Exercise 5+6 - Introduction to Control and Lab Exercises

Kramer, Morten Mejlhede

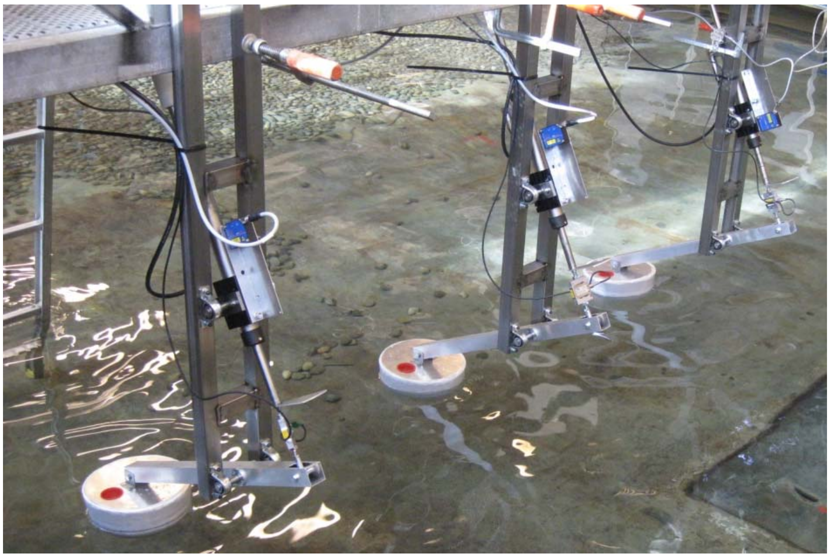
Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Kramer, M. M. (2015, Aug 25). Exercise 5+6 - Introduction to Control and Lab Exercises.

Introduction to Control and Lab Exercises

The laboratory exercises are including both numerical and experimental work. A simulink model is provided to make realtime control on the laboratory setups. The groups are welcome to modify the program during the exercises. The groups are expected to make their own programs for numerical simulations on the device. Hydrodynamic parameters found using WAMIT are provided, but the groups are of course welcome to calculate their own parameters (e.g. using Nemoh).



Exercise 5: Simple control and regular wave

The performance is investigated in the following wave: Regular wave with target ***H* = 0.07 m and *T* = 1.5 s**. Water depth is 5 m. Be aware that the actual measured wave height might be slightly different!

Only resistive control is considered (i.e. only a linear damping gain). The exercise covers:

- Measure experimentally on the Wavestar absorbers the angular motion and PTO-moment, and calculate the power absorption by multiplying the velocity and the moment.
  - Vary the PTO damping coefficient c_c to find the optimal value that gives the maximum average power output
- Make a numerical model and calculate the motion amplitude and power output depending on the control damping gain, and include the results on the plots with experimental results
- Make a Power Point presentation containing:
  - A front page with group number and names of participants
  - A short introduction with pictures and/or other relevant material
  - Plots with damping coefficient on x-axis and y-axes with:
    - average absorbed power and peak absorbed power
    - amplitude of angular position
  - One or more plots with time series (e.g. of angular position, velocity, PTO-moment and power corresponding to the optimal damping value)
  - If time permits: A conclusion or discussion (e.g. experiences)

Remember to include units for all parameters and on figure axes!

If time permits, I suggest that you try out reactive control, i.e. in addition to the damping control gain you also include a stiffness gain.

Exercise 6: Advanced control and irregular wave

The performances are investigated in a **short irregular wave with target H_{m0} = 0.07 m and T_P = 1.5 s**. Water depth is 5 m. **Length of time series = 32 seconds**. The wave is generated using a PM-spectrum and IFFT method, IFFT-length is set to 2^10 = 1024 samples, and sampling frequency 32 Hz, hereby ensuring that the wave is repeated every 1024/32 = 32 seconds. Average values should therefore be calculated over a period of 32 s.

Exercise 6a: Resistive control in irregular wave

The mission is to compare measured motions and power production with numerically calculated motions and power production. The experimental work is the same as performed in the first exercise; the only difference is that now the wave is an irregular wave.

