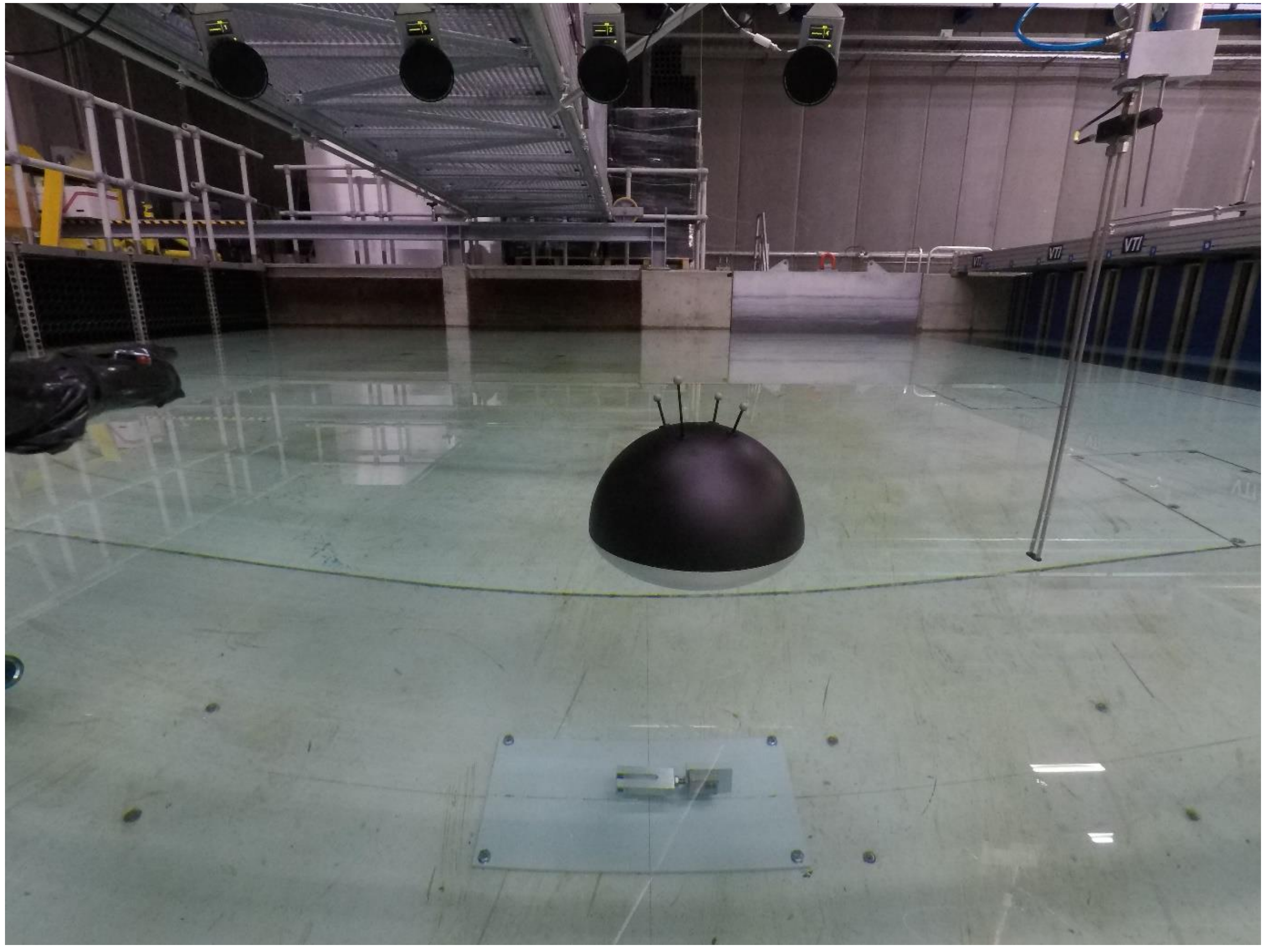
Highly accurate experimental tests with a floating sphere
Kramer Sphere Cases



1. The construction of a model suitable for validation tests
2. Heave decay tests in Aalborg University’s wave basin
3. Future possible validation tests with moving WEC & power absorption

Morten Kramer,

Floating Power Plant & Aalborg University

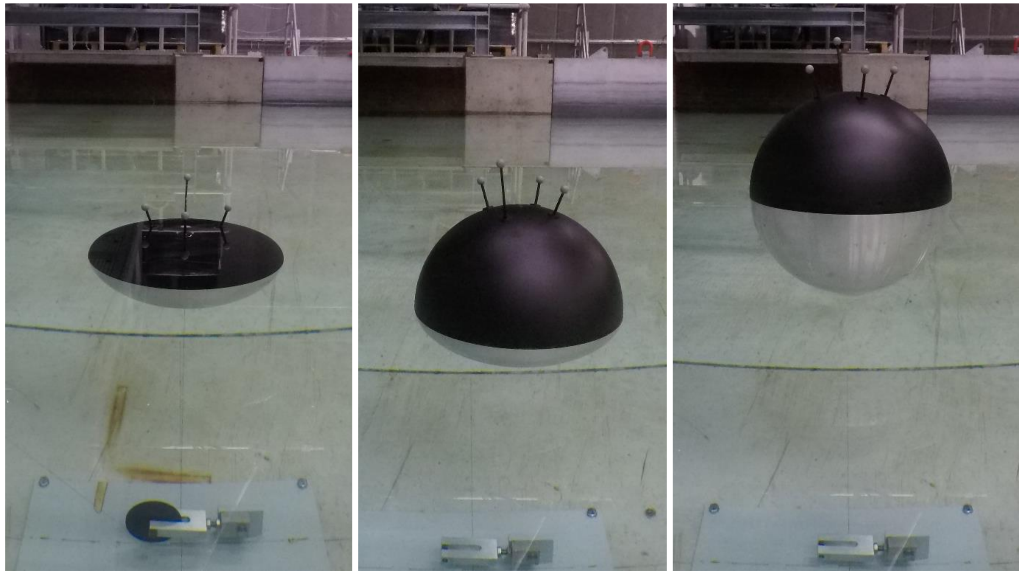
Event: OES TASK 10 WEC MODELLING Workshop 3 on 14th and 15th of November 2019, IBIS Schiphol Hotel, Amsterdam.

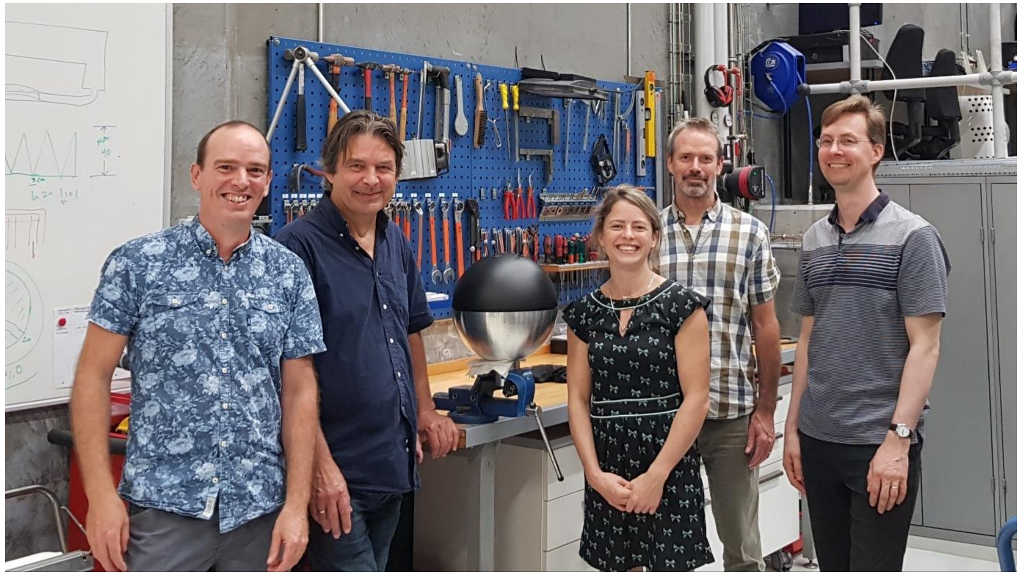
https://www.wecanet.eu/oes-task-10-workshop

This is a slightly modified pdf-version of the original Power Point presentation. Slides showing slow motion videos have been deleted, as the videos are not visible in the pdf.

Introduction # 1

- The International Energy Agency Technology Collaboration Programme for Ocean Energy Systems (OES) initiated the OES Wave Energy Conversion Modelling Task, which focus on the verification and validation of numerical models for simulating wave energy converters (WECs) [1,2,3].
- In order to validate and calibrate numerical models, high quality laboratory data are needed. Such data are currently lacking, and during the Danish EUDP project “OES Task 10 WEC Modelling Verification and Validation” (https://energiforskning.dk/node/9035) a small-scale spherical wave energy absorbing buoy was therefore built, and some initial tests were performed in the wave basin at Aalborg University during 2019.
- Further experimental work is needed, focussing on achieving high quality base-line datasets for WECs. The tests will therefore be specifically designed for numerical model validation and calibration.





Photos of the sphere with a diameter of 300 mm, which was used in the wave basin at Aalborg University (August 2019). Photo on right shows the Danish OES Task 10 group (from left: Morten Kramer, Kim Nielsen, the sphere model, Sarah Thomas, Harry Bingham, Robert Read). Photos on left shows initial position in heave decay tests where the sphere is lifted or submerged to given positions and then dropped and left to move freely in the water. Left: Submerged 150 mm (0.5*D); Middle: Neutral position; Right: Lifted 150 mm (0.5*D).

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Introduction # 2

- As an initial step the purpose was to get experimental values for heave decay tests to compare and validate with numerical estimates, i.e. experimental curves to compare to the figure on right
- The two figures are from the paper [1]:

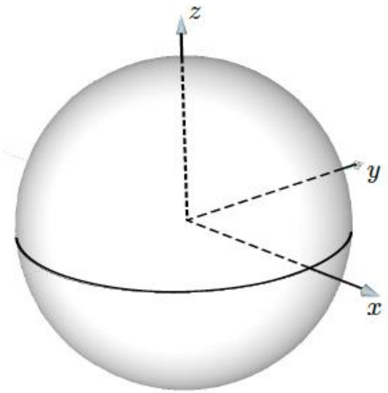
Journal of *Marine Science and Engineering*

MDPI

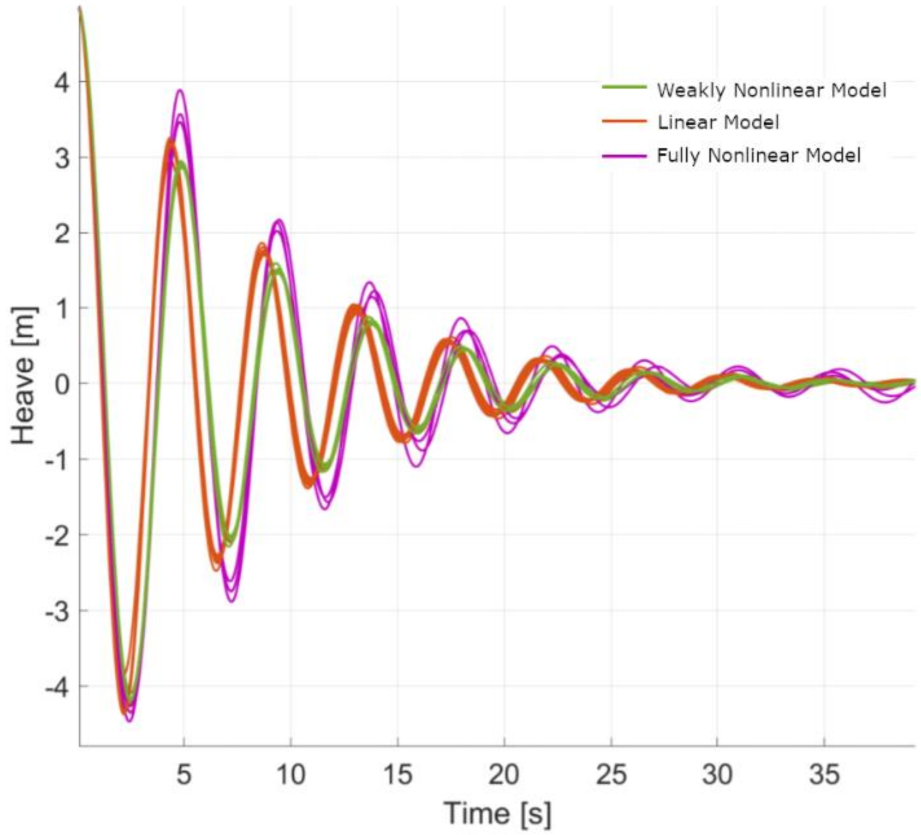
Article

Ocean Energy Systems Wave Energy Modelling Task: Modelling, Verification and Validation of Wave Energy Converters

Fabian Wendt [1], Kim Nielsen [2,3,*], Yi-Hsiang Yu [1], Harry Bingham [4], Claes Eskilsson [3,5], Morten Kramer [3,6], Aurélien Babarit [7], Tim Bunnik [8], Ronan Costello [9], Sarah Crowley [10], Benjamin Gendron [11], Giuseppe Giorgi [12], Simone Giorgi [9], Samuel Girardin [11], Deborah Greaves [13], Pilar Heras [3,6], Johan Hoffman [14], Hafizul Islam [15], Ken-Robert Jakobsen [16], Carl-Erik Janson [17], Johan Jansson [14], Hyun Yul Kim [18], Jeong-Seok Kim [19], Kyong-Hwan Kim [19], Adi Kurniawan [3,§], Massimiliano Leoni [14,20], Thomas Mathai [1], Bo-Woo Nam [19], Sewan Park [19], Krishnakumar Rajagopalan [21], Edward Ransley [13], Robert Read [4], John V. Ringwood [12], José Miguel Rodrigues [15,‡], Benjamin Rosenthal [18], André Roy [22], Kelley Ruehl [23], Paul Schofield [24], Wanan Sheng [25,†], Abolfazl Shiri [26], Sarah Thomas [6], Imanol Touzon [27] and Imai Yasutaka [28]



Parameter	Value
Mass	261.8 x 10³ kg
Centre of Gravity	(0, 0, -2) m
Radius	5 m
Draft	5 m
Water Depth	infinite
Water Density	1000 kg/m³



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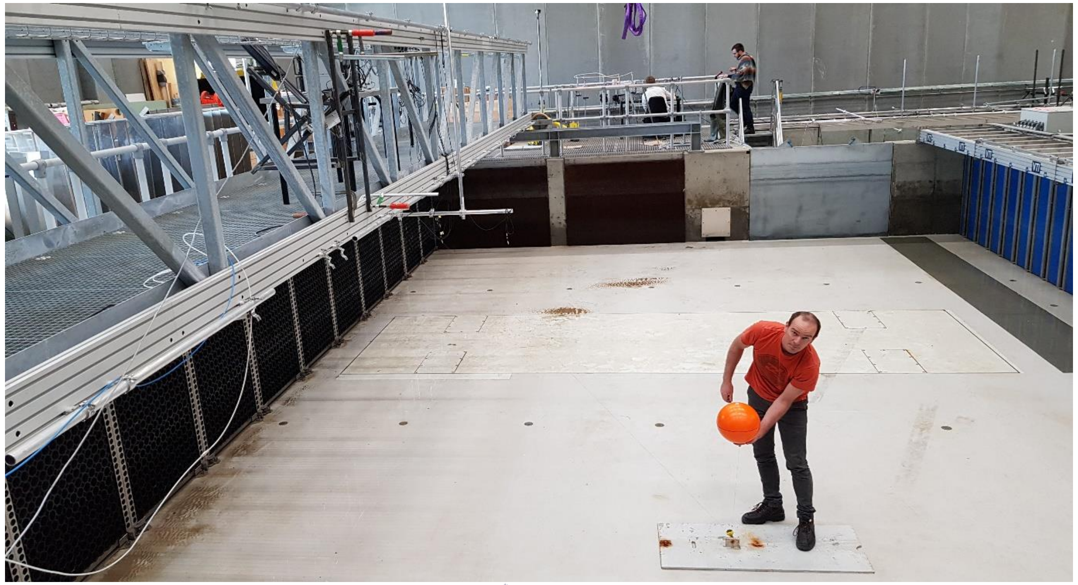
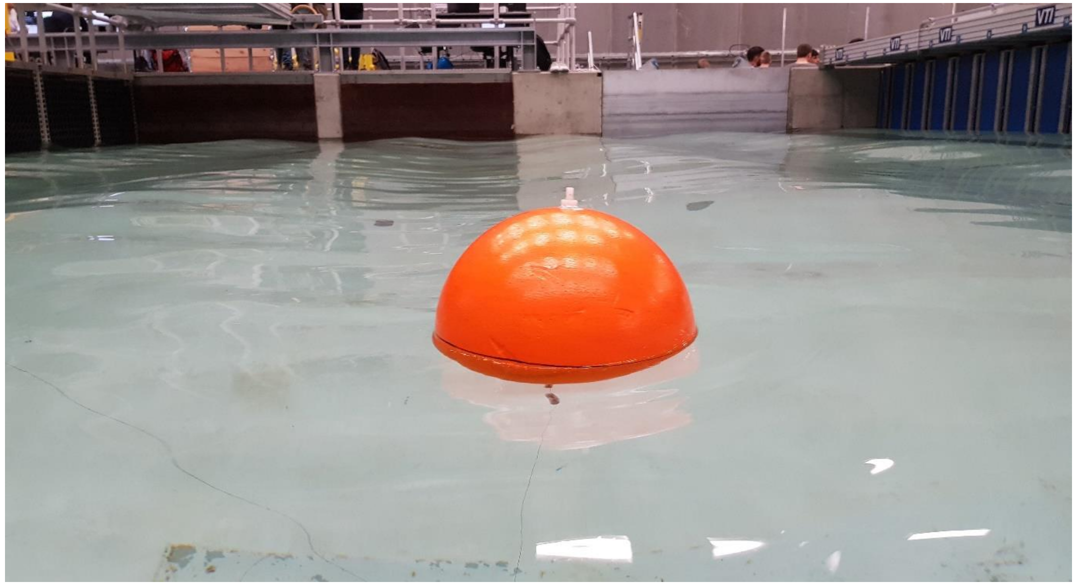
Part 1:
The construction of a model suitable for validation tests

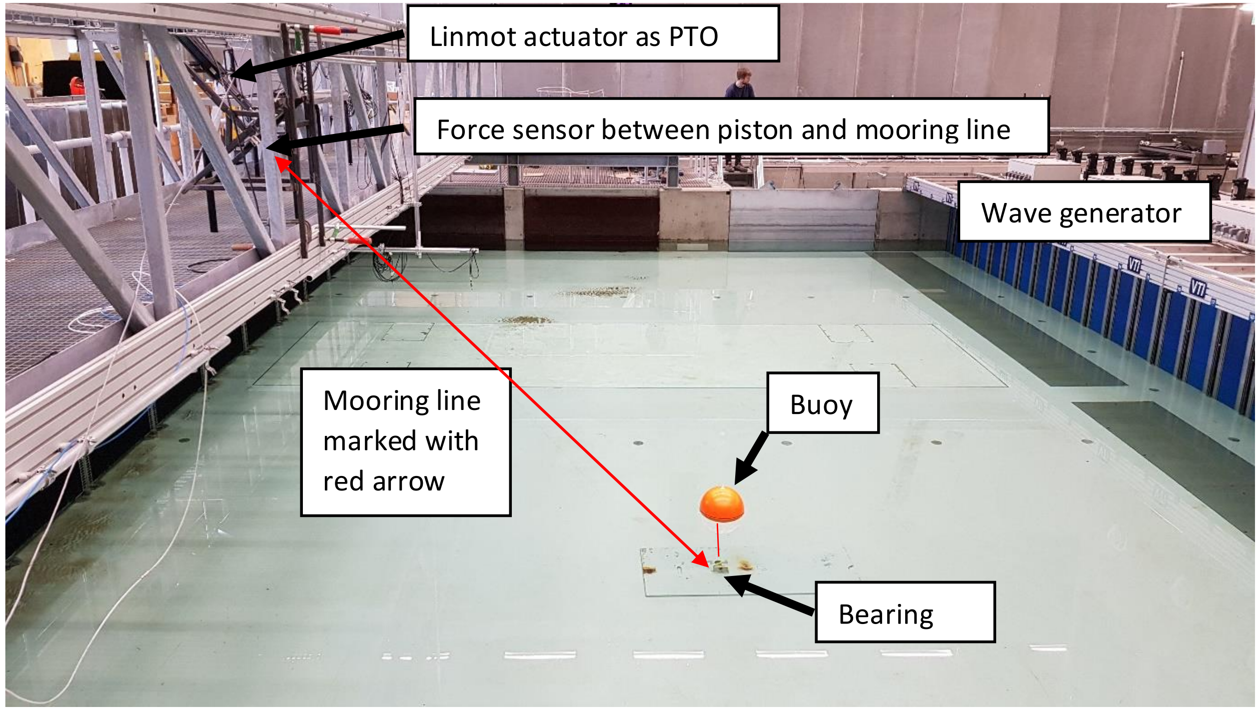
Initial pre-tests, introduction

- An experimental setup and few tests were performed in the wave basin at Aalborg University on 16 and 18 April 2018 to investigate if a simple setup with a spherical buoy could be a proper case for further investigation in the OES Task 10.
- The idea and belief prior to the testing was, that the setup could be a simple case, which would be able to provide high quality experimental data appropriate for numerical model validation.
- The intention with the testing was not to provide final test results useful for analysis, but only to investigate if the setup would be appropriate for OES task 10, and to identify problems and concerns.
- As the intention was not to do detailed tests only a very “rough and fast” setup was built by using existing components from Aalborg University's laboratory.

