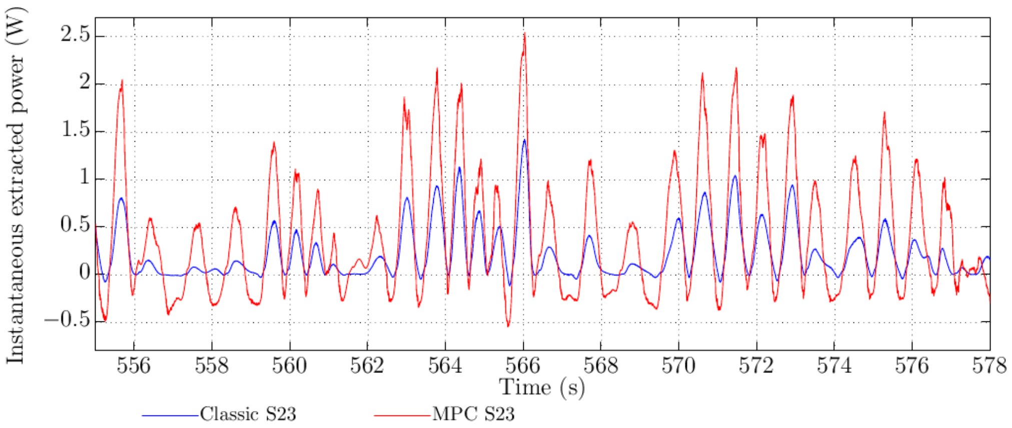
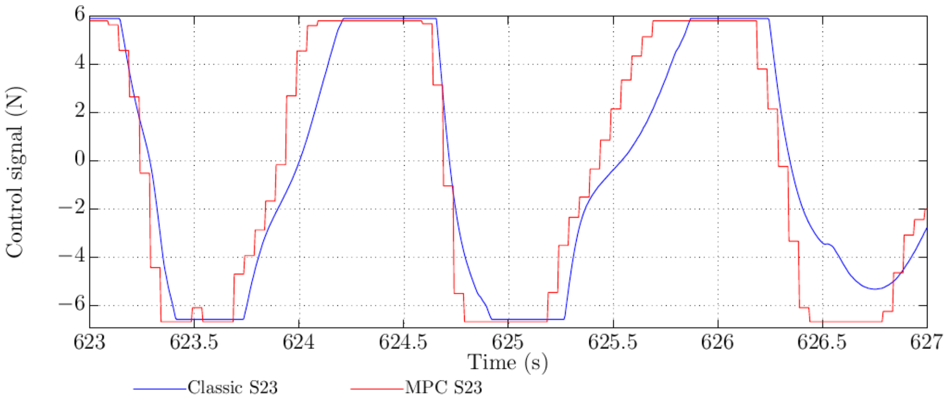
FIRST EXPERIMENTAL ASSESSMENT OF MPC: MODEL PREDICTIVE CONTROL

- MPC
  - runs in real-time with $T_s = 50\text{ms}$
  - harvests more energy than reference PI controllers
    - after retuning of internal weightings to cope with slow (i.e. non negligible) PTO dynamics

Power gain MPC / PI control [%]	Waves				
	S1	S2	S3	S4	S23
MPC gain	**41.4**	**7.6**	**-**	**-**	**-**
MPC PTO gain	**-**	**15.7**	**20.9**	**7.6**	**81.5**

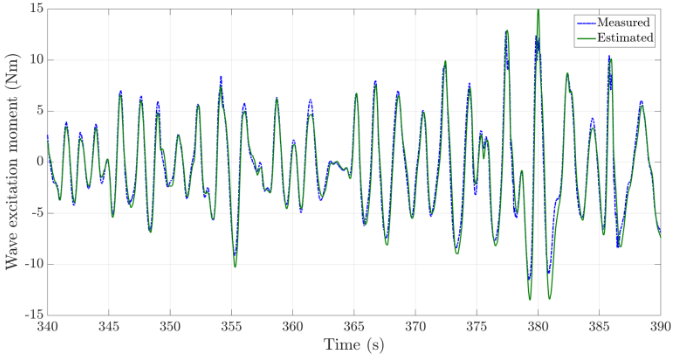




- MPC allows larger reactive power excursions in order to increase extracted power
- MPC respects constraints on control signal (force setpoint) while PI output is just clamped

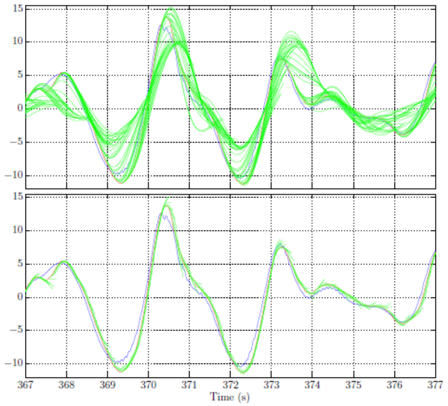
FIRST EXPERIMENTAL ASSESSMENT OF MPC: SUMMARY