- Measure experimentally on the Wavestar absorbers the angular motion and PTO-moment, and calculate the power absorption by multiplying the velocity and the moment.
    - Vary the PTO damping coefficient c_c to find the optimal value that gives the maximum average power output
- Calculate numerically the motion and power absorption for the waves using the applied control strategy.
- Extend the Power Point presentation from the first exercise by including:
    - Plots with damping coefficient on x-axis and y-axes with (one curve with numerical estimates, and points showing measurements):
        - average and peak absorbed power
        - peak (positive and negative) angular position
    - One or more plots with time series (e.g. of angular position, velocity, PTO-moment and power corresponding to the optimal damping value)
    - Discuss reasons for possible differences between numerical estimates and experimental results

Exercise 6b: Reactive control in irregular wave

Same procedure as for previous exercise, but now using reactive control (k_c and c_c). The power point is extended with the new results.

Reactive control without restrictions or constraints is normally leading to unrealistic large motions and large violations of physical limits of the linear wave theory. Include your experiences regarding this issue in the presentation.

Exercise 6c: Reactive control in irregular wave, including constraints

The numerical model and experimental work is extended by including constraints on PTO moment M_C and PTO efficiency. Additional more advanced control strategies (m_c, k_c, c_c, integral term on motion, and possibly use wave elevation measurements and real-time prediction of wave excitation force) could also be tested.

Advanced control strategies and constraints are included in the control software and tested on the absorbers. The goal is to get the highest possible experimentally measured average electrical power output.

The groups compete in getting the highest measured average electrical power. There will be a price to the winning group.

Two constraints must be included:

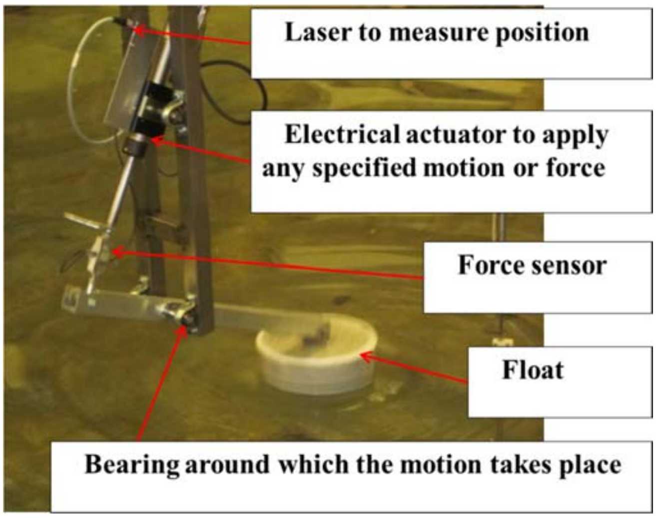
- A PTO efficiency of 70 % (identical for both positive and negative power transfer). The model to be applied for the PTO efficiency is described in the lecture slides.
- A constraint on the maximum PTO moment (saturation value) of M_C = +/-6.25 Nm. This value corresponds to the Wavestar Hanstholm cylinder capabilities scaled to the laboratory model size.

The power point is extended with the new results. It is recommended to discuss (or even do investigations on) influences of non-ideal characteristics of the set-up, such as:

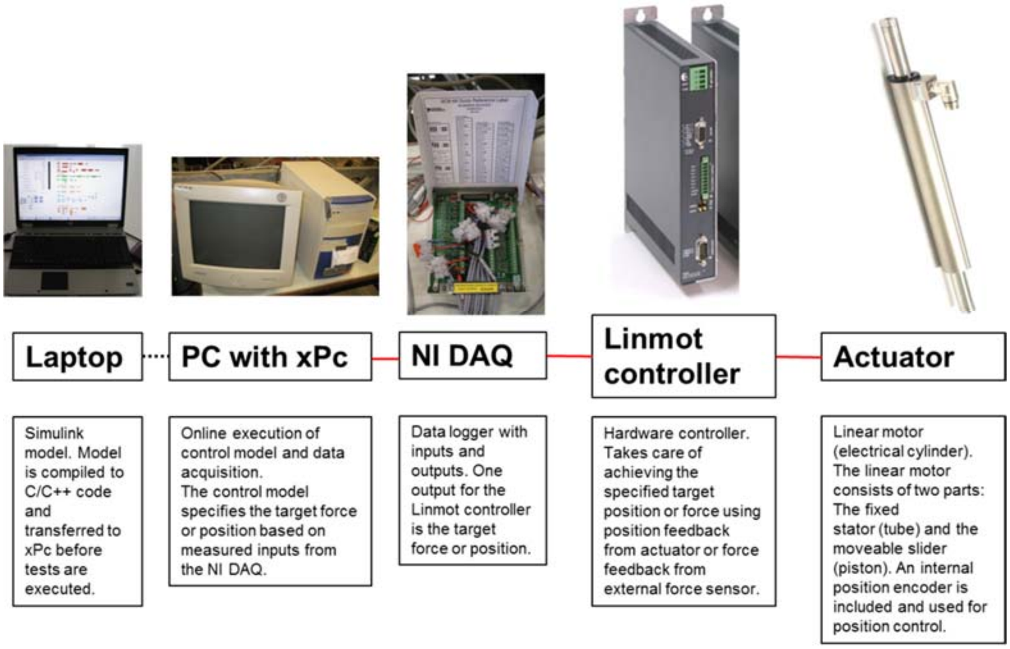
- The actual control force is in practice different from the target control force due to the capability of the PTO to act instantaneously according to the demands. The relation between the actual force and the target force is often for simplicity modelled by use of a transfer function.
- Information of the motion is in practice non-ideal due to measurement noise and delays of signals. The signal delays in the experiments are mainly due to digital filtering.
- Friction forces in bearings affects the motions. The friction forces can be measured and a friction model could potentially be included in the numerical model in order to investigate the influence of friction on the performance.

Appendix A: Description of experimental set-up

Each individual point absorber is equipped with an electrical actuator, a controller and a computer. Measurements of motions are performed by a laser, and forces are measured by a strain gauge force transducer. The computer software can in principle apply any force or motion (within some wide ranges) using a given control strategy. Pre-made software for simple types of control is used in the exercise, but the option to elaborate further on the software using more advanced control is readily available if the time permits. In each sea state the control parameters are changed in order to find the values that result in the maximum average power output. Using measurements of force and motion the instantaneous absorbed power is calculated, and the mean value is calculated by taking the average over a given time period.



Sketch of the hardware used for the control:



Simulink model. Model is compiled to C/C++ code and transferred to xPc before tests are executed.

Online execution of control model and data acquisition. The control model specifies the target force or position based on measured inputs from the NI DAQ.

Data logger with inputs and outputs. One output for the Linmot controller is the target force or position.

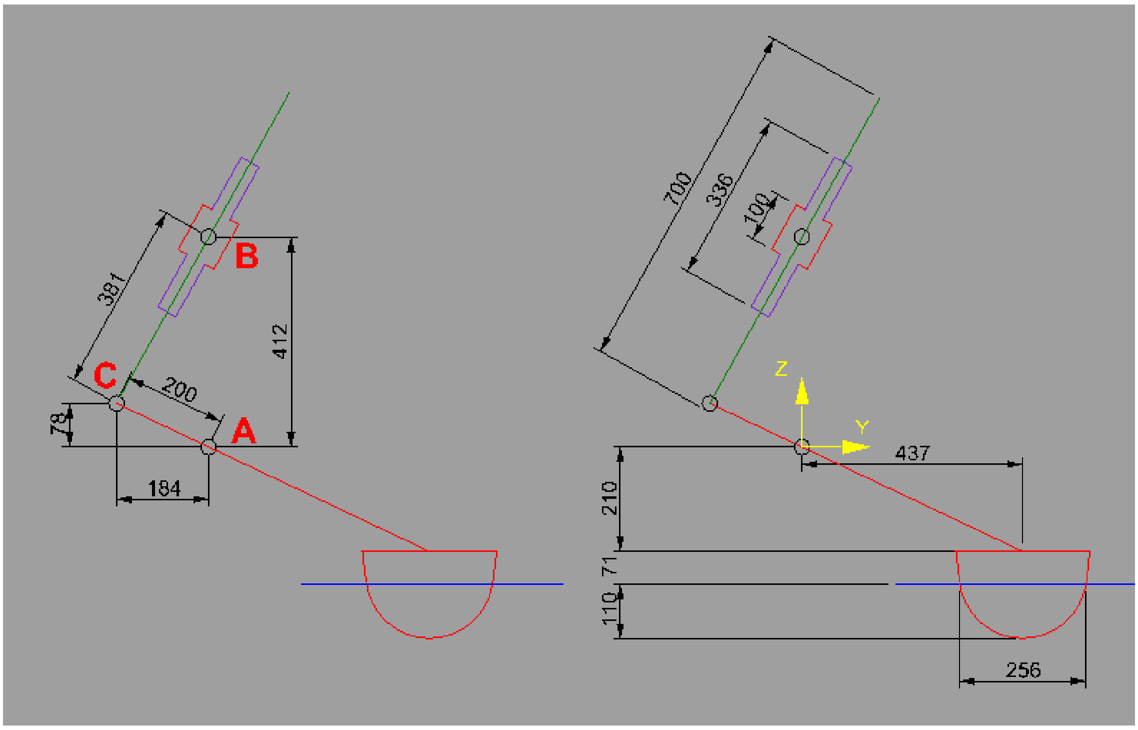
Hardware controller. Takes care of achieving the specified target position or force using position feedback from actuator or force feedback from external force sensor.