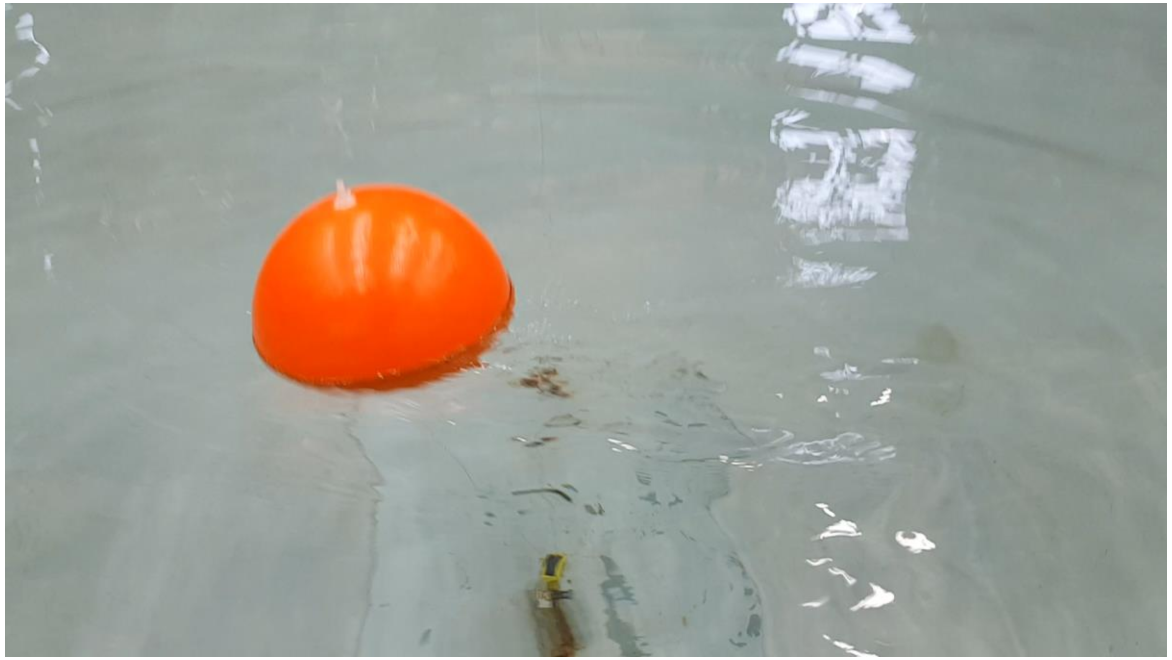


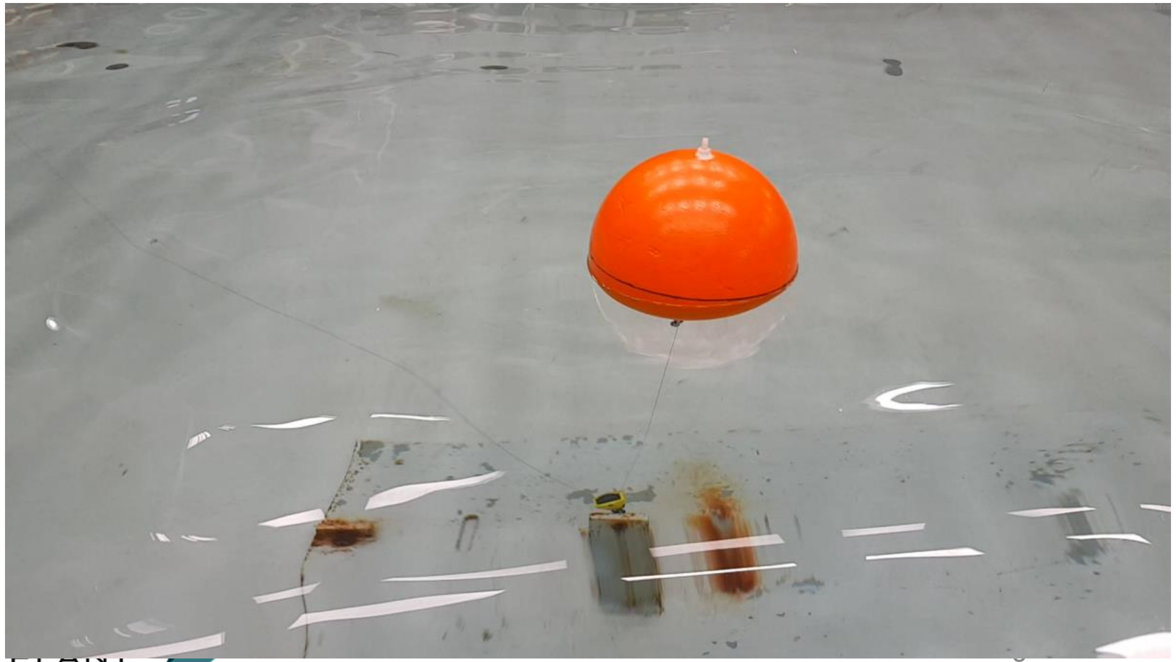


Initial pre-tests, setup



Videos on right: Upper video: Regular wave with T = 1.2 s (unstable in surge, roll), Lower video: Irregular waves with motion only in surge, heave, pitch.





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Initial pre-tests, conclusions

- The testing and setup was successful in demonstrating that the setup was appropriate for further investigation and testing in relation to OES Task 10.
- The setup was very easy to setup (done in one day at Aalborg University), and it is easy to transport and setup in any other lab, so it is also suited for a Tank2Tank comparison (e.g. apply to Marinet2 for tests at 4 different labs, one week at each place).
- Generally the setup performed fine with 2D motion of the buoy in irregular waves (motion in surge, heave and pitch only), and also in most regular waves. However, it was realised that for the specific wave period T = 1.2 s the absorber motion became unstable. In the beginning of the test the motion was 2D (surge, heave, pitch) with significant motion of the linear motor which was used as PTO. After some time the motion became 3D with a circular motion in surge, sway, heave, roll, pitch, and the linear motor was not moving due to the lack of driving force. In the latter case it was seen visually that the buoy motion was dissipating energy in waves from the sideway motions, as waves were radiated to the sides. This behaviour was only found for regular wave attack, for the irregular waves no such behaviour was identified.

The following issues were known or realised during the testing. These things should be taken care of before real tests are performed:

- Controller should be made faster and more robust, e.g. by switching to current control
- Ballast in buoy should be fixed (sand was used in current tests, and that moves around)
- Force measure by bottom of buoy should be included
- 3D 6 DoF motion measure of buoy should be included
- Proper calibration of Linmot force feedback, and also target force, should be done
- Complete mass matrix of buoy (i.e. including inertia moments) should be established
- Knowledge about all geometries and accuracy of all parameters should be known.

Criteria for development of a new sphere model

The new model should fulfil the following:

- Ballast in buoy should be easily changeable to a wide range of ballast conditions (i.e. the sphere itself should be relatively light), and the ballast should be fixed to the sphere (i.e. no moveable ballast like sand or water).
- There should be attachments by the bottom and top for mounting moorings and for lifting the absorber upwards (e.g. to be used for decay tests with initial conditions from elevated as well as submerged positions).
- The model shape should be very stiff such that structural deformations are neglectable
- The surface should be smooth
- The model should be rotational symmetric about the centre vertical line
- Force measure by bottom of buoy should be included (between buoy and the mooring line)
- 3D 6 DoF motion measure of buoy should be included
- Complete mass matrix of buoy (i.e. including inertia moments) should be established from detailed and precise drawings and measured estimations.
- Knowledge about all geometrical uncertainties and accuracy of all parameters should be known in great detail. A consistent representation of statistical uncertainty on every parameter should be possible.

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Model diameter

The model was decided to be 300 mm in diameter mainly due to:

- The forces would suit the existing electrical actuators which would be used for the PTO
- The model size would be appropriate for use in typical existing “normal-size” wave basins
- The model would be easy to transport and handle manually, without use of cranes
- The model would be cheap and relatively easy to instrument

Model construction

Initially the plan was to buy a pre-fabricated sphere in a stiff material. Many ideas were examined, like using bowling balls and other typical round shapes. Most ideas were easily disregarded (e.g. all bowling balls are too small), but the following models were constructed as shown in the following:

A. Pre-fabricated hollow stainless-steel sphere
B. 3D printed sphere in ABS plastic material
C. CNC machined sphere in aluminium (final model that met most criteria)

Model A: Pre-fabricated hollow stainless-steel sphere

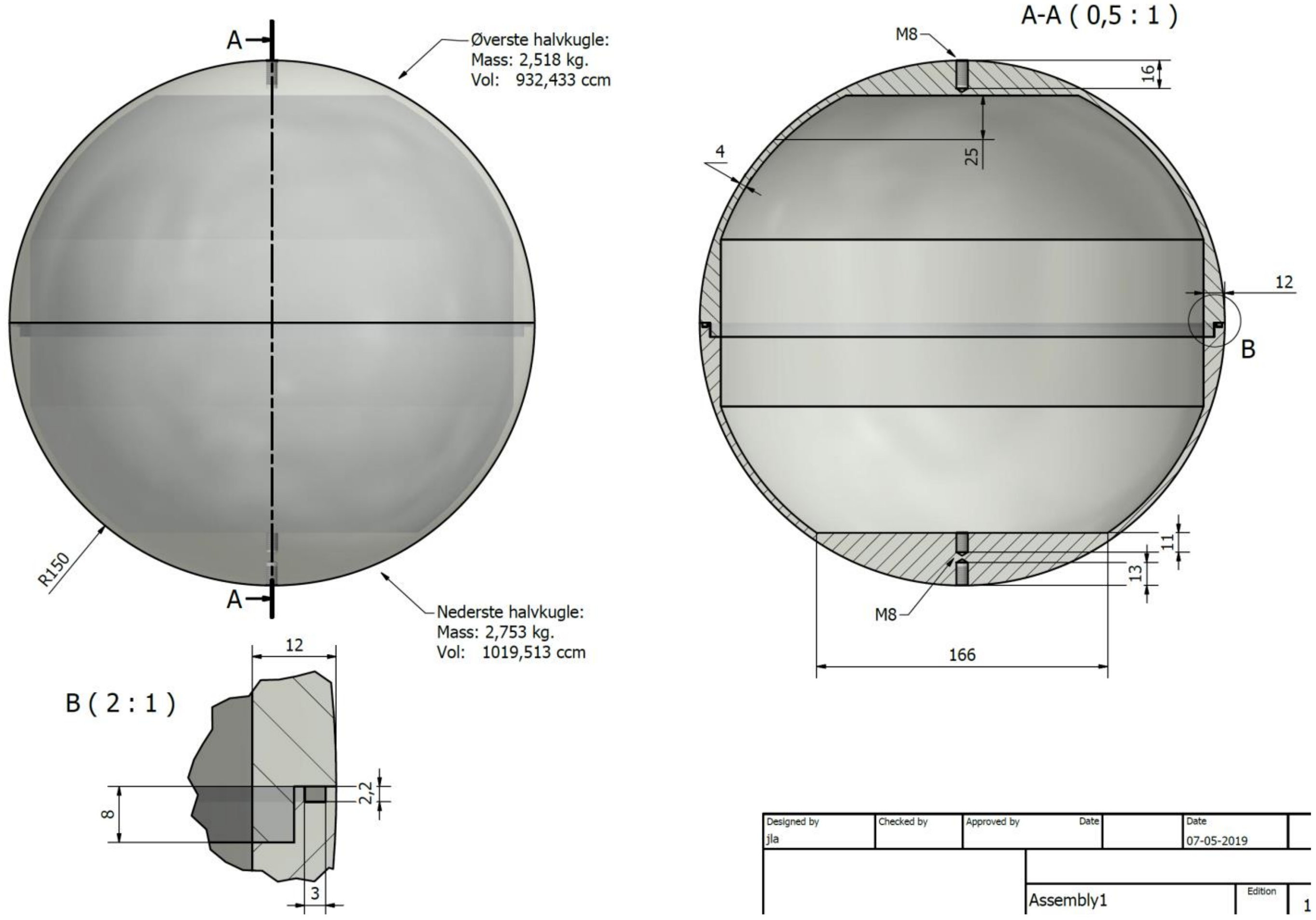
A pre-fabricated hollow stainless-steel sphere were bought from the company Kugle-Teknik.dk, as they were considered experts in delivering pre-fabricated spheres with the best achievable accuracy. The sphere was examined at AAU, and it turned out that the shape did not meet the criteria for the shape tolerances as the diameter varied about 2 mm. The sphere was made from two parts which were welded together, and this was the reason for the rather inaccurate shape.

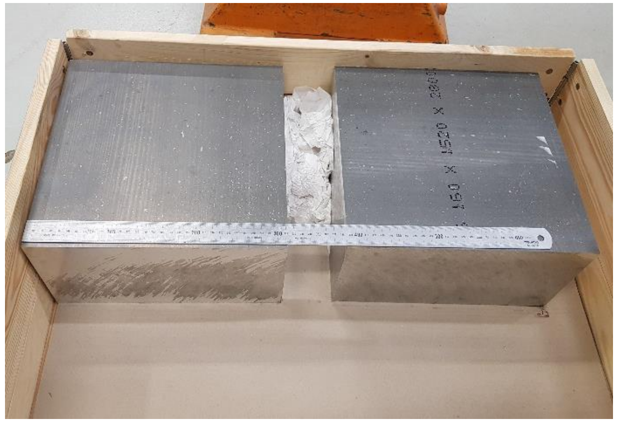
Model B: 3D printed sphere in ABS plastic material

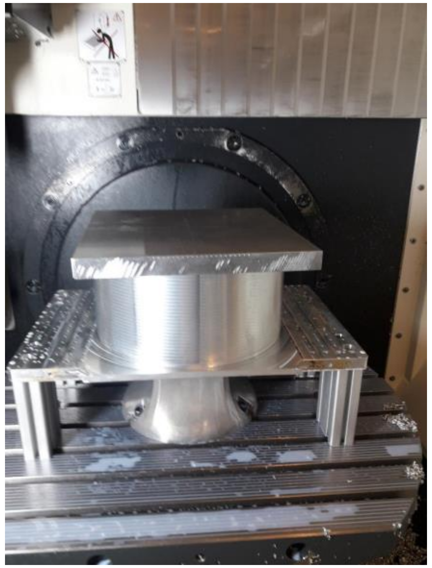
A number of 3D drawings were made to try to 3D print a sphere using ABS plastic. Several test objects were printed, e.g. "a big red lid" for a Ø300 mm model, and a white very small complete demonstration model containing main part and lid.

Unfortunately, the quality and accuracy of the physical objects were poor, and it was decided to give up on the 3D printing.

Model C: CNC machined sphere in aluminium







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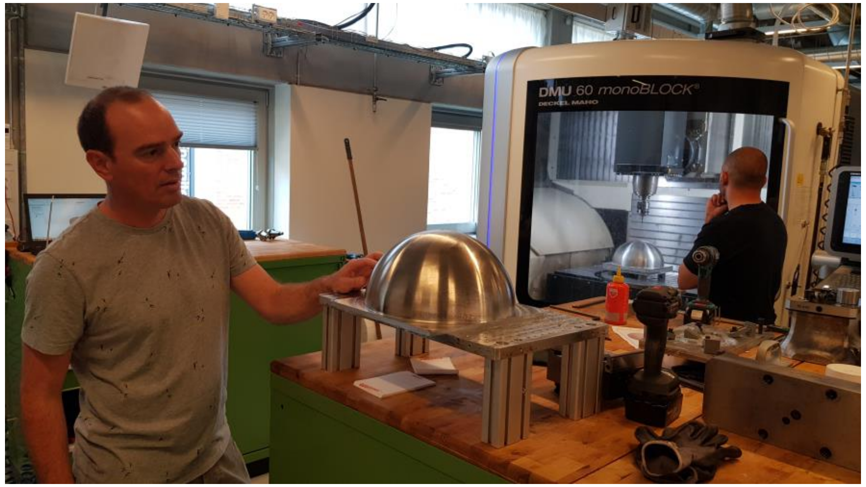
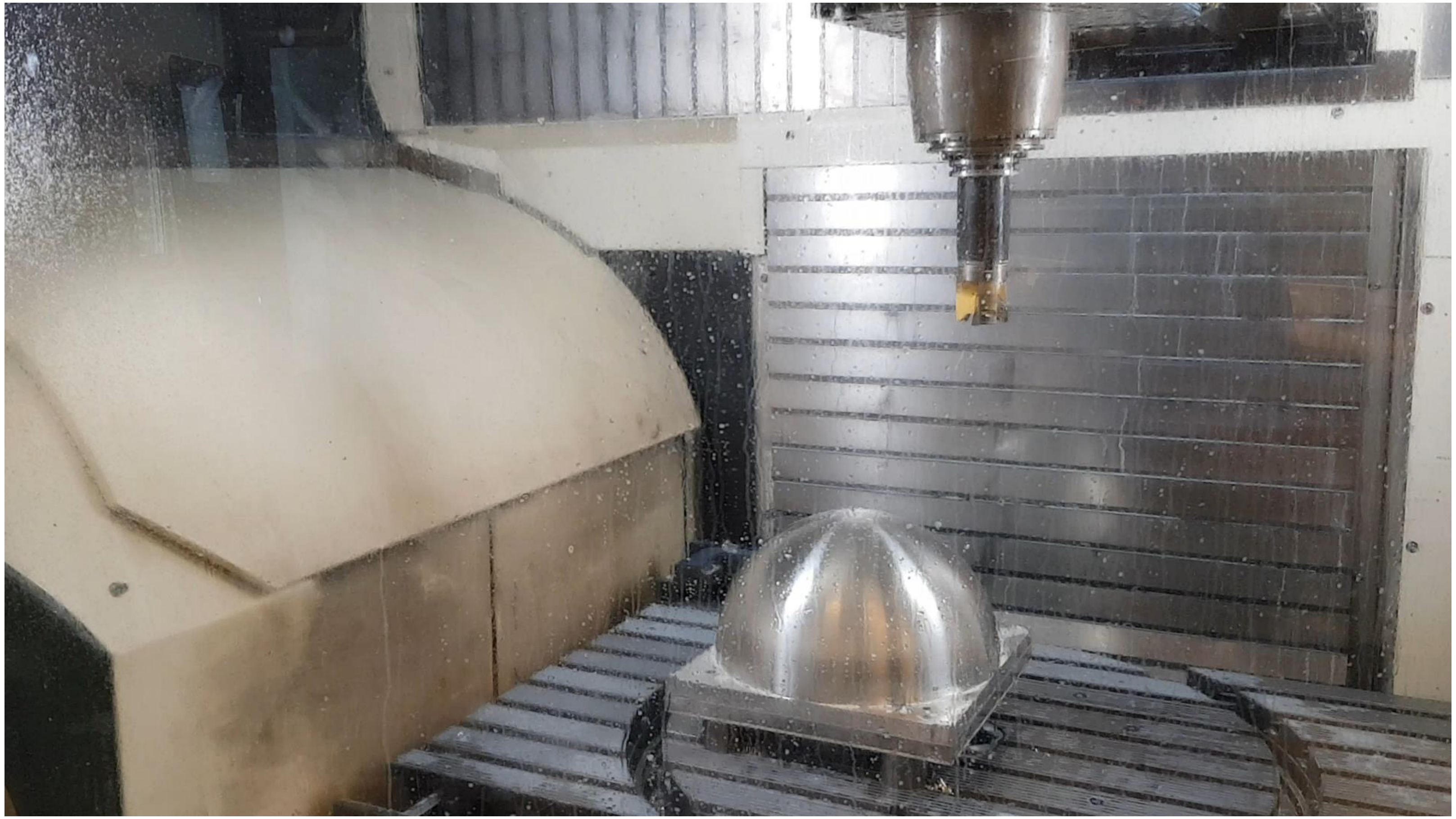
CNC machining