(Off-line) measured vs. estimated forces



- Excellent results for wave excitation force estimation

25- / 4-step ahead predictions

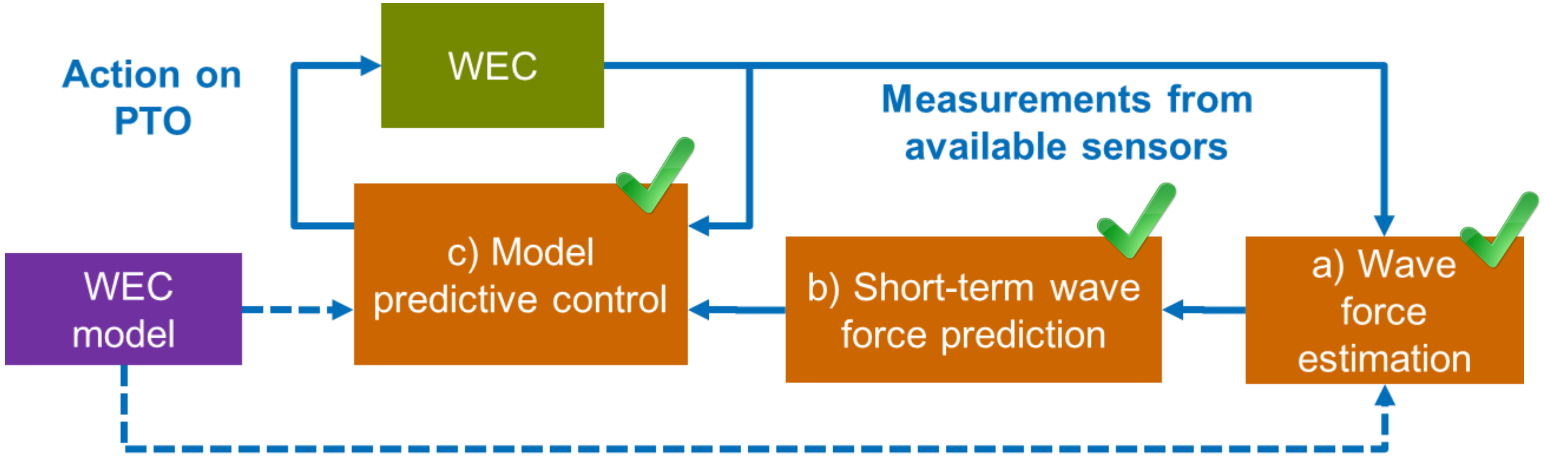


- Acceptable prediction performance

Gain MPC / PI control [%]

Wave	S1L	S2L	S3L	S4L	S23L
MPC	41.4	7.6	-	-	-
MPC PTO	-	15.7	20.9	8.7	81.5

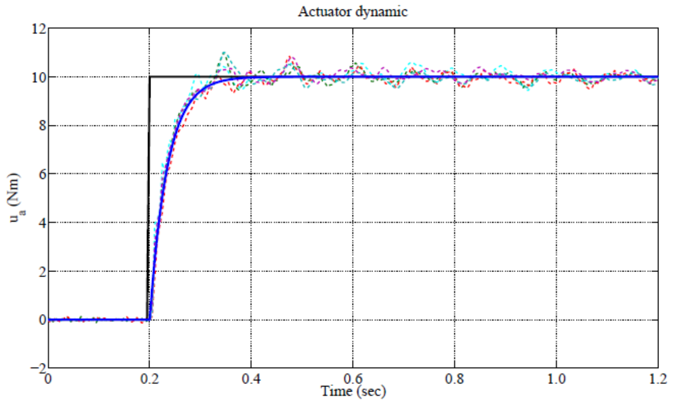
- MPC ran in real-time with $T_s = \mathbf{50ms}$
- MPC harvested more energy than the PI controllers with gain computed by Wavestar (after retuning)



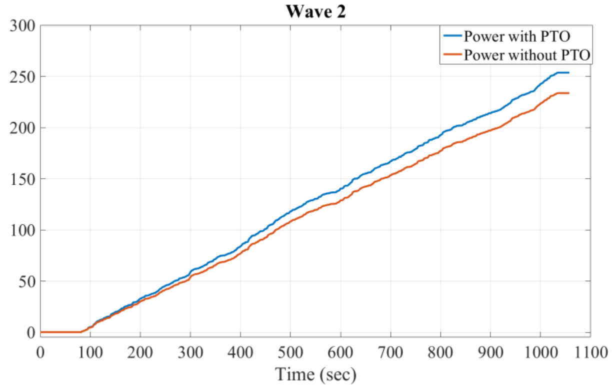
First reported successful real-time implementation of a full-fledged NMPC for a WEC in a realistic setup