Linear motor (electrical cylinder). The linear motor consists of two parts: The fixed stator (tube) and the moveable slider (piston). An internal position encoder is included and used for position control.

The laboratory model is a scale 1:20 of the Wavestar Hanstholm prototype (please note that the actual values for the model may in reality differ slightly from the target ones provided in the table):

Parameter		**Hanstholm prototype**	**Laboratory model**
Scale	-	1	0.05
Mass	kg	3.535E+04	4.004
Mass inertia moment	kgm^2	2.555E+06	1.00
Draft	m	2.134	0.110
Diameter of float at water line	m	4.946	0.256
Centre of gravity $y_{G,0}$	m	6.428	0.415
Centre of gravity $z_{G,0}$	m	-3.973	-0.206
Centre of buoyancy $y_{E,0}$	m	8.660	0.437
Centre of buoyancy $z_{E,0}$	m	-6.293	-0.321

The experimental set-up is shown below. Measures are in mm.



Appendix B: Numerical model and hydrodynamic parameters

The Wavestar absorbers are described by a single degree of freedom (DOF); rotation around the bearing. The equations of motion is therefore given using moments and rotational motions (rotational angle, rotational velocity, and rotational acceleration). The control in the numerical model is done by applying the control moment M_c.

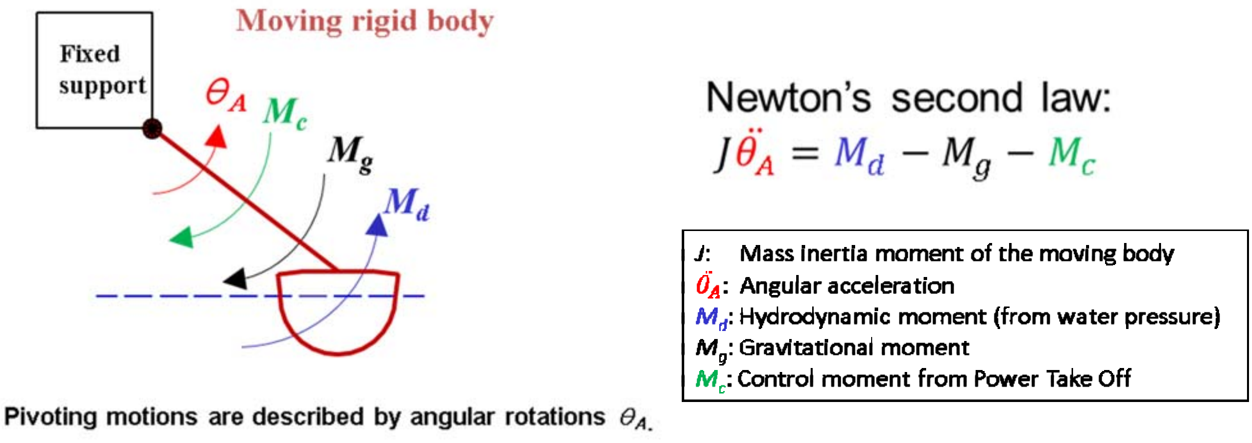