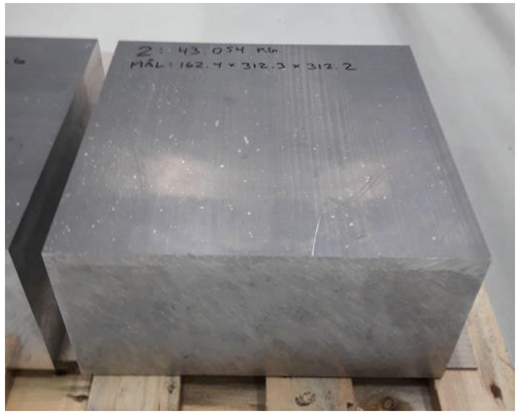


The final shell

Densities

- The density of the aluminium used for the shell was measured at 20°C by measuring the size and weight of the two rectangular blocks

Block no	Mas [kg]	Volume [mm^3]	Density [kg/m^3]
1	43.069	15844534.25	2718.2
2	43.054	15834009.74	2719.1
		Average:	2718.7

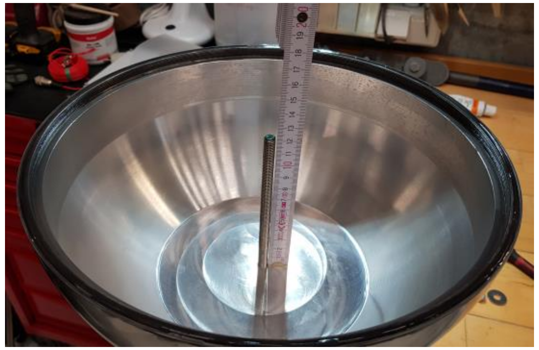


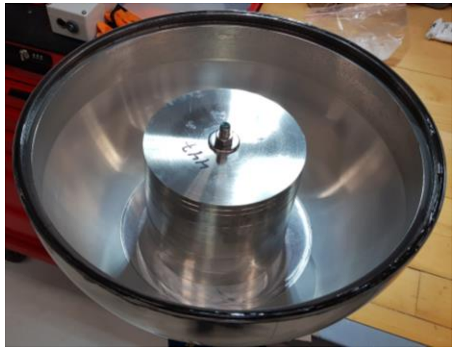
Material	Density [kg/m^3]	Notes
Water	998.21	Taken from table, fresh water at 20 degrees.
Aluminium	2718.65	Measured average from two big alu blocks (weight and size measured), 20 degree celcius.
Stainless steel	7905.45	Measured from a big steel cylinder (weight and size measured), 20 degree celcius.

Ballast weights

- Different sizes of circular ballast weights have been made in stainless steel. The weights allow adjustment of any ballast all the way to complete submergence.

Block no	Weight [g]	Height [mm]	Diameter [mm]	Notes
1	1780.8	20.0	120.0	D_hole = 8.0 mm (all blocks, no 1-13)
2	1775.0	20.0	120.0	
3	1774.5	20.0	120.0	
4	896.7	10.0	120.4	
5	891.4	10.0	120.4	
6	886.2	9.9	120.4	
7	447.6	5.0	120.3	
8	446.1	5.0	120.3	
9	446.1	5.0	120.3	
10	151.6	10.0	50.0	
11	76.0	5.0	50.0	
12	76.0	5.0	50.0	
13	76.0	5.0	50.0	
Big washer	5.4	1.93	23.6	D_hole = 8.5 mm
Small washer	1.5	1.49	15.8	D_hole = 8.5 mm
M8 nut	4.5	6.1	13.0	Nut with 6 sides and rounded edges





Weights and ballast to half submergence

Main parts	Weight [g]	Height [mm]	CoG_z [mm above bottom]
Upper shell part	2530.1	157.96	214.2
Lower shell part	2773.9	149.96	69.5
O-ring w. grease	10.9	2.2	148.9
Total shell	5314.9		138.5

Secondary parts	Weight [g]	Height [mm]	CoG_z [mm above bottom]
Centre rod	41.1	133.4	85.8
Top connection nut	2.4	10.7	294.7
Bottom connection nut	2.4	10.7	5.4
Marker 1	1.7	40.8	311.0
Marker 2	1.7	40.8	311.0
Marker 3	1.7	40.8	311.0
Marker 4	2.2	82.4	330.7
Total connection parts	53.2		123.3

Lightest condition

Total mass	5.327	kg (excluding the centre rod, which is not needed)
Pre-tension	16.98	N (to submerge the sphere to equator)

Ballast to half submergence

Volume of half sphere [m^3]	0.007069
Water density (kg/m^3)	998.21
Wanted total mass (g)	7055.9
Wanted ballast weight (g)	1687.8

Actual ballasting	Weight [g]	CoG_z [mm from bottom]
Block 4	896.7	35.0
Block 7	447.6	42.5
Block 10	151.6	50.0
Block 11	76.0	57.5
Block 12	76.0	62.5
6 big washers	32.16	70.8
2 small washers	3.06	78.1
M8 nut	4.5	82.6
Total ballast	1687.6	41.5
Total actual weight	**7055.7**	115.2
Difference wanted VS actual weight:	0.2	

- Weights were measured with precision of 0.1 g (measured on high precision scale at Aalborg University).
- All distances are with precision of 0.1 mm, or better.

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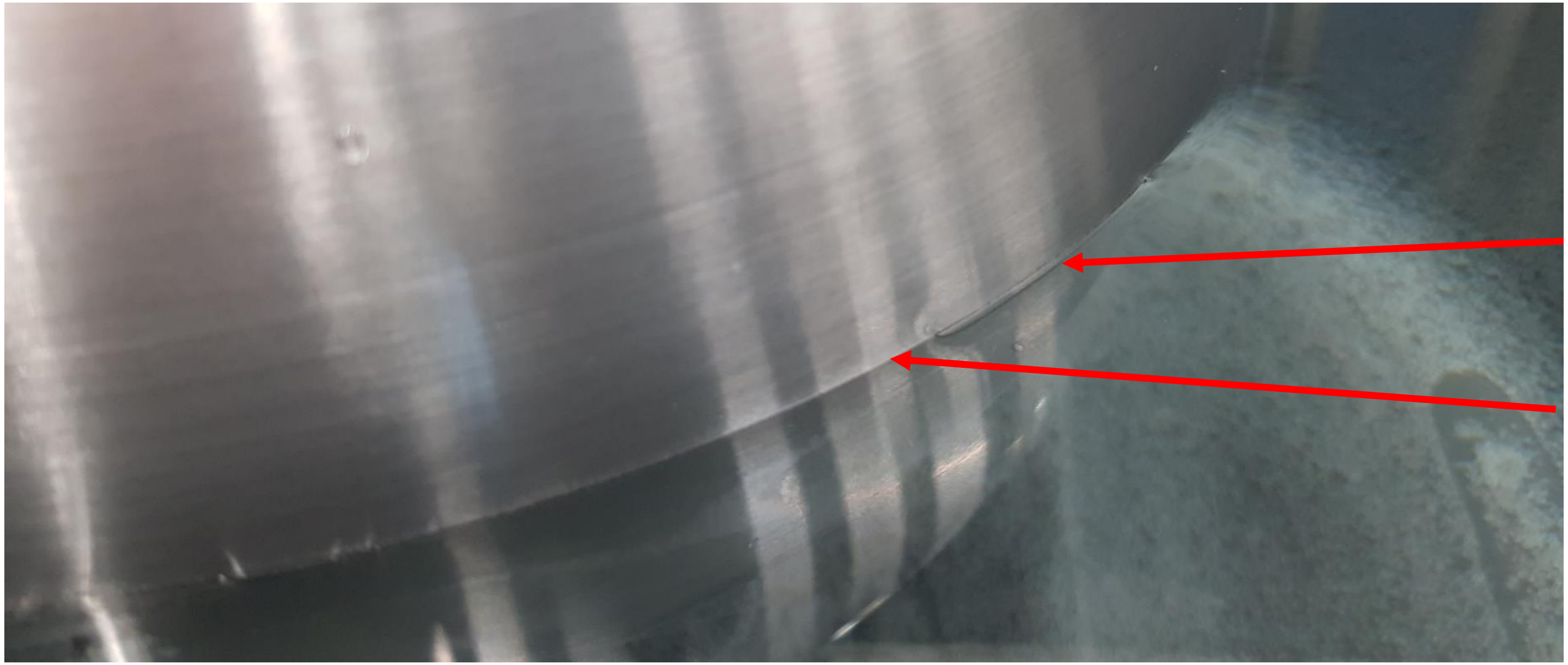
Checking floating level, ballast to half submergence

The water level was exactly at the center line when ballasted and freely floating. At some parts along the circumference the water level was slightly below the center line and at some parts it was slightly above (a small fraction of a mm). The difference was caused due to the water surface tension making the water either stick to the upper shell (surface bending upward) or lower shell (surface bending downward).



Water level is slightly **below** center line at this point

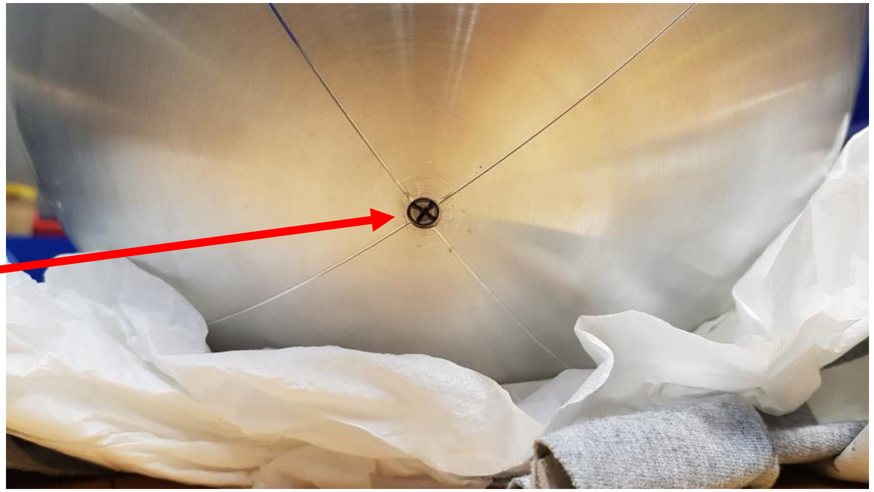
Water level is slightly **above** center line at this point

Mooring line and attachment to sphere

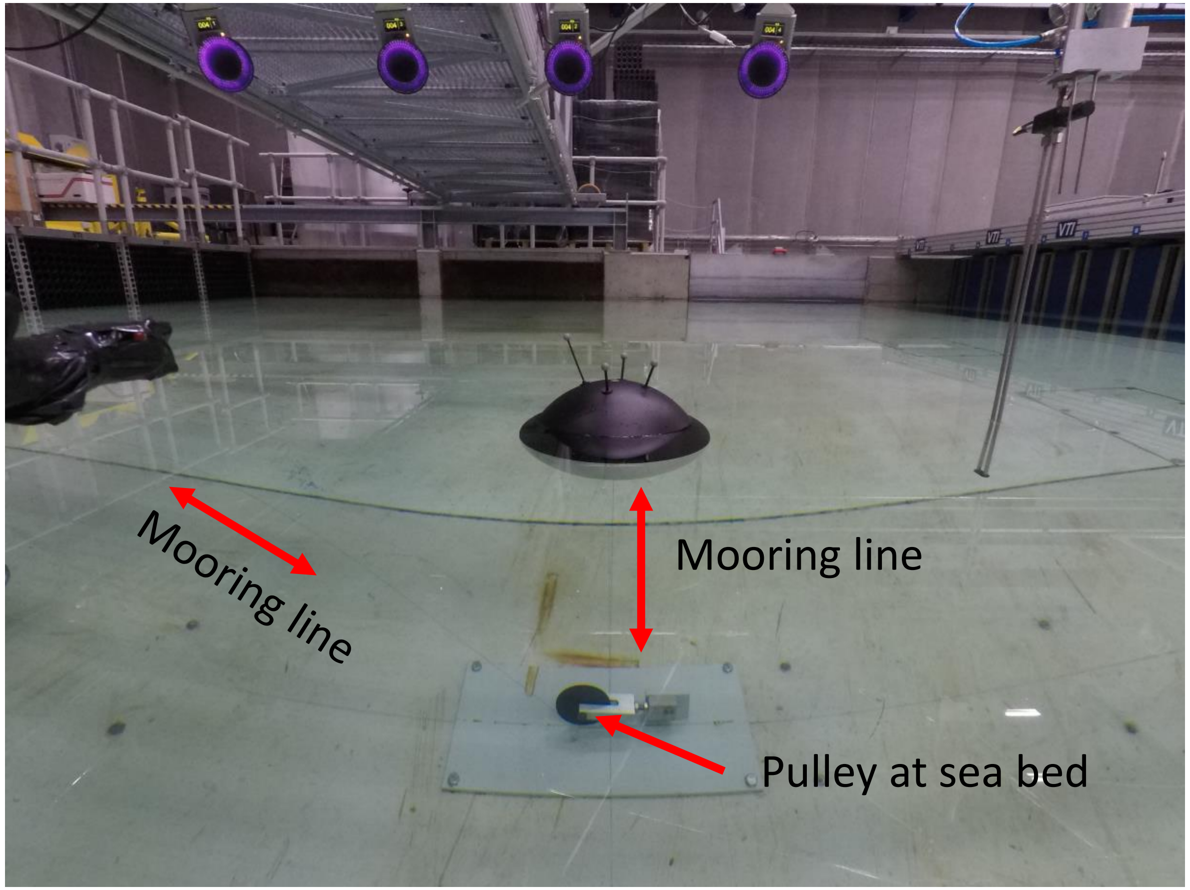
Mooring line details		
Type:	Fishing line, Sufix 832 Advanced Superline	
Diameter:	0.33	mm
Strength:	28.5	kg
Weight:	? (not measured yet)	kg/m
Stiffness:	? (not measured yet)	N/m

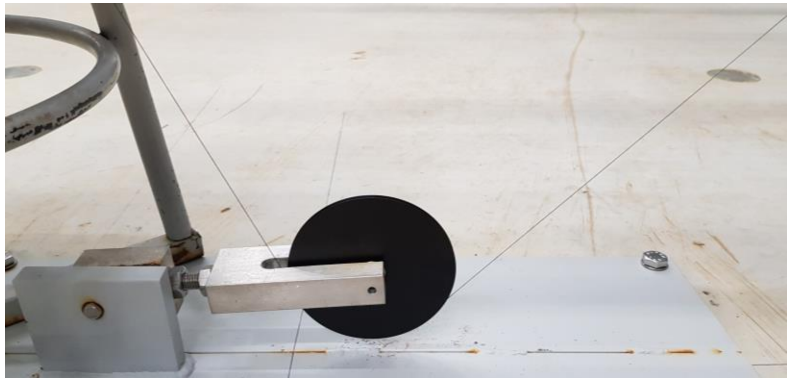
Description by manufacturer, details:
8 Fibers (Featuring one GORE performance fiber and 7 Dyneema fibers)
32 pics (weaves) per inch
R8 Precision braiding technology
Patent-Pending construction
Ultimate abrasion resistance
Unbeatable strength
Proven castability improvements
TGP technology enhances color retention

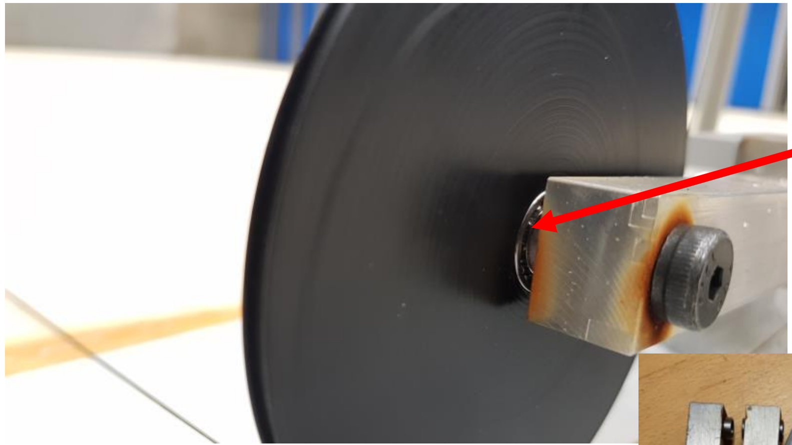
Custom made M8 nut



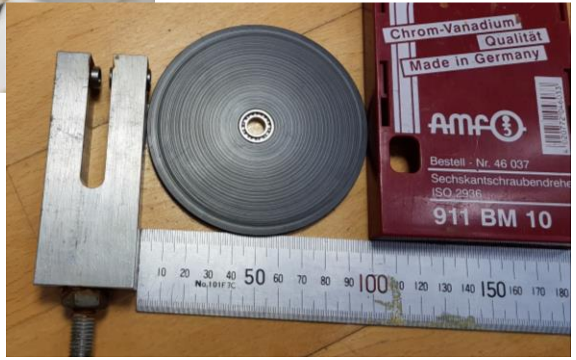
Pulley system at sea bed used to pull the sphere downward (connection to PTO)







Low-friction stainless steel bearing in pulley



Conclusions on model construction

- The sphere model has proved very accurate in the construction
- The sphere model is a bit heavy compared to the initial wishes and ideas. The intention was to built it very light to allow for large variations in mass. With the chosen model size (diameter of 300 mm) it turned out to be too difficult to make the model relatively light and at the same time accurate and stiff. However, the model is suitable for further testing, which is demonstrated in the following part 2 and 3 of the presentation.