CURRENT WORK AND PERSPECTIVES:
TAKING INTO ACCOUNT PTO DYNAMICS IN MPC DESIGN

- PTO dynamics should be fast enough with respect to WEC dynamics to be neglected
- If it is not the case, PTO dynamics must be included in the control design
- This has already be done for linear dynamics



New MPC formulation with PTO dynamics included in control model



PTO dynamics of the small-scale set-up in AAU

Expected increase in power production

- Non linear or discrete PTO dynamics are more difficult to take into account
  - This issue concerns all control strategies, though

CURRENT WORK AND PERSPECTIVES: TAKING INTO ACCOUNT NON CONSTANT PTO EFFICIENCY

- PTO efficiency is not constant in reality
  - For several PTOs it can be considered constant above a rated power threshold (errors affect mostly small-power operating zones)
- The original MPC formulation of [1] can take into account variable efficiencies function of rated power, in the form of look-up tables
- The real-time compatible MPC formulation should be extended accordingly

CURRENT WORK AND PERSPECTIVES: COORDINATED MODEL PREDICTIVE CONTROL

- Interactions among floats can be very strong in some WEC designs

FLOATING POWER PLANT

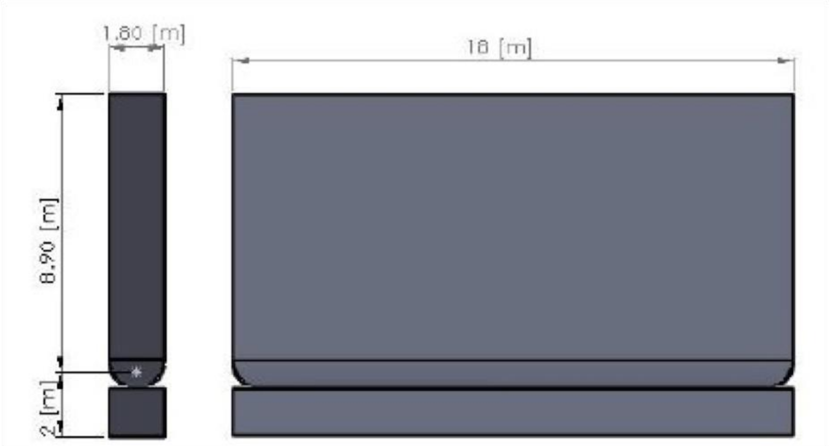
Eco Wave Power

WAVESTAR

- The performance of decentralised MPC (single-float control) has not been assessed yet for those systems
- A centralised (coordinated) controller should perform better than decentralised ones
  - Designing a centralised MPC is a challenging task

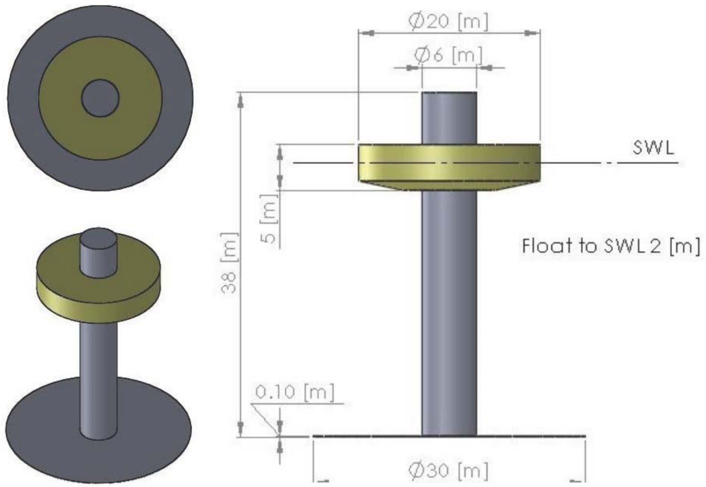
CURRENT WORK AND PERSPECTIVES: ADAPTATIONS OF MPC TO OTHER DEVICES

- Extensions of the MPC solution to other machines are being studied
  - For machines with (dominant) 1 DOF movements they are relatively straightforward
    - An adaptation of wave force estimation algorithm to take into account drag force may be needed
  - Once the design adapted, expected performances must be evaluated to verify if the improvement in energy harvesting brought by MPC is significant
  - For machines with more complex motion, new developments are needed



OSWEC

WECs modelled in WEC-Sim



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