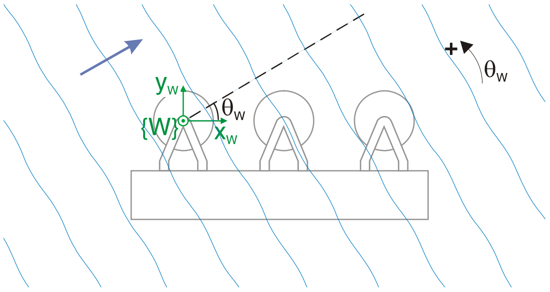
Figure 1: Equation of motion for the pivoting Wavestar absorbers.

Three simple strategies are:

- No control: $M_{\boldsymbol{c}} = 0$
- Resistive control: $M_{\boldsymbol{c}} = \boldsymbol{c_c}\dot{\theta}_A$
- Reactive control: $M_c = \boldsymbol{c_c}\dot{\theta}_A + \boldsymbol{k_c}\theta_A$

The task for the optimization is to find the optimal values of the gain factors (i.e. c_c and k_c in case of reactive control).

The wave direction is defined according to a wave coordinate system {W}. The wave angle θ_w is defined as the angle between the x-axis of the wave coordinate system and the wave direction.

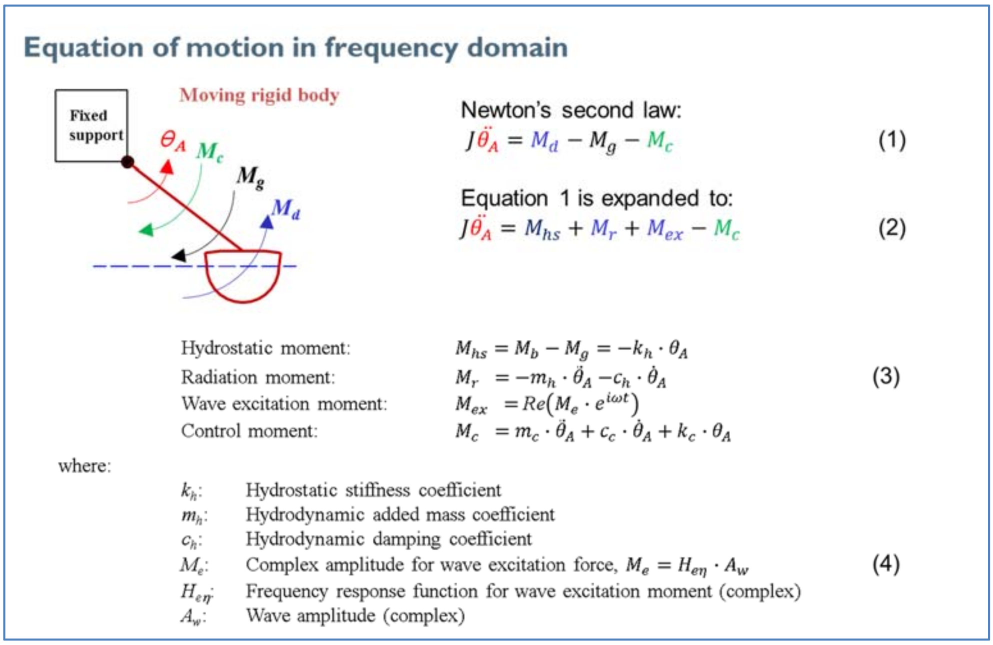


Laboratory experiments have been performed to measure experimentally the as-built hydrostatic stiffness and mass inertia moment. The main results are:

Hydrostatic stiffness: k_h = 92.1 Nm/rad

Mass inertia moment: J = 1.00 kgm^2

Hydrodynamic parameters in the frequency domain (i.e. the Frequency Response Functions, FRF) have been calculated for the wave direction +90° using Wamit. Recall the definitions from the slide in the presentation:



Equation of motion in frequency domain

Newton's second law:

$$J\ddot{\theta}_A = M_d - M_g - M_c \quad (1)$$

Equation 1 is expanded to:

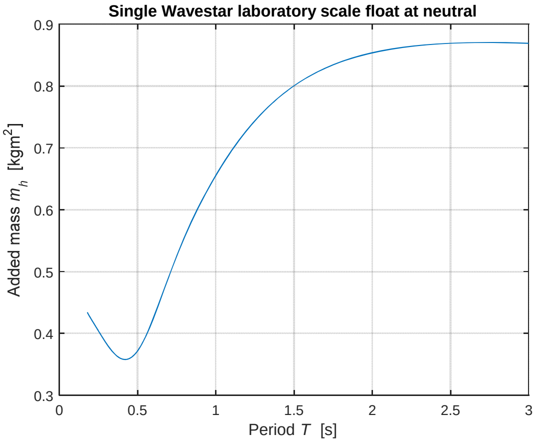
$$J\ddot{\theta}_A = M_{hs} + M_r + M_{ex} - M_c \quad (2)$$

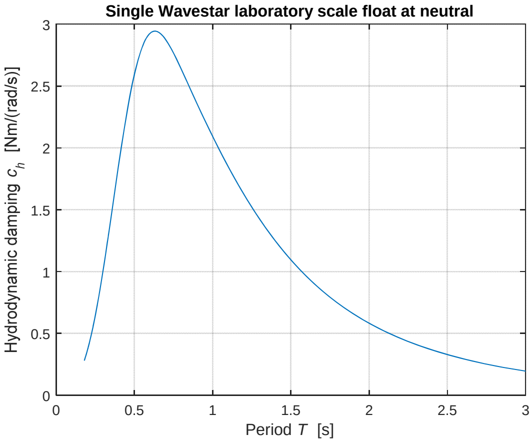
Hydrostatic moment: $M_{hs} = M_b - M_g = -k_h \cdot \theta_A$
Radiation moment: $M_r = -m_h \cdot \ddot{\theta}_A - c_h \cdot \dot{\theta}_A$ (3)
Wave excitation moment: $M_{ex} = Re\left(M_e \cdot e^{i\omega t}\right)$
Control moment: $M_c = m_c \cdot \ddot{\theta}_A + c_c \cdot \dot{\theta}_A + k_c \cdot \theta_A$

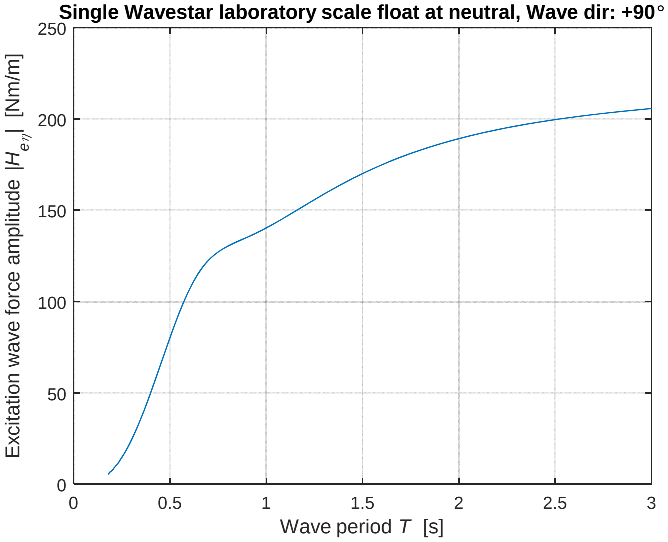
where:

k_h: Hydrostatic stiffness coefficient
m_h: Hydrodynamic added mass coefficient
c_h: Hydrodynamic damping coefficient
M_e: Complex amplitude for wave excitation force, $M_e = H_{e\eta} \cdot A_w$ (4)
$H_{e\eta}$: Frequency response function for wave excitation moment (complex)
A_w: Wave amplitude (complex)