Part 2:
Heave decay tests in Aalborg University’s wave basin

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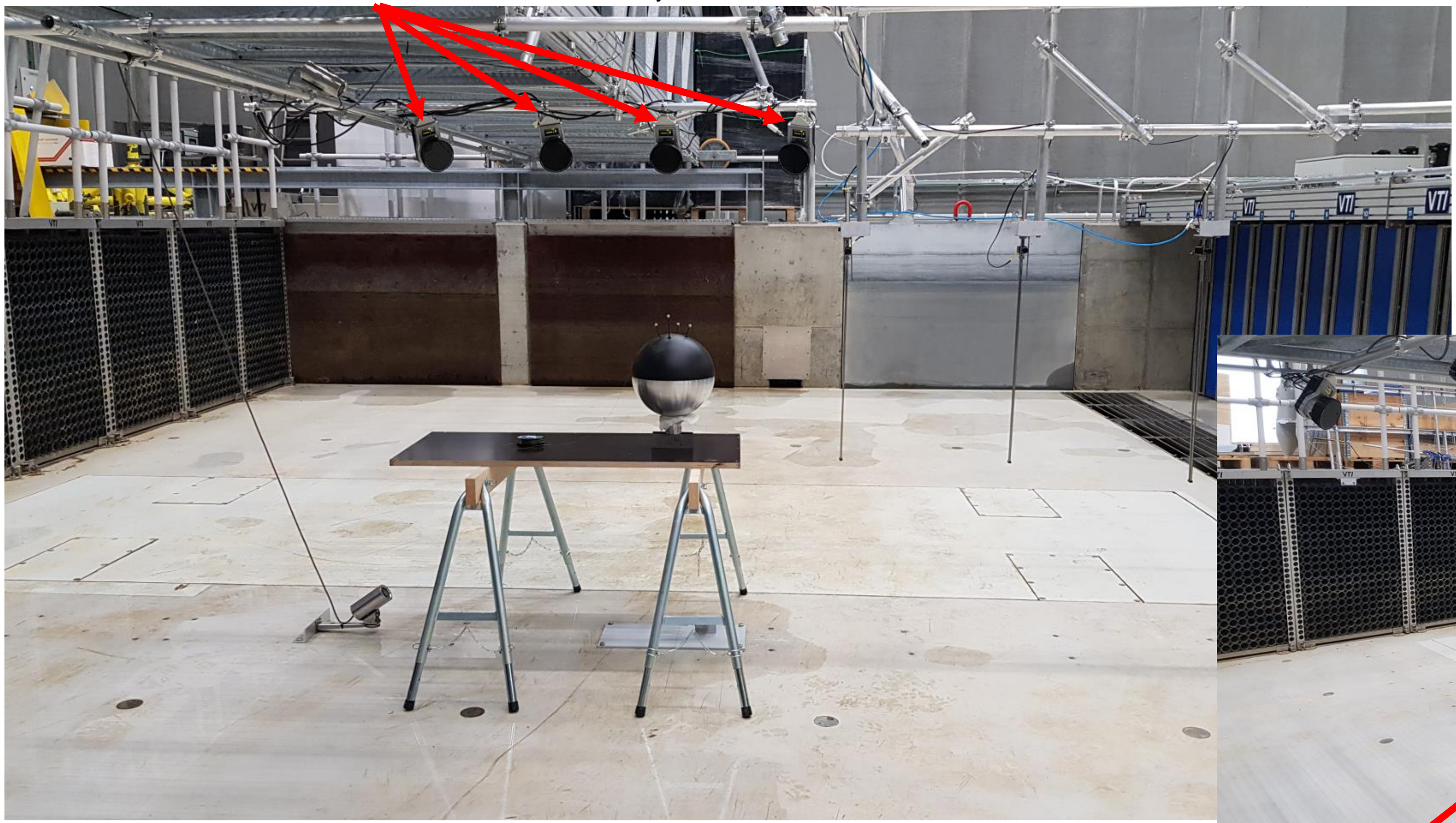
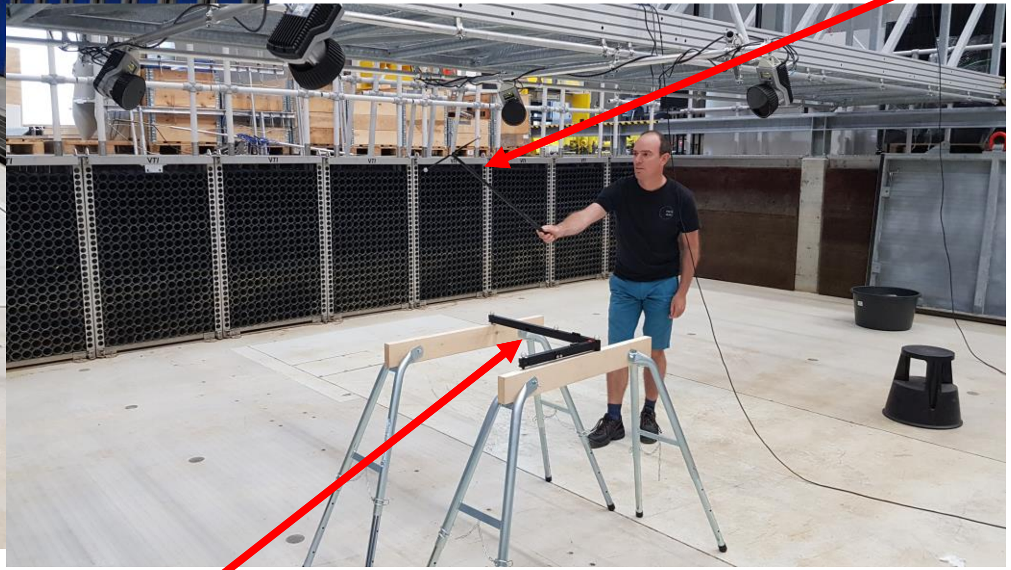
Camera system for motion tracking (Qualisys)

4 cameras, Qualisys 12 MP



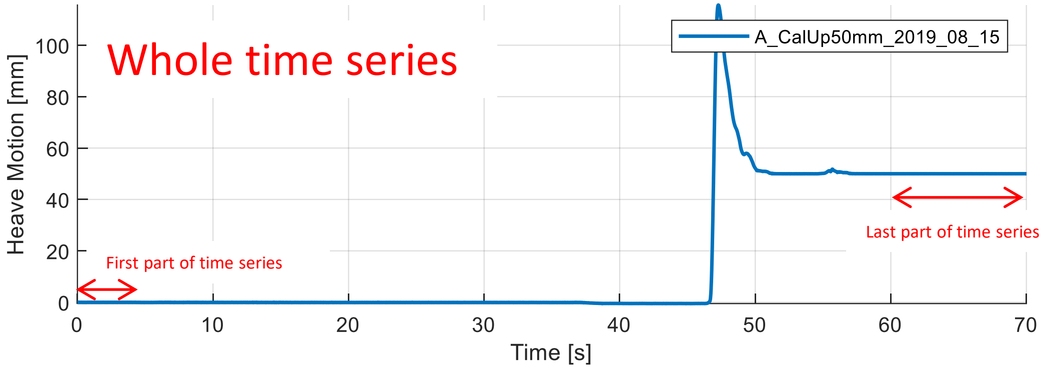
Calibration of system with wand

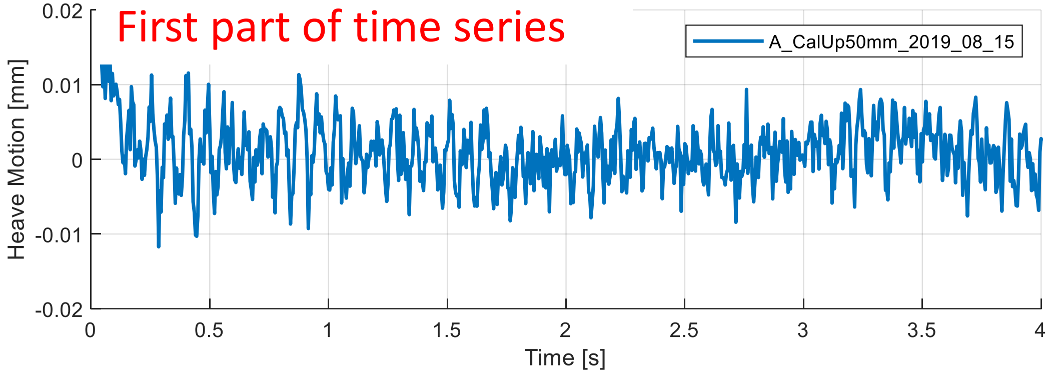


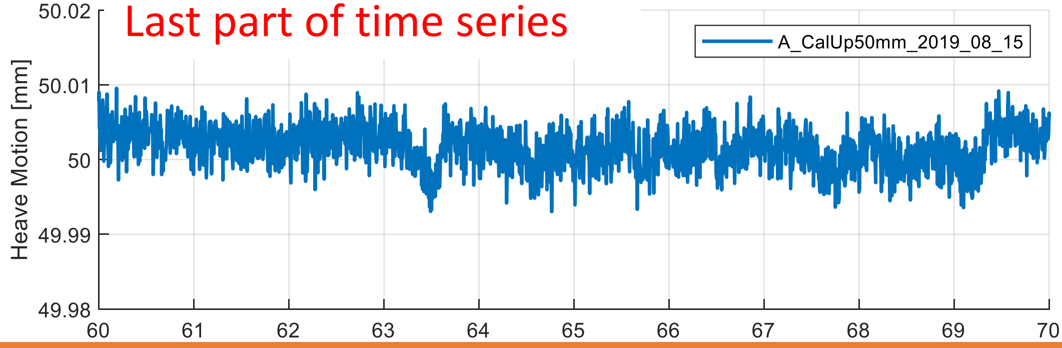
Frame for defining coordinate system

Checking the position measurement in heave

Placing the sphere on blocks exactly 50.00 mm high

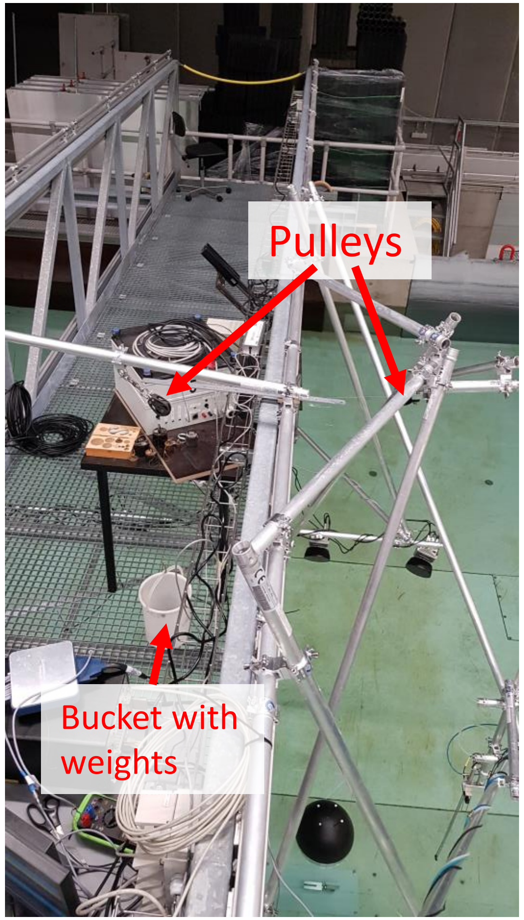


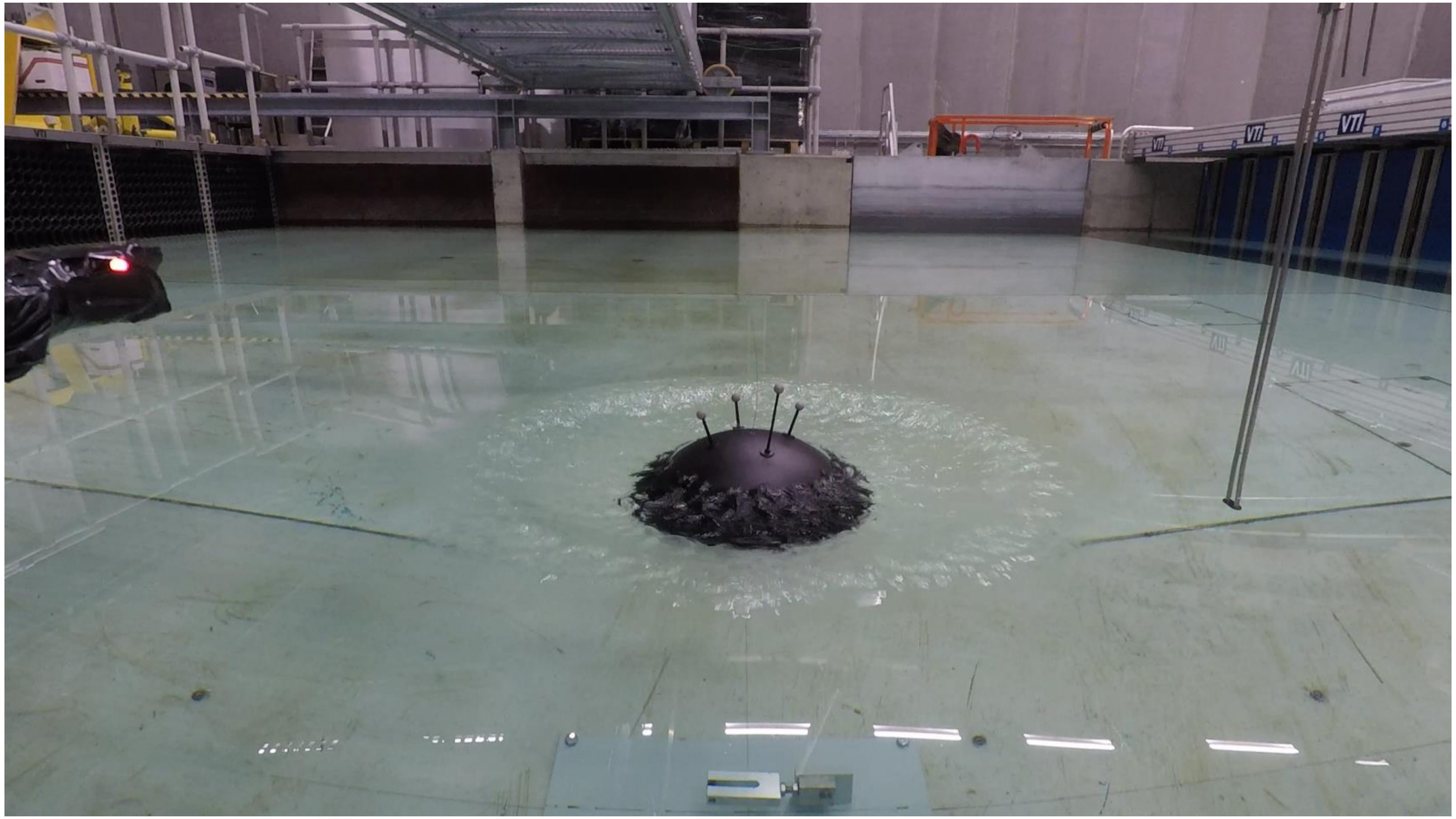




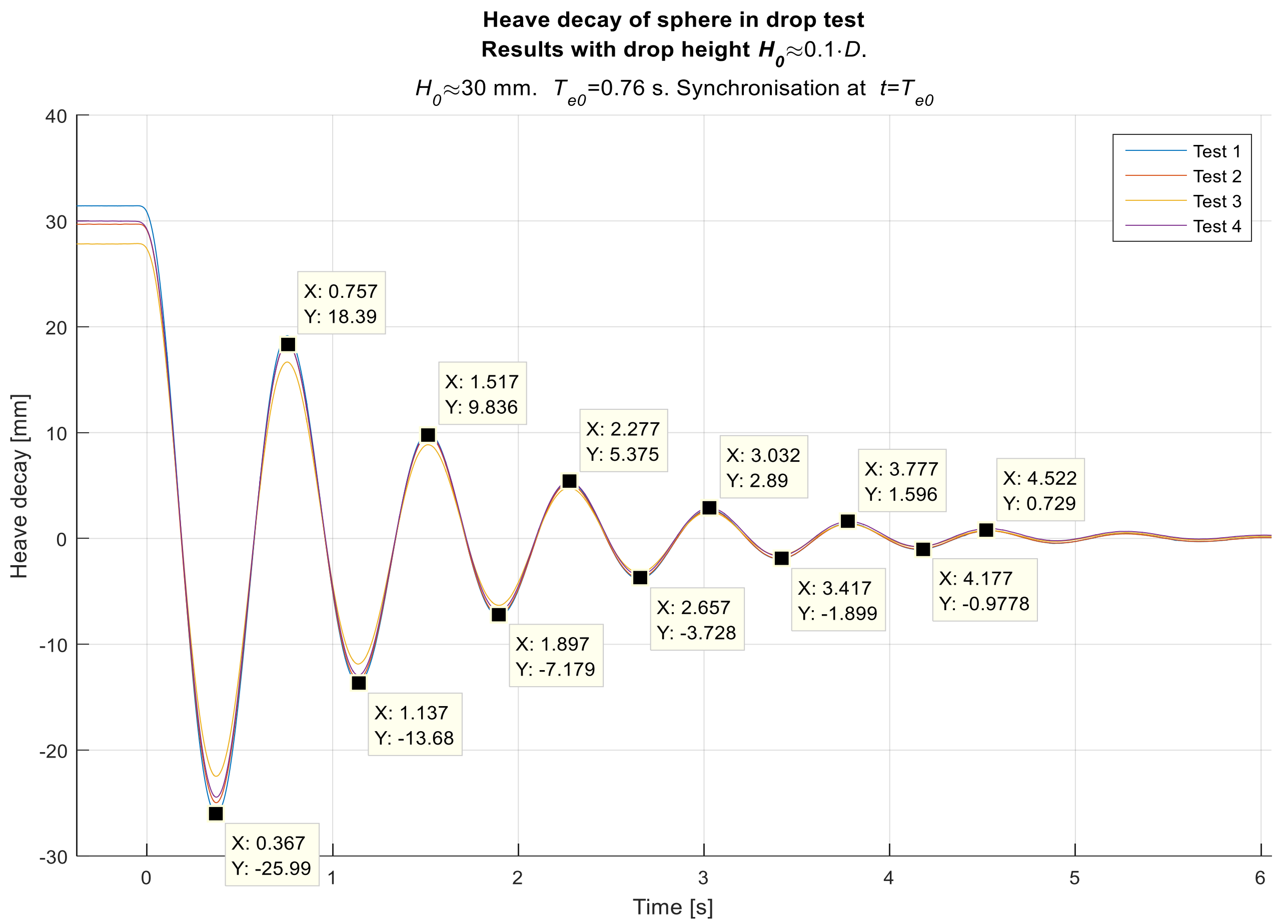
Conclusion: Precision with static motion in heave is very high, in the order of +/- 0.01 mm (much less than the target of 0.1).

Example of first series of decay tests using a manual release and pulley system





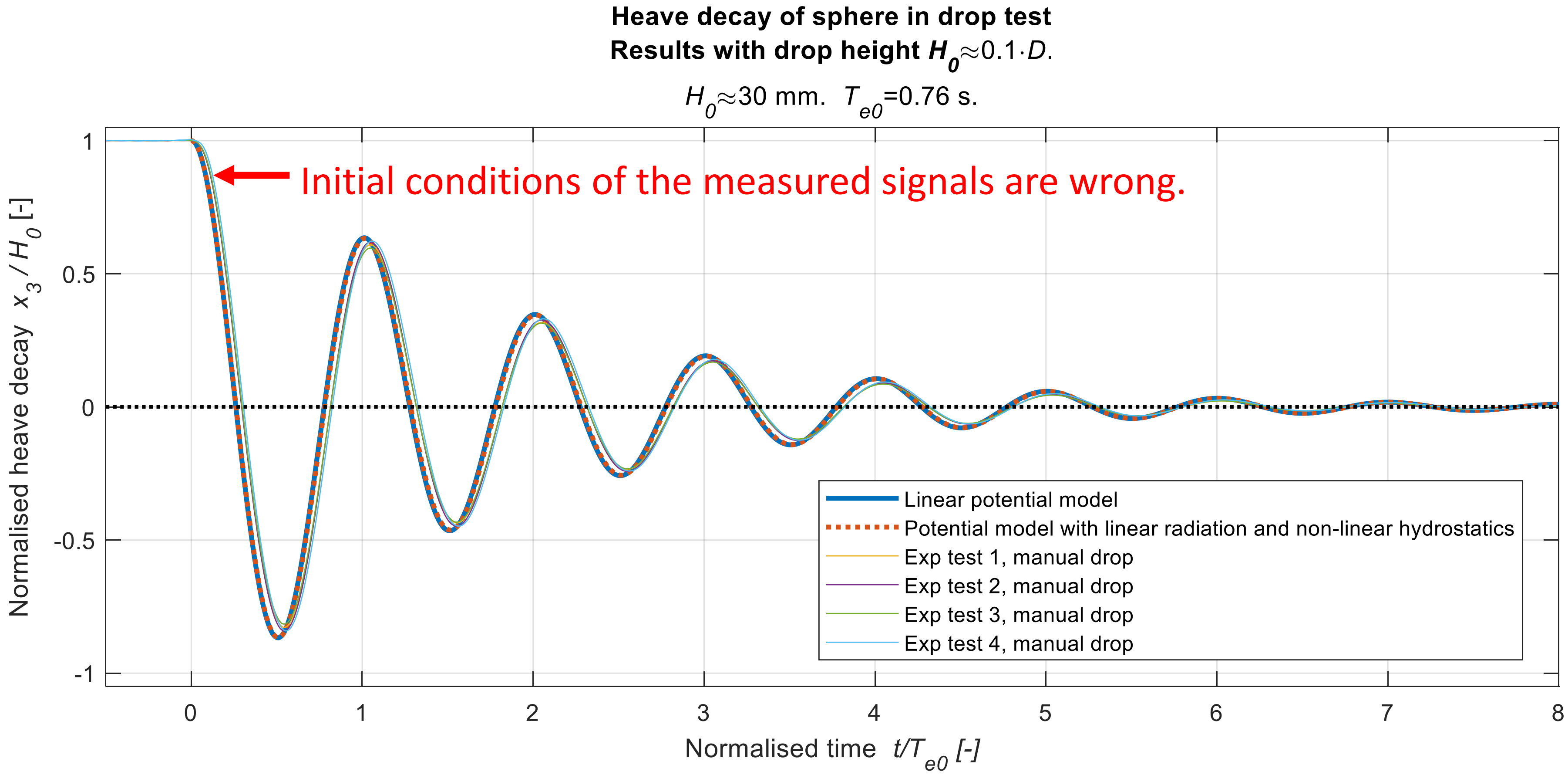
Measured eigen period



Up or Down marker	t (s)	z-value (mm)	dt (s)
Down	0.367	-25.99	
Down	1.137	-13.68	0.770
Down	1.897	-7.18	0.760
Down	2.657	-3.73	0.760
Down	3.417	-1.90	0.760
Down	4.177	-0.98	0.760
Up	0.757	18.39	
Up	1.517	9.84	0.760
Up	2.277	5.38	0.760
Up	3.032	2.89	0.755
Up	3.777	1.60	0.745
Up	4.522	0.73	0.745
	Average eigen period (s):		0.758

Water depth in all tests = 3**D* (900 mm)

Example of first series of decay tests using a manual release



A detailed analysis by Harry Bingham revealed, that the manual release took place during 1/10 of a second, thereby giving the wrong initial accelerations of the sphere.

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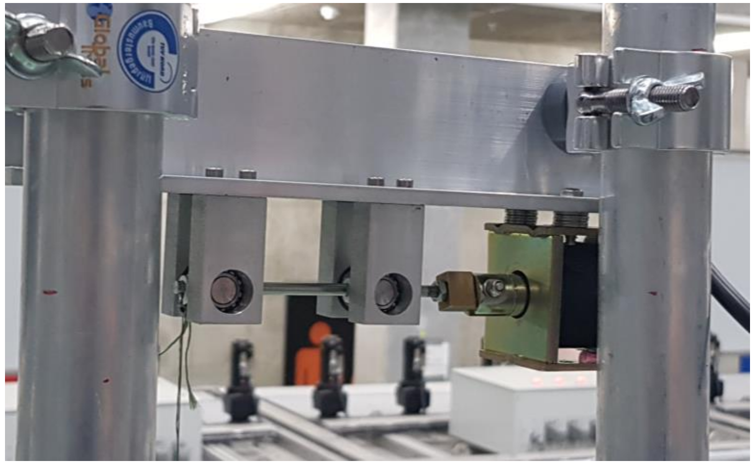
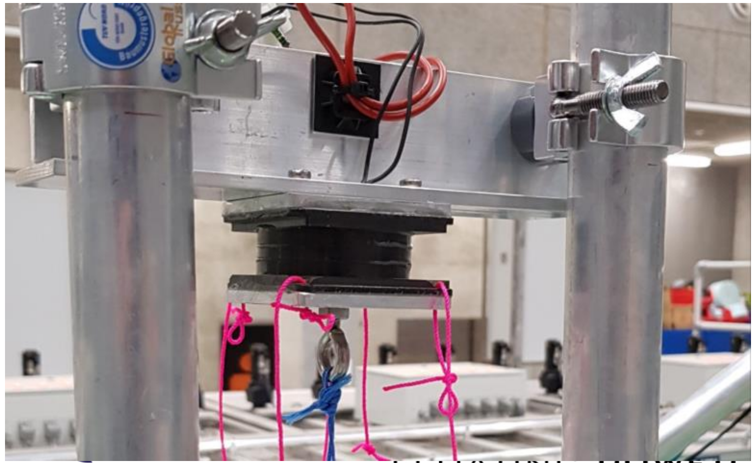
Design of automatic and fast release systems

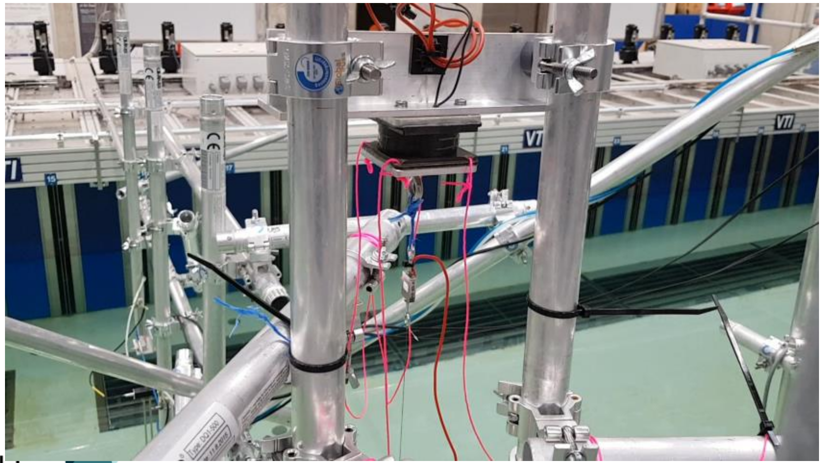
Two types of release systems were build and tested:

1. A mechanical mechanism using a small electrical actuator and pushrod (design by Nikolaj Holk)



2. A mechanism using an electronic magnet (design by Flemming Buus Bendixen)

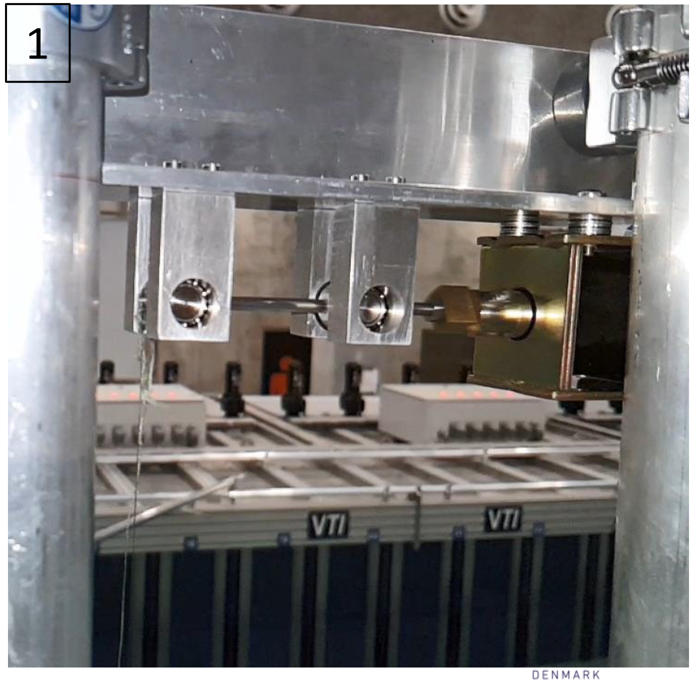


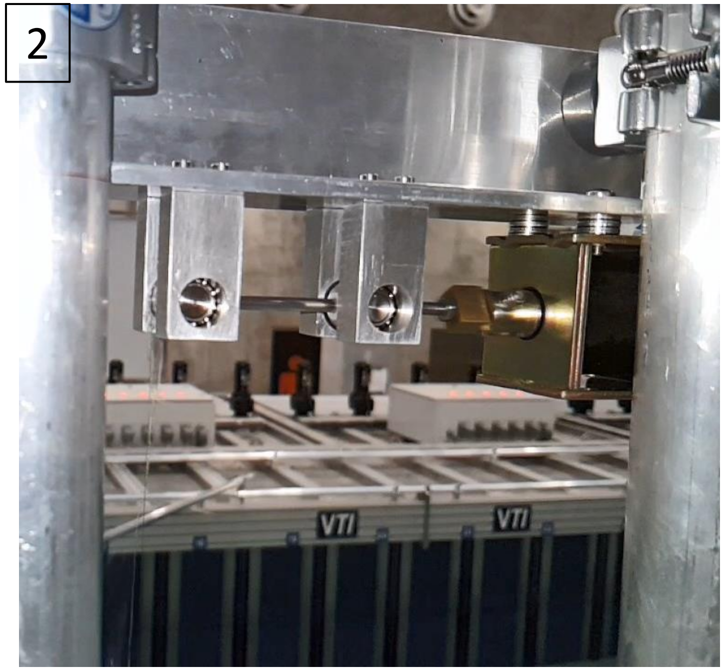


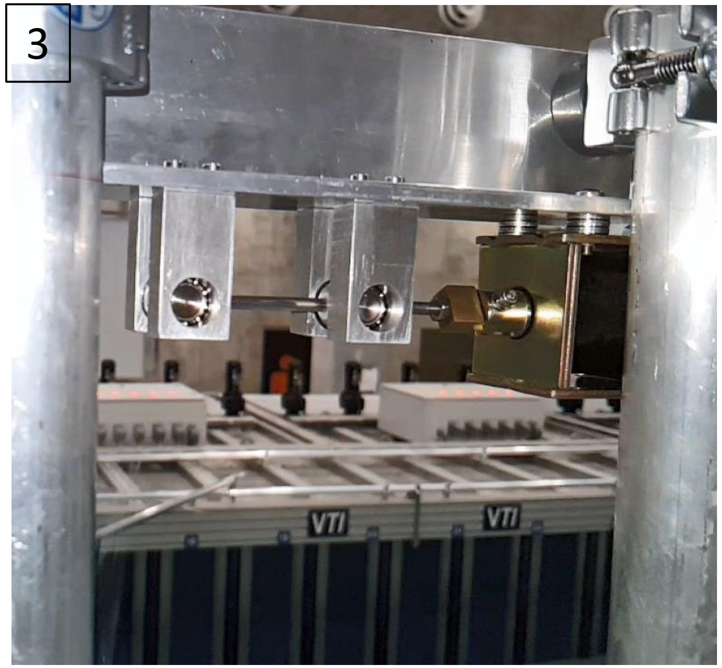
Performance of mechanical pushrod mechanism

Right: Video recorded in superslow (960 FPS). Playback at 30 FPS (1/32 real time)

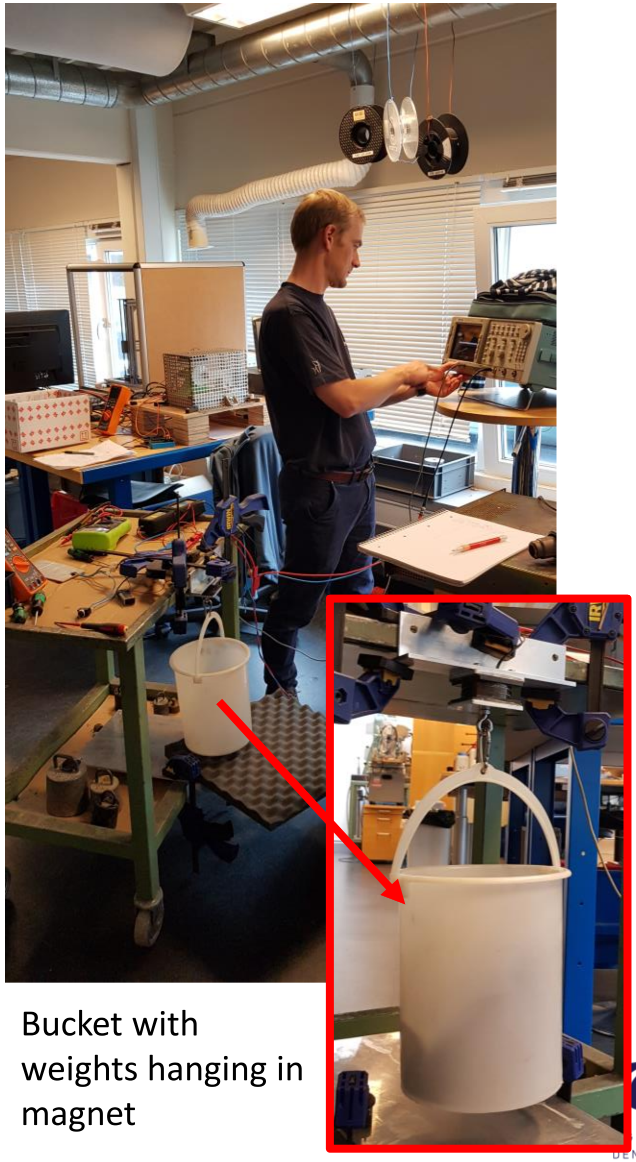
Below: Three succeeding frames during the release.
Conclusion: Release time is at least ~1/960 seconds (say in the order of ~1 ms)







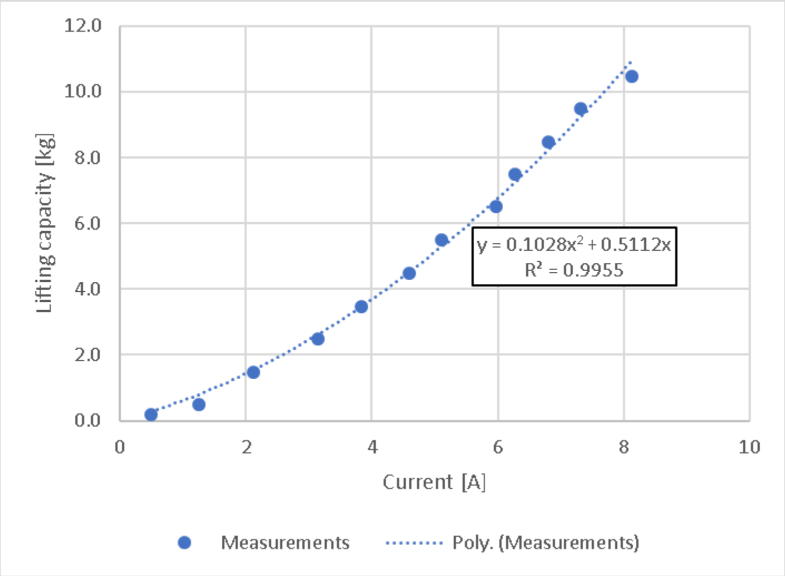
Performance of magnetic release mechanism



Bucket with weights hanging in magnet

Measurements of lifting capacity depending on current through coil.

Conclusion: About 8 A is needed to lift 10 kg, i.e. a magnetic force of 100 N.

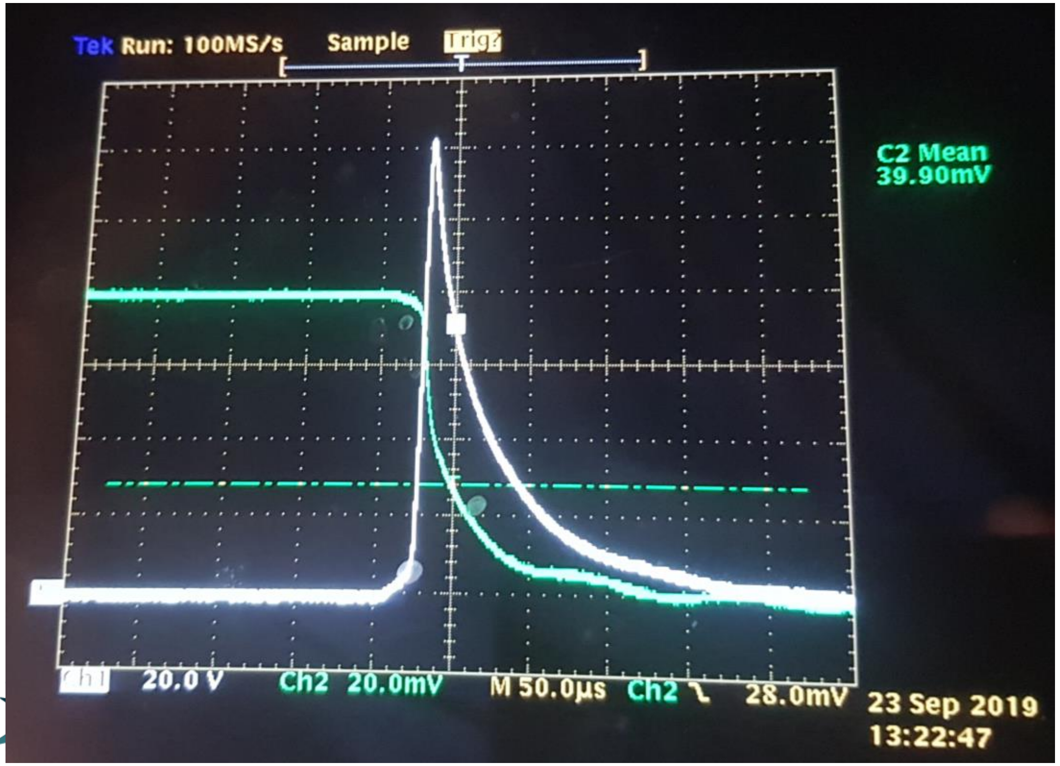


Measurement during release tests with initial 8A current (sampling speed: 100 MS/s)

White curve: Voltage across coil

Green curve Current through coil

Conclusion: Release time is ~150 micro seconds (say in the order of ~0.15 ms)



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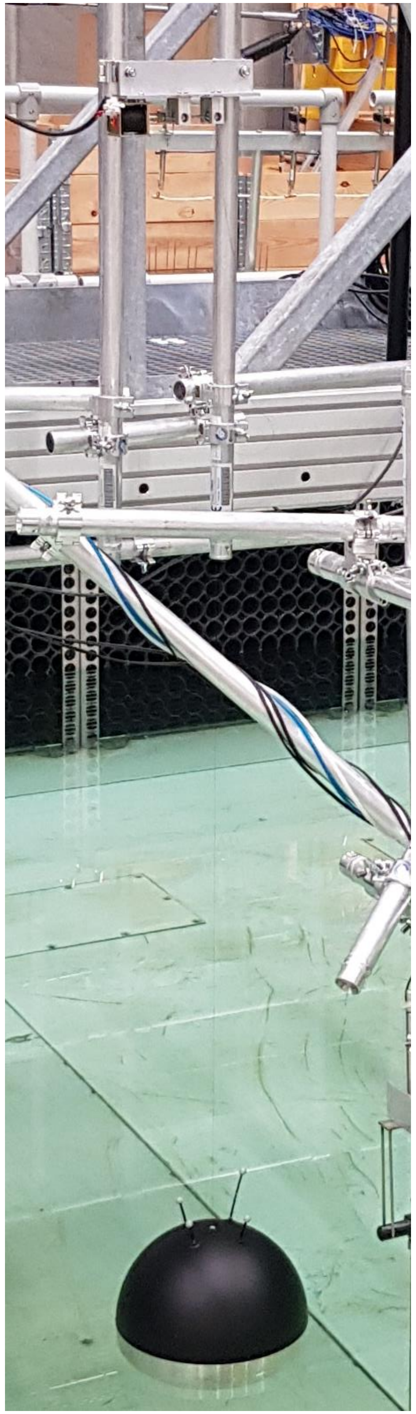
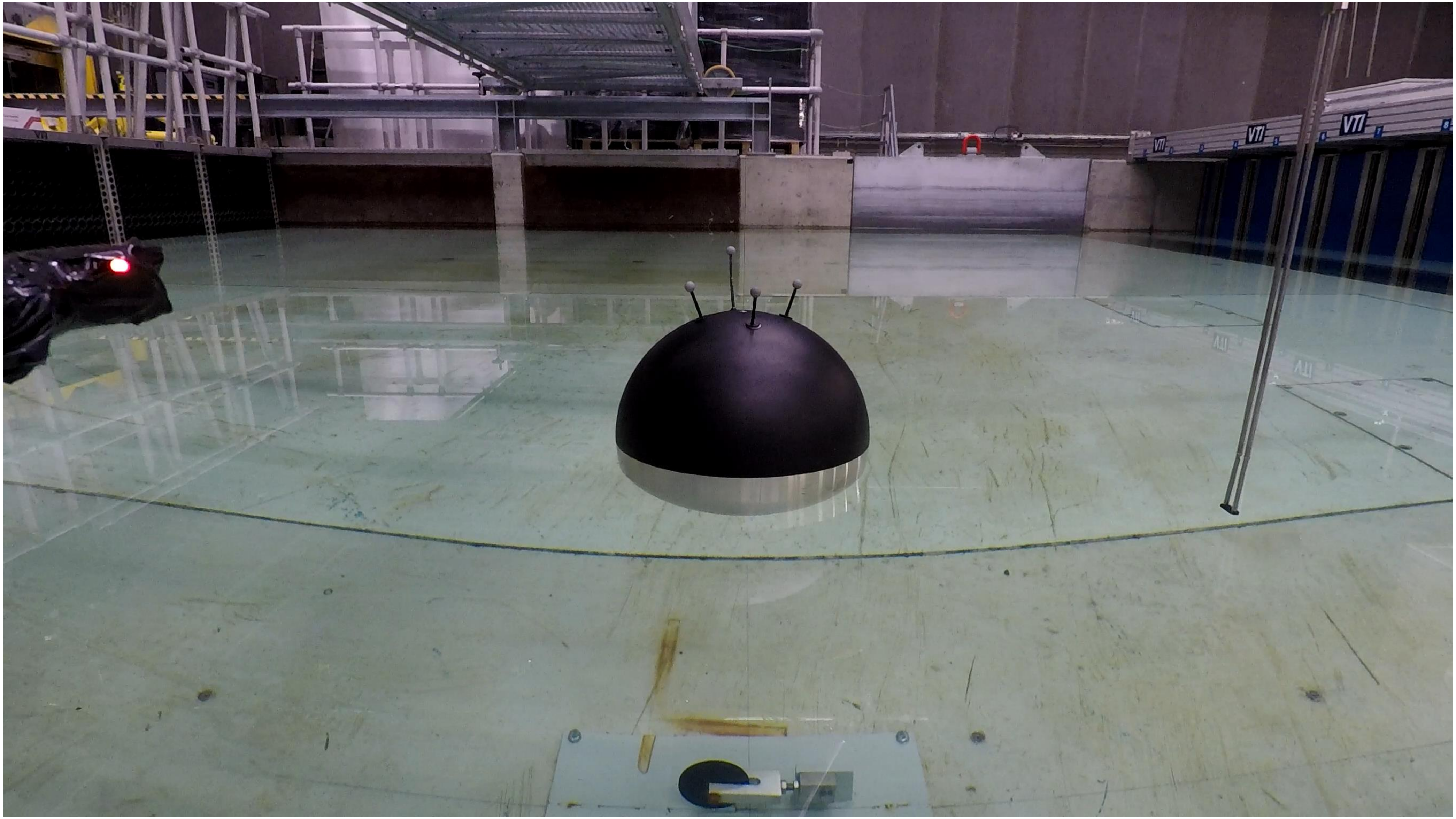
Magnetic release mechanism in setup