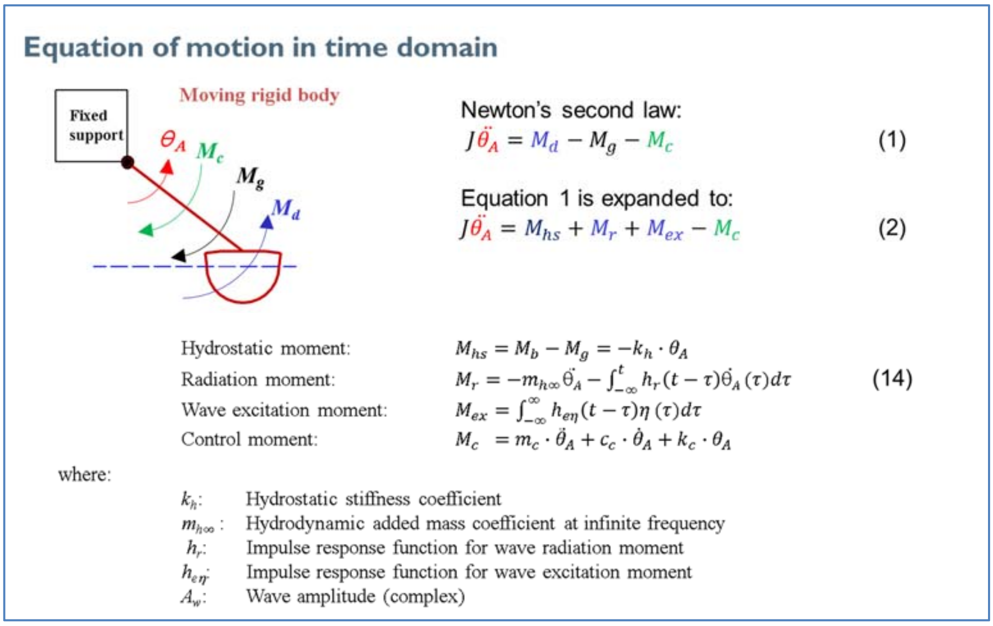
The parameters are loaded using the Matlab program "Parameters_FrequencyDomain.m".


Single Wavestar laboratory scale float at neutral


Single Wavestar laboratory scale float at neutral


Single Wavestar laboratory scale float at neutral, Wave dir: +90°

The Impulse Response Functions (IRF's) to be used for time domain simulations have been calculated for the wave direction +90° using the FRF's from Wamit. The parameters are loaded using the Matlab program "Parameters_TimeDomain.m".



Equation of motion in time domain

Newton's second law:

$$J\ddot{\theta}_A = M_d - M_g - M_c \qquad (1)$$

Equation 1 is expanded to:

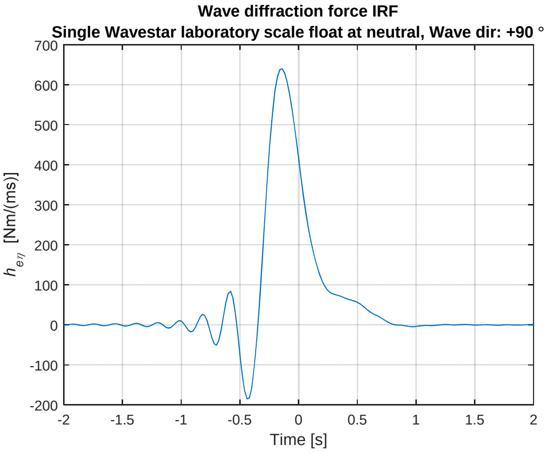
$$J\ddot{\theta}_A = M_{hs} + M_r + M_{ex} - M_c \qquad (2)$$

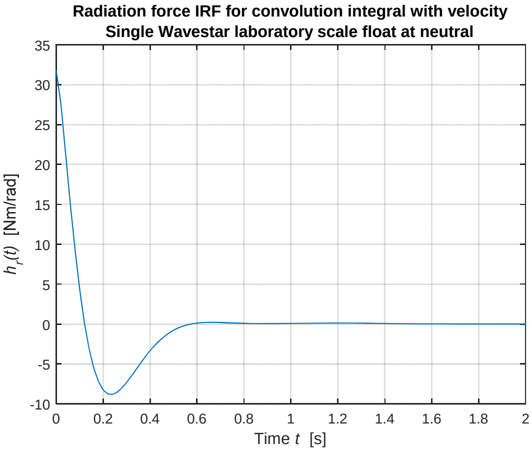
$$\begin{aligned} &\text{Hydrostatic moment:} && M_{hs} = M_b - M_g = -k_h \cdot \theta_A \\ &\text{Radiation moment:} && M_r = -m_{h\infty}\ddot{\theta}_A - \int_{-\infty}^{t} h_r(t-\tau)\dot{\theta}_A(\tau)d\tau \\ &\text{Wave excitation moment:} && M_{ex} = \int_{-\infty}^{\infty} h_{e\eta}(t-\tau)\eta(\tau)d\tau \\ &\text{Control moment:} && M_c = m_c \cdot \ddot{\theta}_A + c_c \cdot \dot{\theta}_A + k_c \cdot \theta_A \end{aligned} \qquad (14)$$