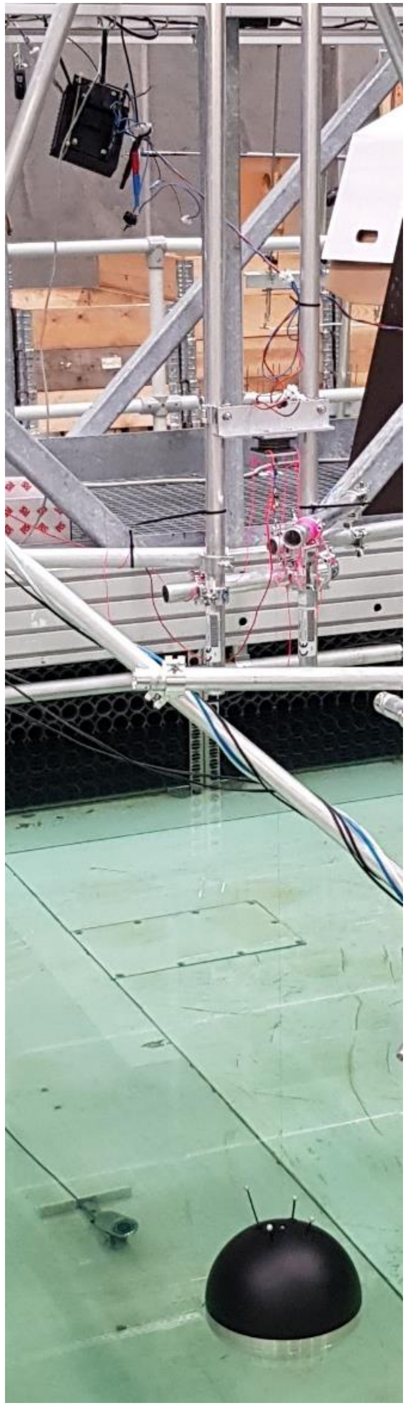
Video recorded in superslow (960 FPS). Playback at 30 FPS (1/32 real time)

A benefit by the magnetic release system is the exact knowledge of the release time.
A drawback is the mass of the connection plate, which together with the elastic mooring line introduces additional dynamics (a second DoF), i.e. the mooring line does not go slack in the exact instant of the release.

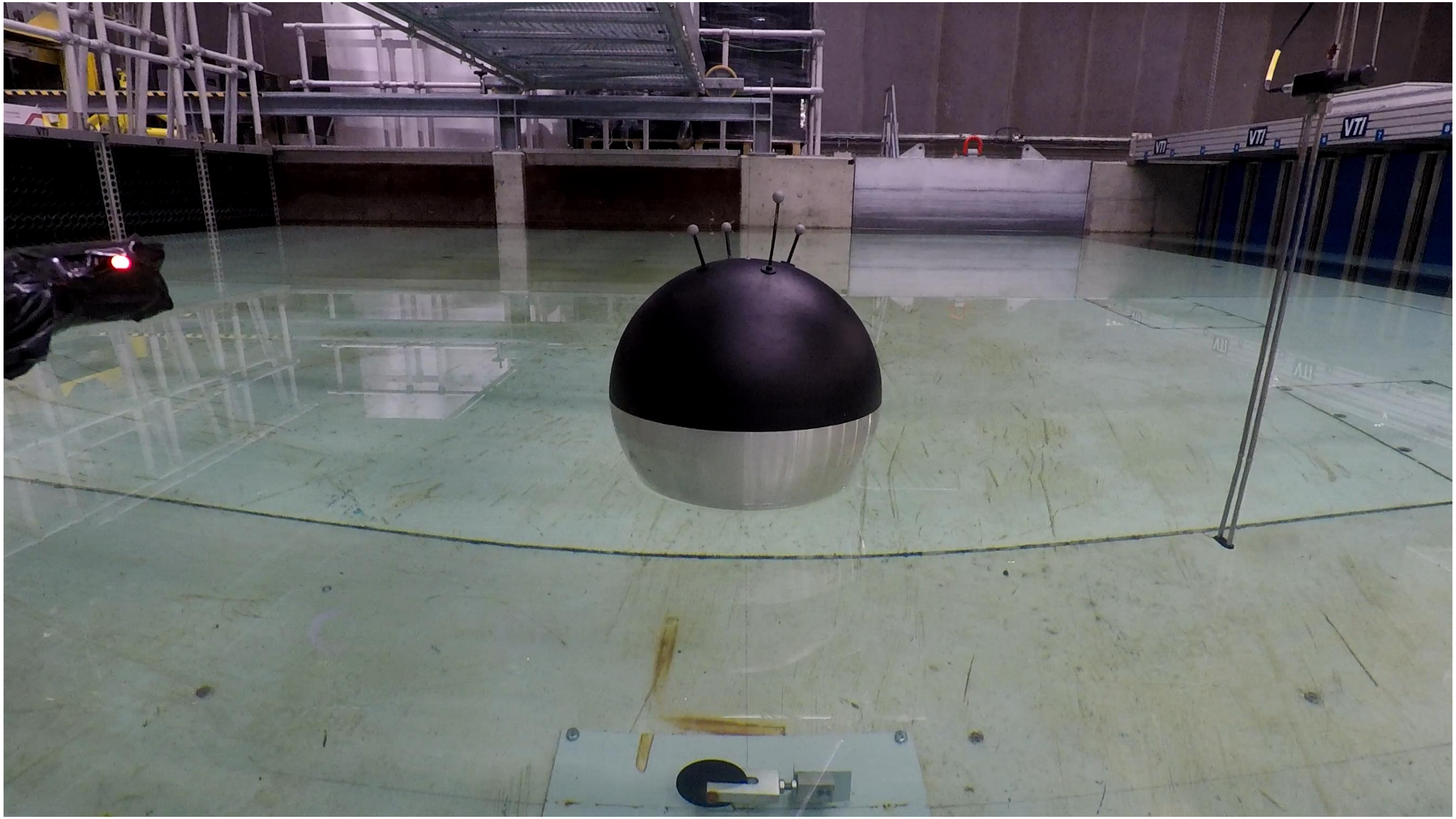


Video below is showing a release in real-time (drop = 0.1*D = 30 mm).





Video below is showing a release in real-time (drop = 0.3*D = 90 mm).



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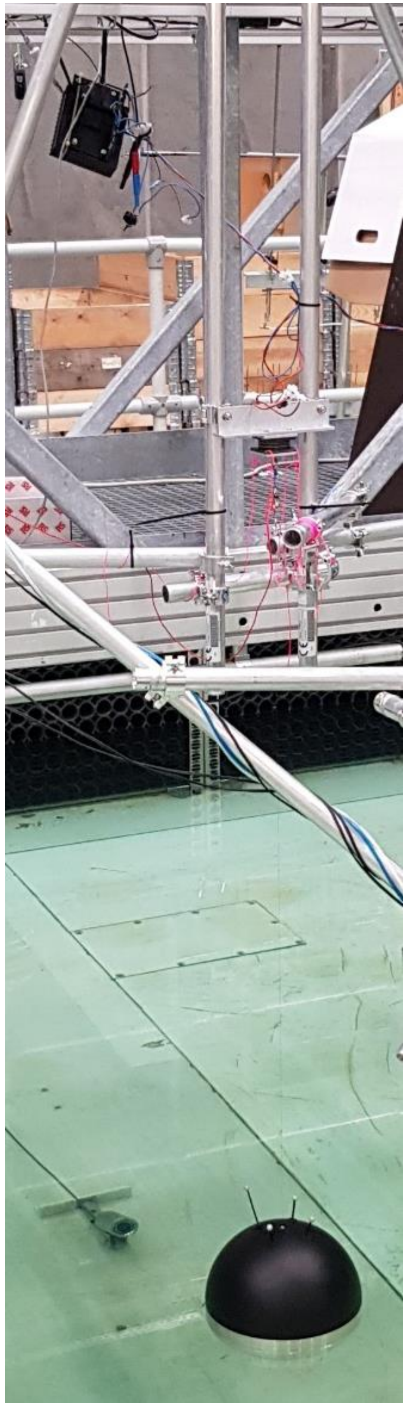
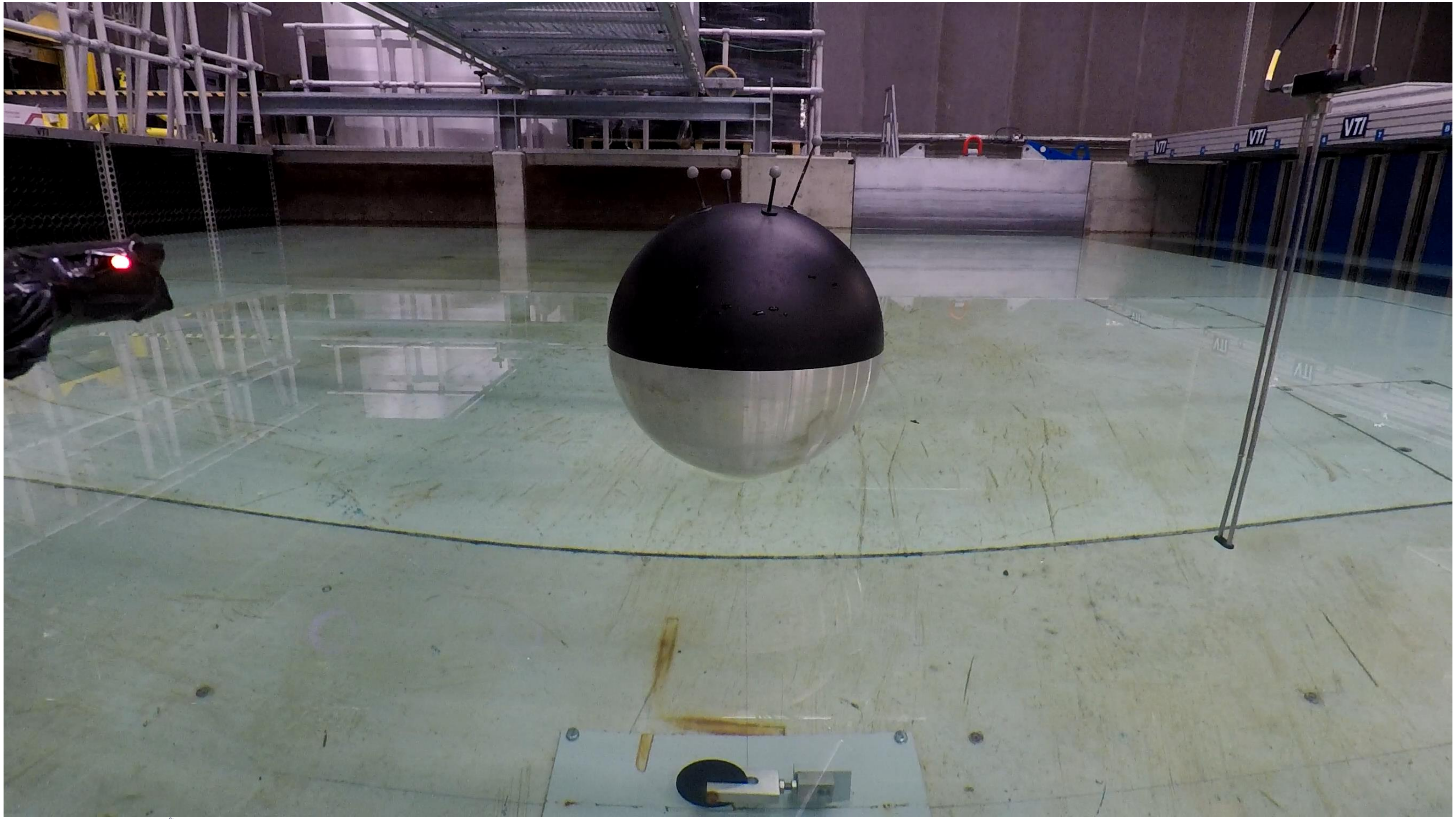
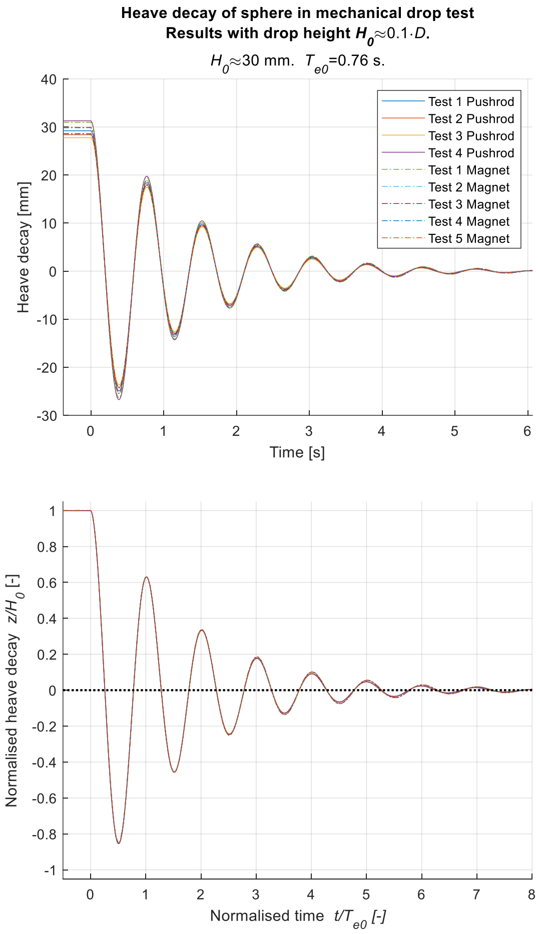


Video below is showing a release in real-time (drop = 0.5*D = 150 mm).

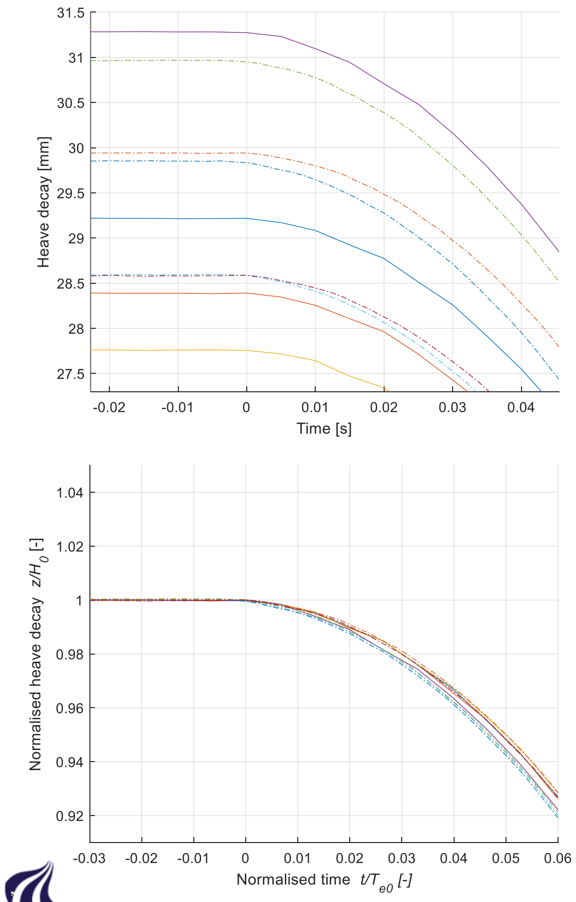


Release system performance & repeatability # 1

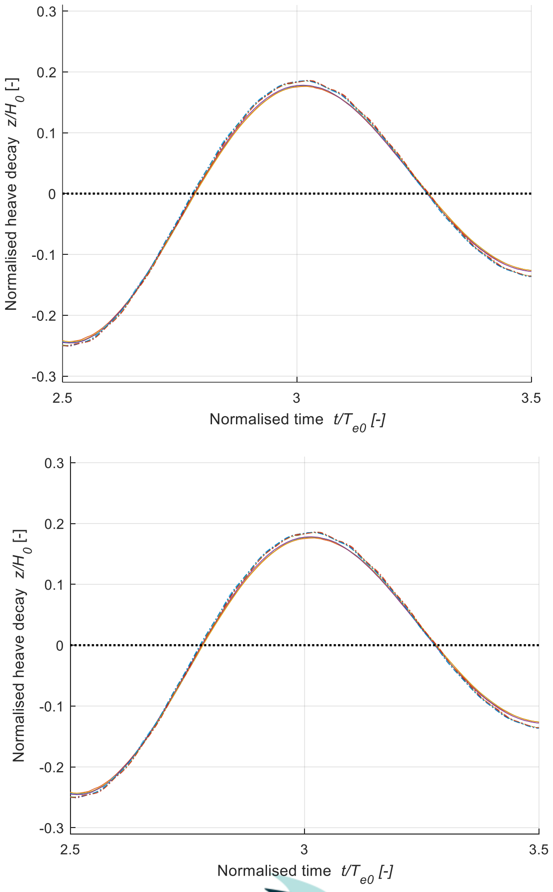
- Both the pushrod system and the magnet system was very fast, and results using the two system are fairly in agreement. Below is an example from the low drop height. A slight discrepancy is seen between the two systems.



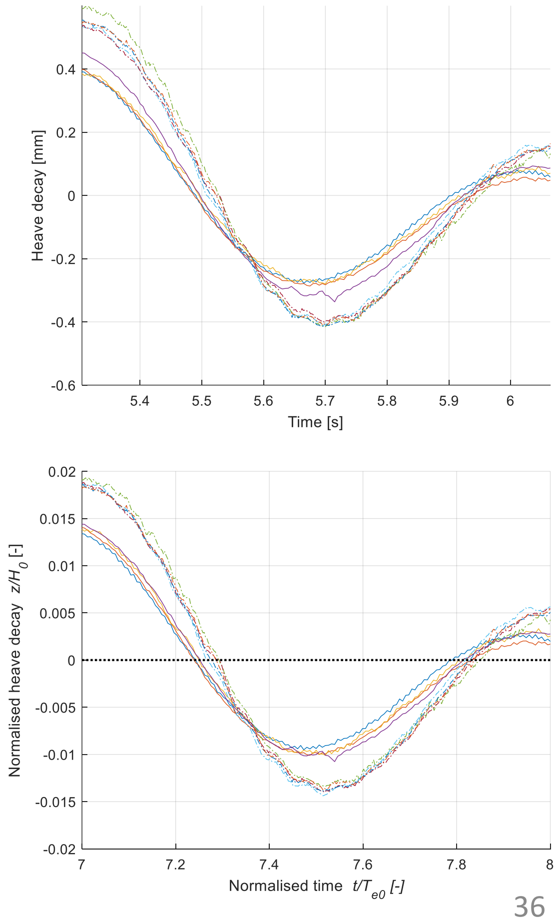
Zoom 1 (initial)



Zoom 2 (mid)

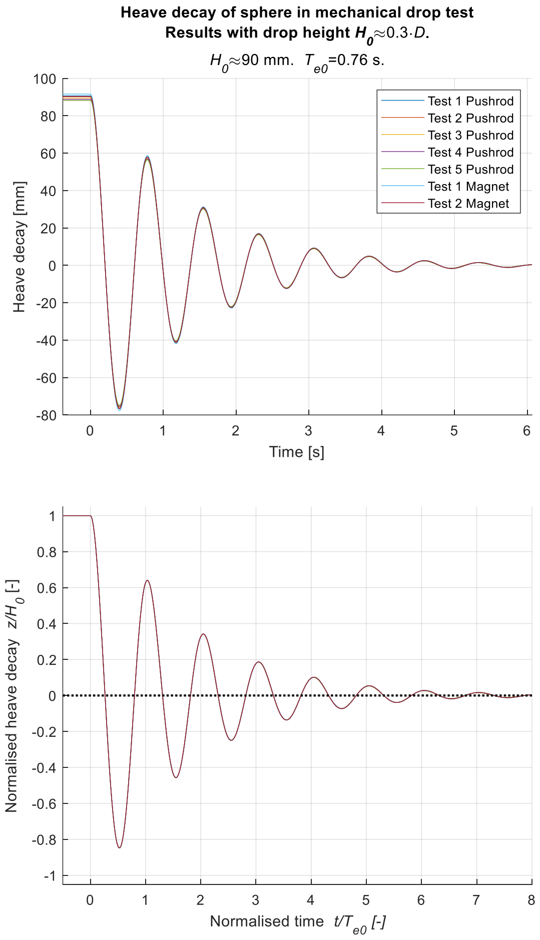


Zoom 3 (end)

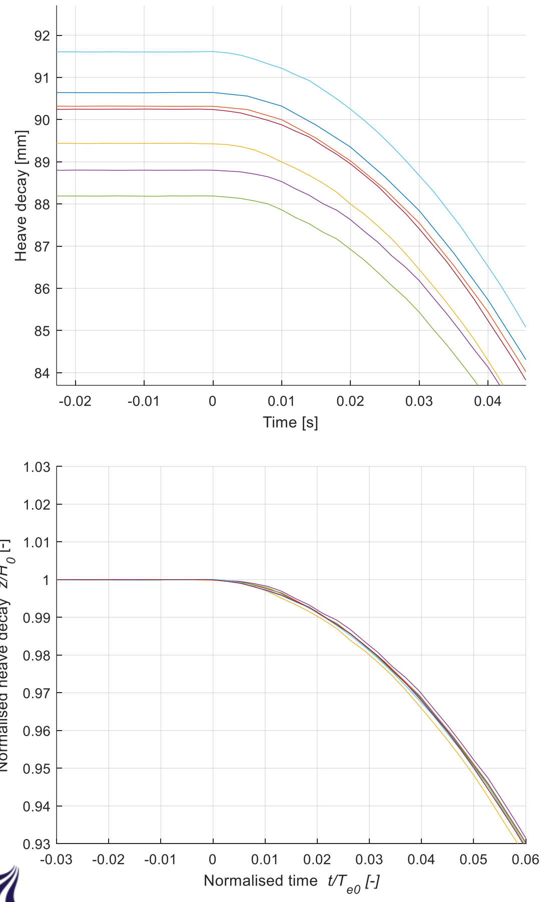


Release system performance & repeatability # 2

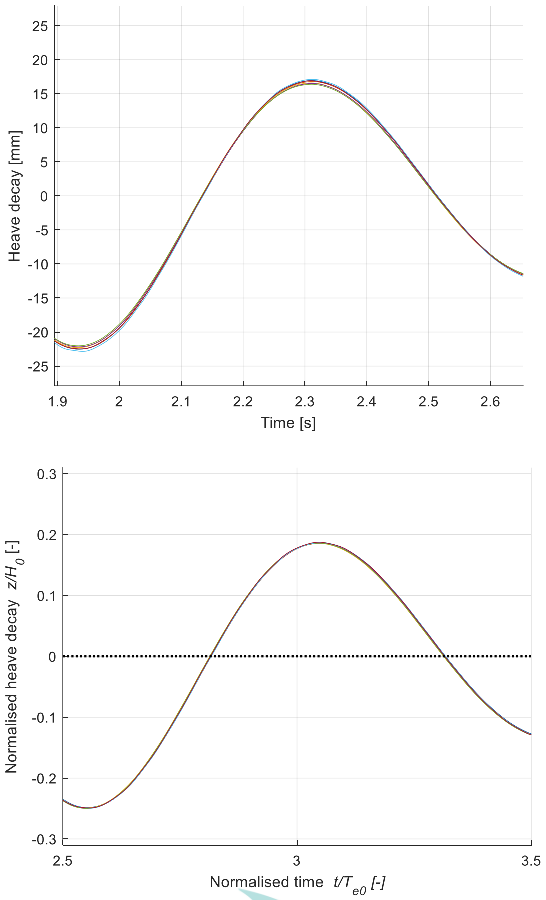
- Example with medium drop height.



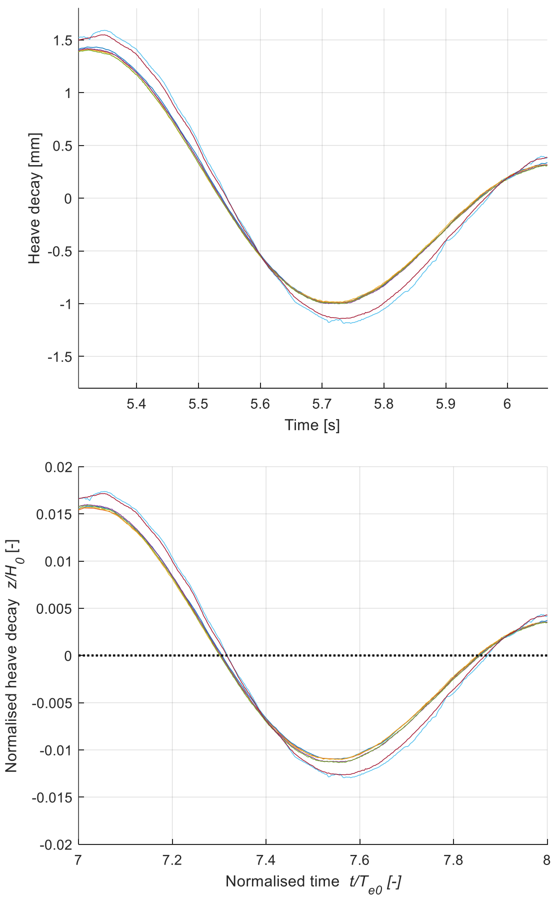
Zoom 1 (initial)



Zoom 2 (mid)

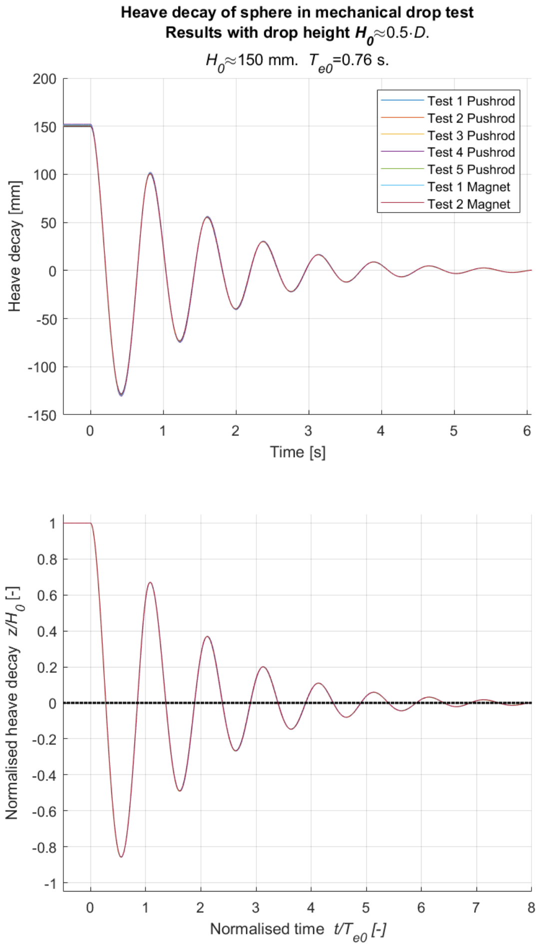


Zoom 3 (end)

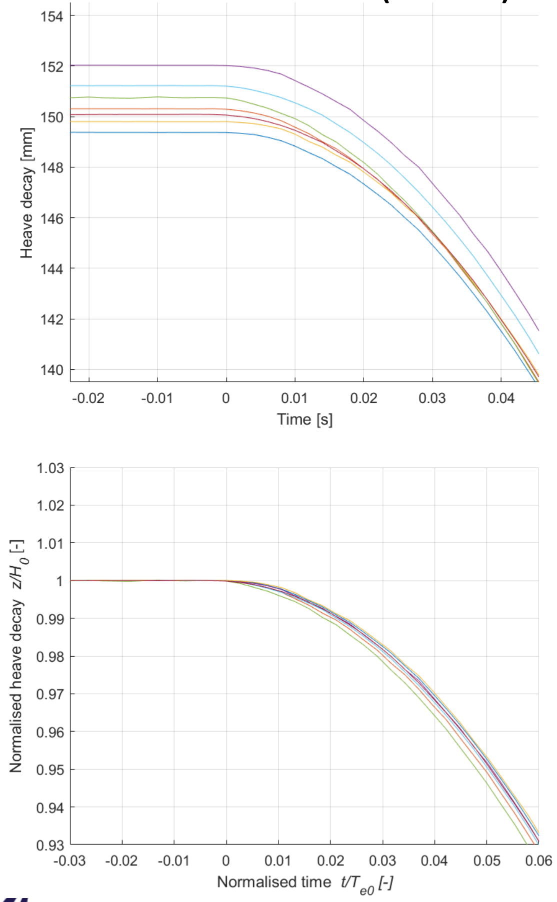


Release system performance & repeatability # 3

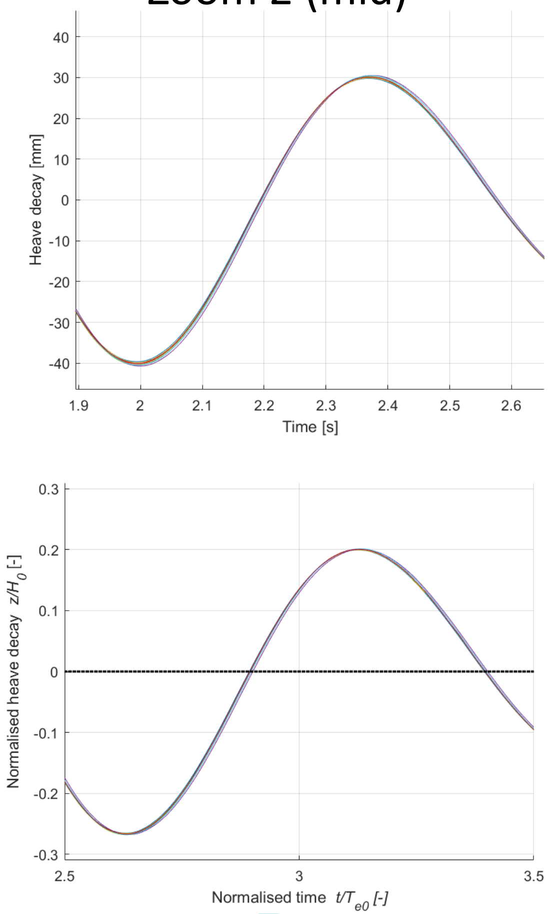
- Example with high drop height. Here the difference between the curves is also not significant.



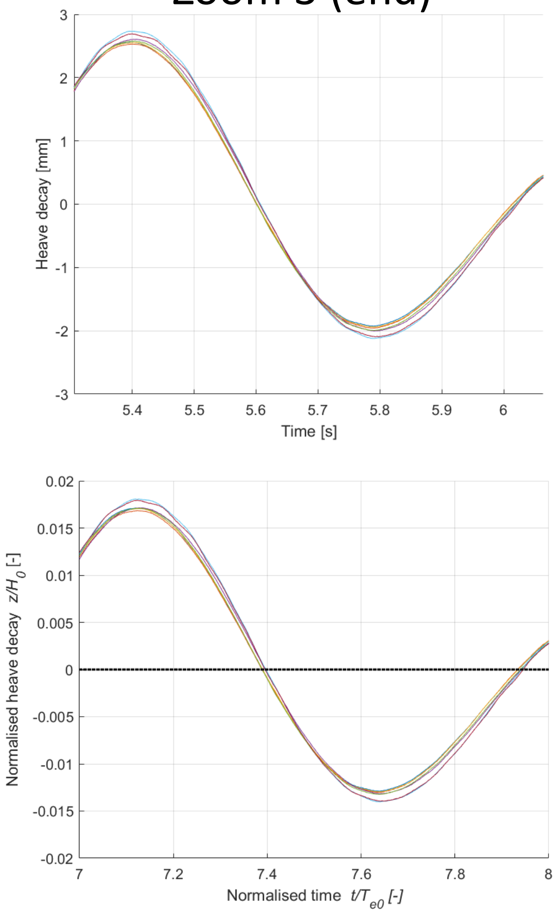
Zoom 1 (initial)



Zoom 2 (mid)



Zoom 3 (end)

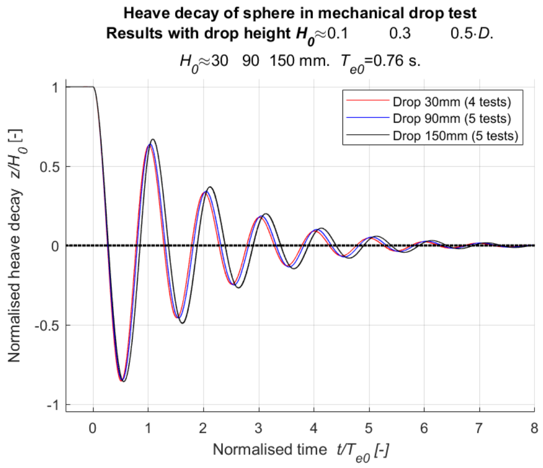


Conclusion on repeatability and release system performance

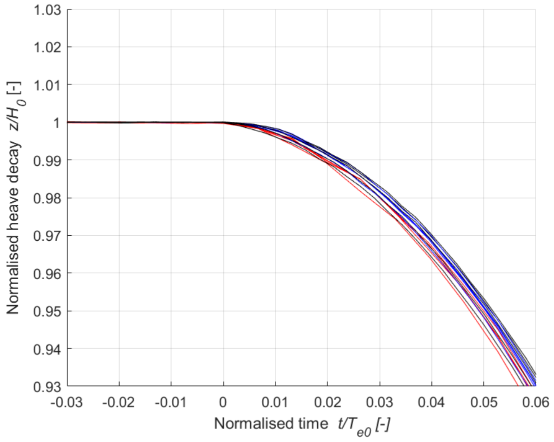
- Repeatability is very good. Measured curves are almost identical.
- The performance of the pushrod release system seems slightly better than the magnet system. Reasons are believed to be caused by:
  - The magnet system is introducing additional dynamics (as discussed in slide 32)
  - The camera system was mounted under the bridge in the wave basin, and so was the release systems. When the magnet was dropped and catched by additional lines it caused some small mechanical vibrations in the bridge, which were transferred to the cameras thereby causing a slight instability in the measurements.

- Only the measurements using the pushrod system is used in the following

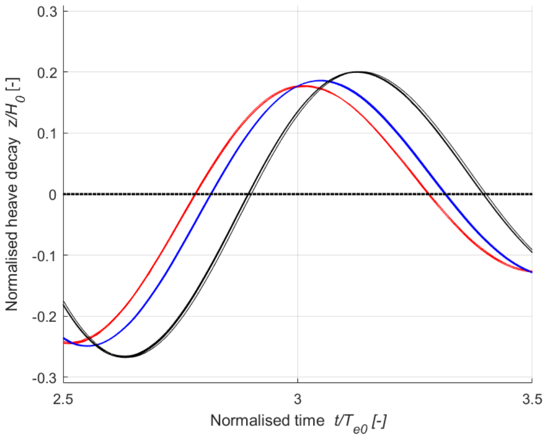
Different drop height



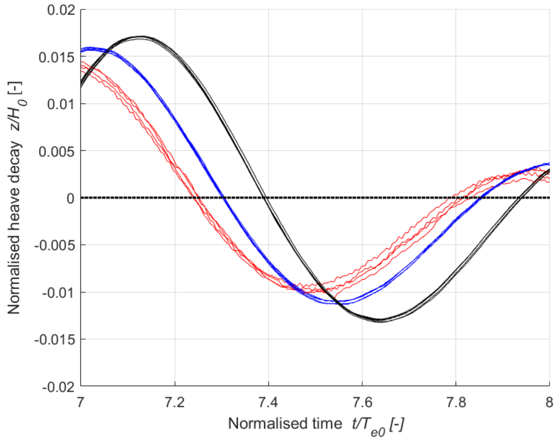
Zoom 1 (initial)

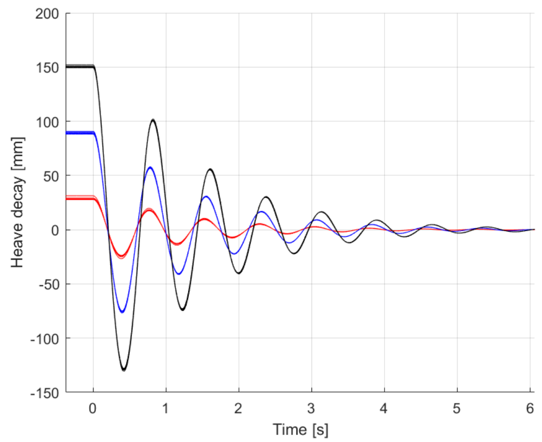


Zoom 2 (mid)



Zoom 3 (end)





- The measurements clearly shows that non-linearities are present for the higher drop heights:
  - A phase difference is taking place during the first part of the signal (higher drop => a slower response)
  - The amplitude is altered sightly. There is clearly a reatively higher amplitude for the large drop height.

This issue will be threated in the following slides, when compared to numerical model estimates

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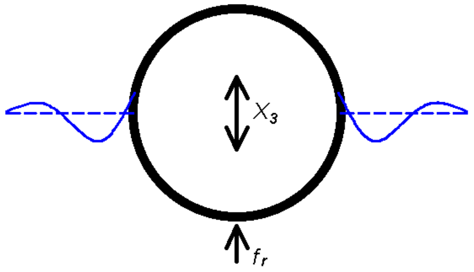
Linear potential model

Wave radiation



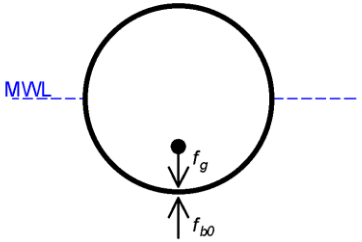
Forces due to oscillatory motion of the sphere in otherwise calm water (no incoming waves) are termed radiation forces f_r:

$$f_r \; = -m_h \cdot \ddot{x}_3 - c_h \cdot \dot{x}_3$$

m_h is hydrodynamic added mass and c_h is hydrodynamic damping.