where:

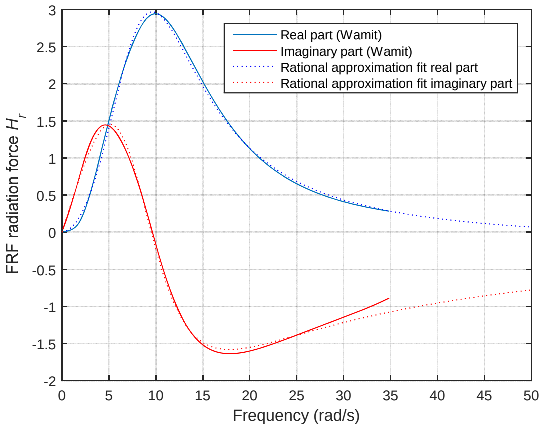
k_h:	Hydrostatic stiffness coefficient
$m_{h\infty}$:	Hydrodynamic added mass coefficient at infinite frequency
h_r:	Impulse response function for wave radiation moment
$h_{e\eta}$:	Impulse response function for wave excitation moment
A_w:	Wave amplitude (complex)

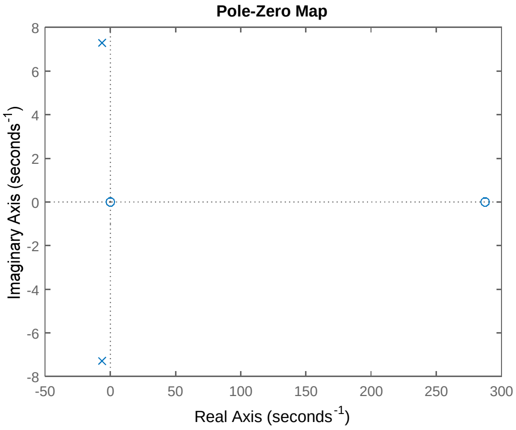
Added mass at infinite frequency is: $m_{h\infty}$ = 0.459 kgm^2.

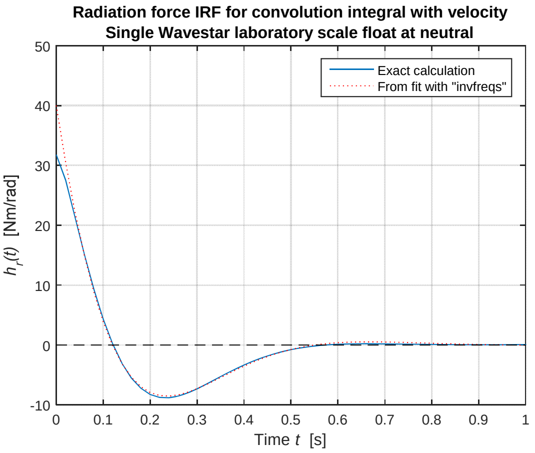

Wave diffraction force IRF
Single Wavestar laboratory scale float at neutral, Wave dir: +90 °


Radiation force IRF for convolution integral with velocity
Single Wavestar laboratory scale float at neutral

The radiation IRF and FRF can be substituted by a rational approximation as shown in "RationalApproximationRadiation.m". The function plots the figures below. Example with a second order fit.




Pole-Zero Map


Radiation force IRF for convolution integral with velocity
Single Wavestar laboratory scale float at neutral

The corresponding continuous time transfer function is:

$$\frac{-0.1333 s^2 + 38.29 s + 0.9097}{s^2 + 12.9 s + 94.76}$$