Hydrostatics

At rest in calm water with no PTO force



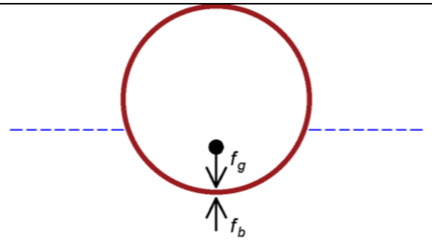
The hydrostatic force is zero as gravity force f_g is balanced by buoyancy force f_{b0}.

$$f_h = f_{b0} - f_g = 0 \quad \text{as} \quad f_{b0} = f_g$$

$$f_g = mg \quad \text{and} \quad f_{b0} = \rho g V_{s0}$$

m is mass of sphere, g is gravity constant, ρ is density of water, V_{s0} is submerged volume when at rest in calm water.

When displaced in calm water



The hydrostatic force is decreased when moving upward as the buoyancy force is decreased due to that the submerged volume becomes smaller.

The submerged volume may be linearized to:

$$V_s \cong V_{S0} - A_{WP} X_3$$

Thereby the hydrostatic force becomes:

$$f_h = f_b - f_g \cong -\rho g A_{WP} X_3$$

$$f_h \cong -k_h X_3 \quad \text{,with} \quad k_h = \rho g A_{WP}$$

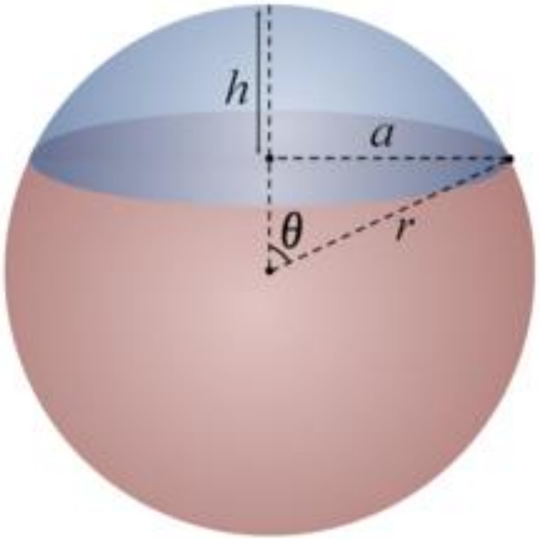
A_{WP} is the water plane area (i.e. the area of the circle as the sphere is half submerged)

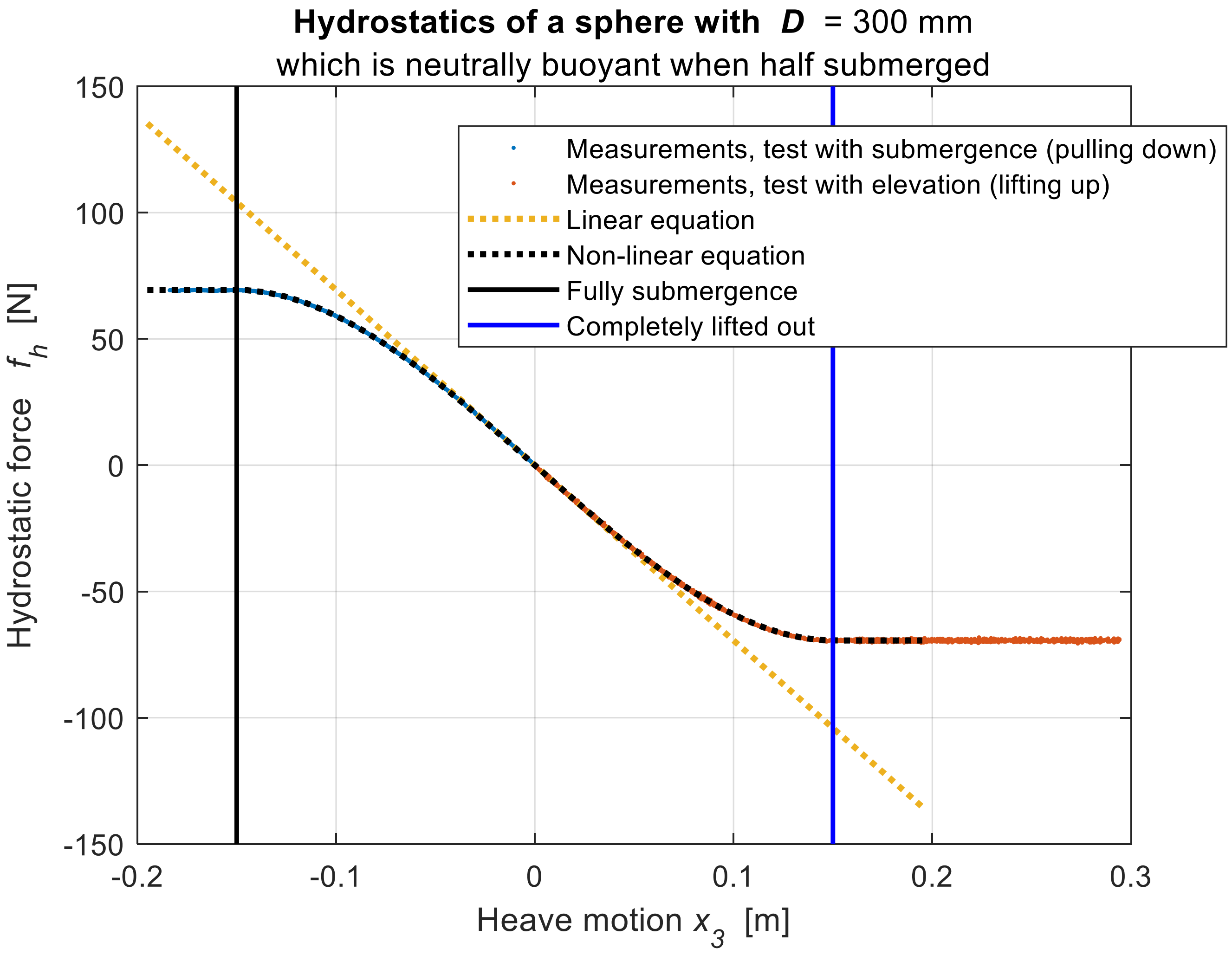
Non-linear hydrostatics by using a non-linear buoyancy force

The non-linear buoyancy force is calculated by:
$f_h = f_b - f_g = V_s \rho g - mg$

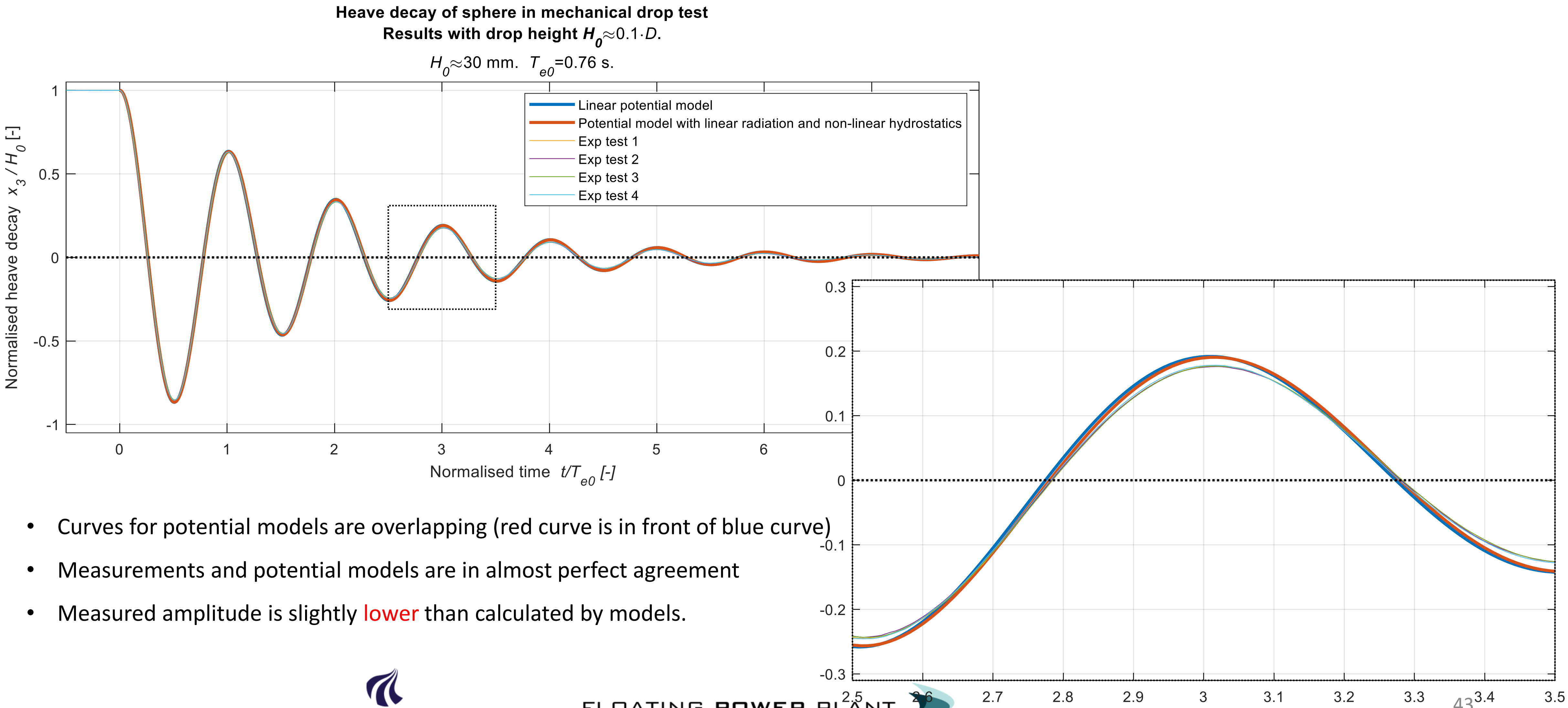
The exact submerged volume is calculated by:
$V_s = \frac{\pi h^2}{3}(3r - h)$,

where $h = r - x_3$ with limits 0 and D





Measurements of decay, small drop height



- Curves for potential models are overlapping (red curve is in front of blue curve)
- Measurements and potential models are in almost perfect agreement
- Measured amplitude is slightly lower than calculated by models.

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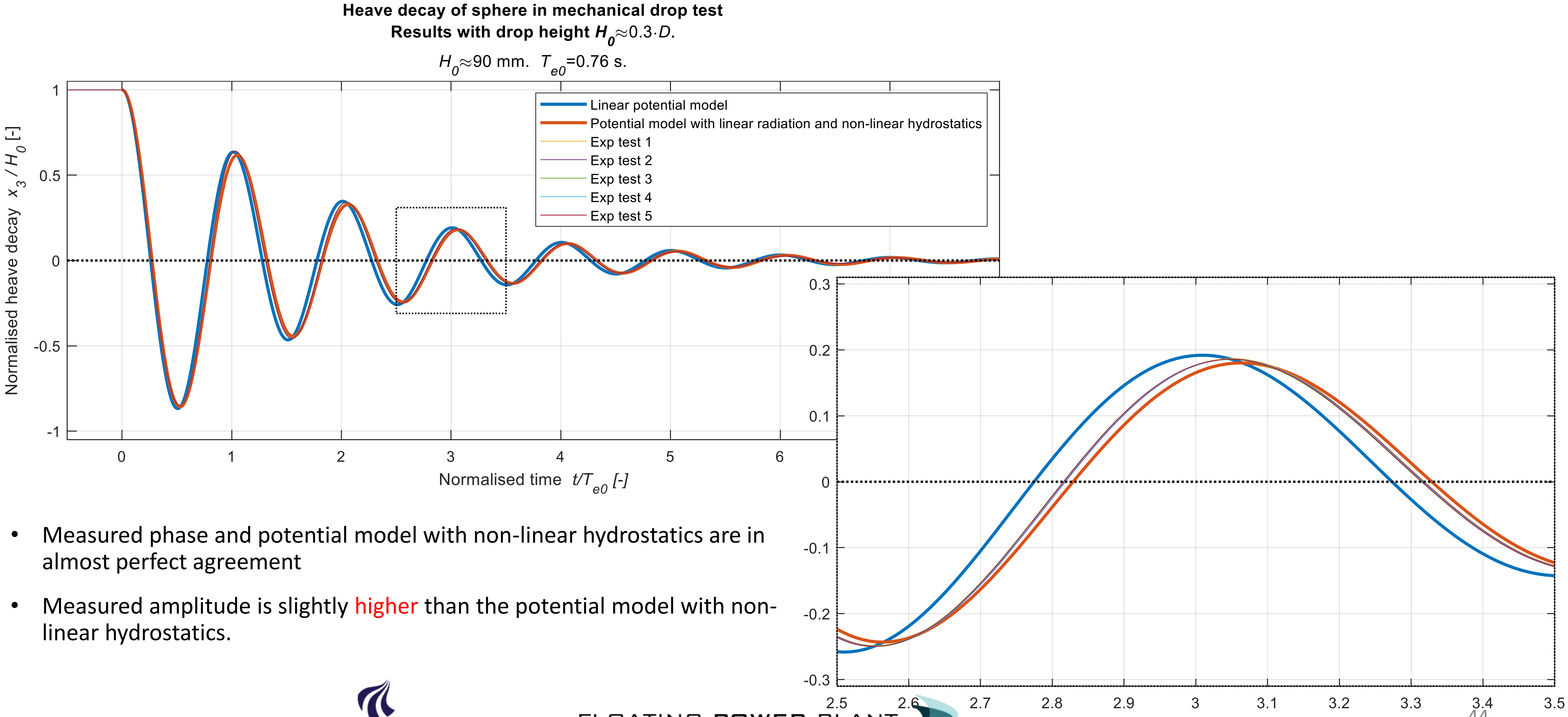
Measurements of decay, medium drop height



- Measured phase and potential model with non-linear hydrostatics are in almost perfect agreement
- Measured amplitude is slightly higher than the potential model with non-linear hydrostatics.

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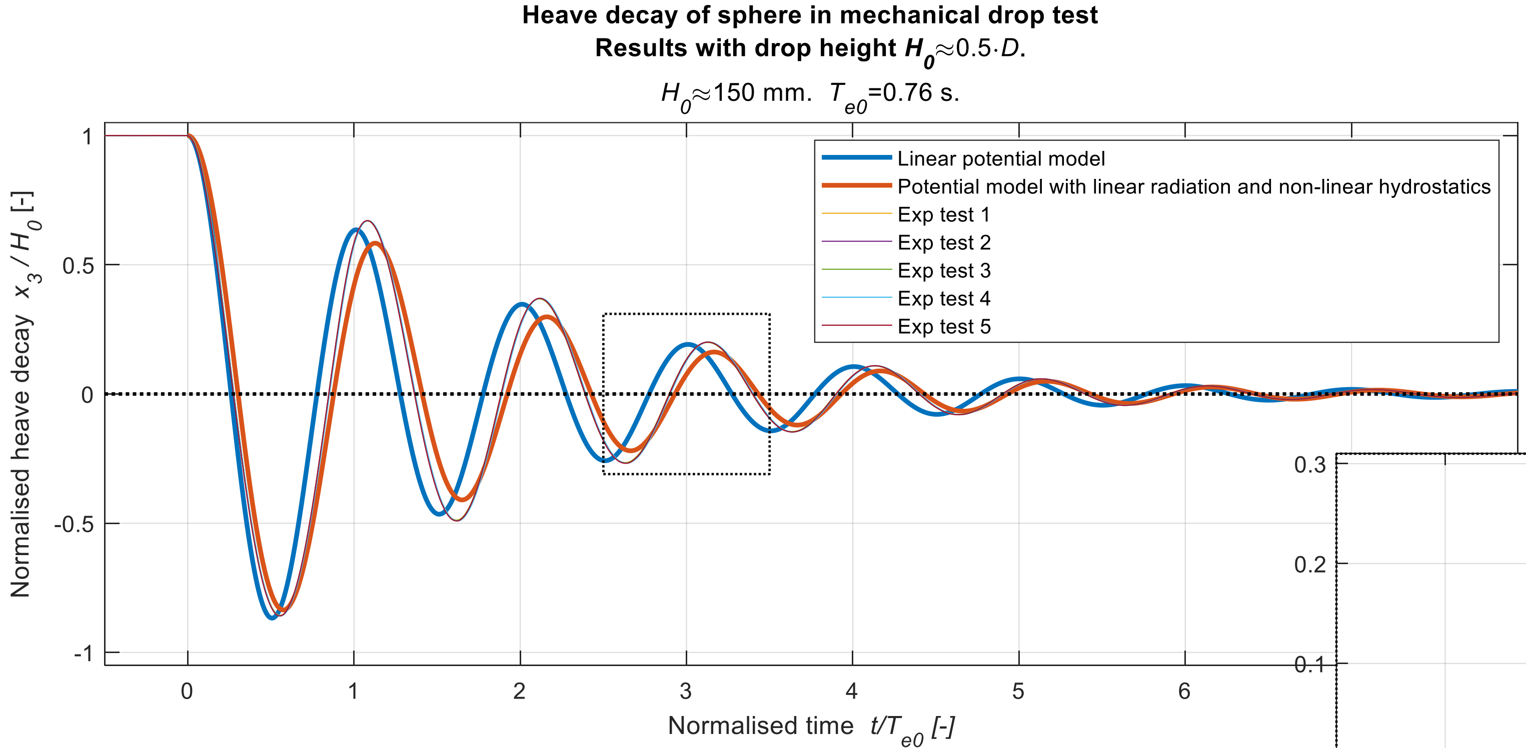
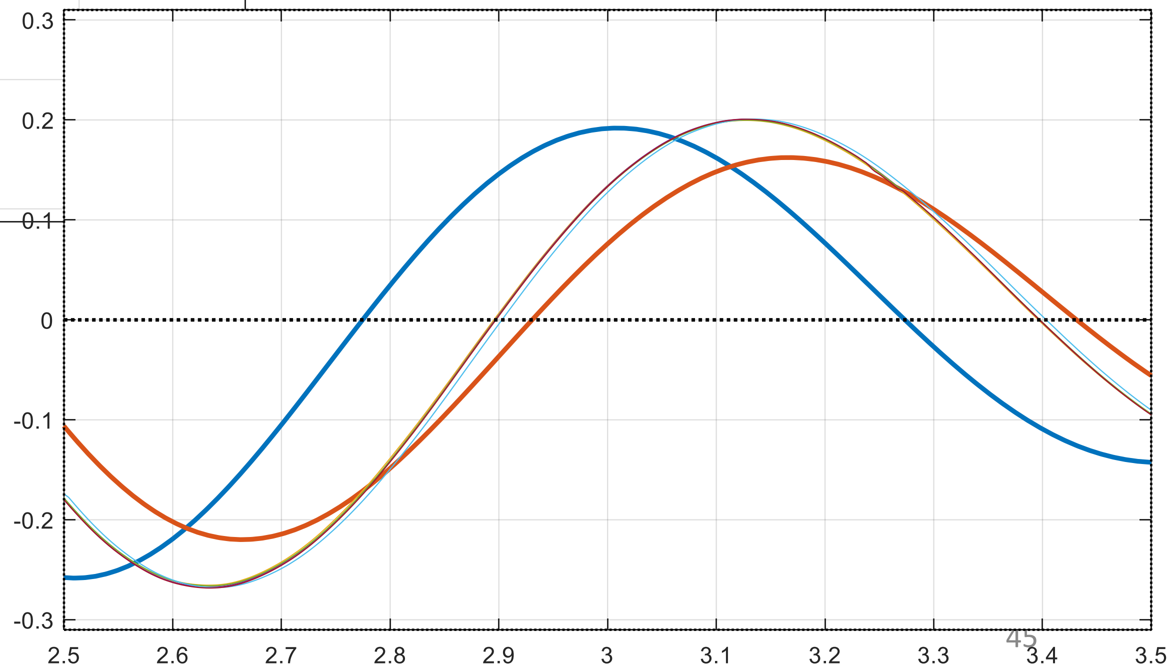
Measurements of decay, large drop height

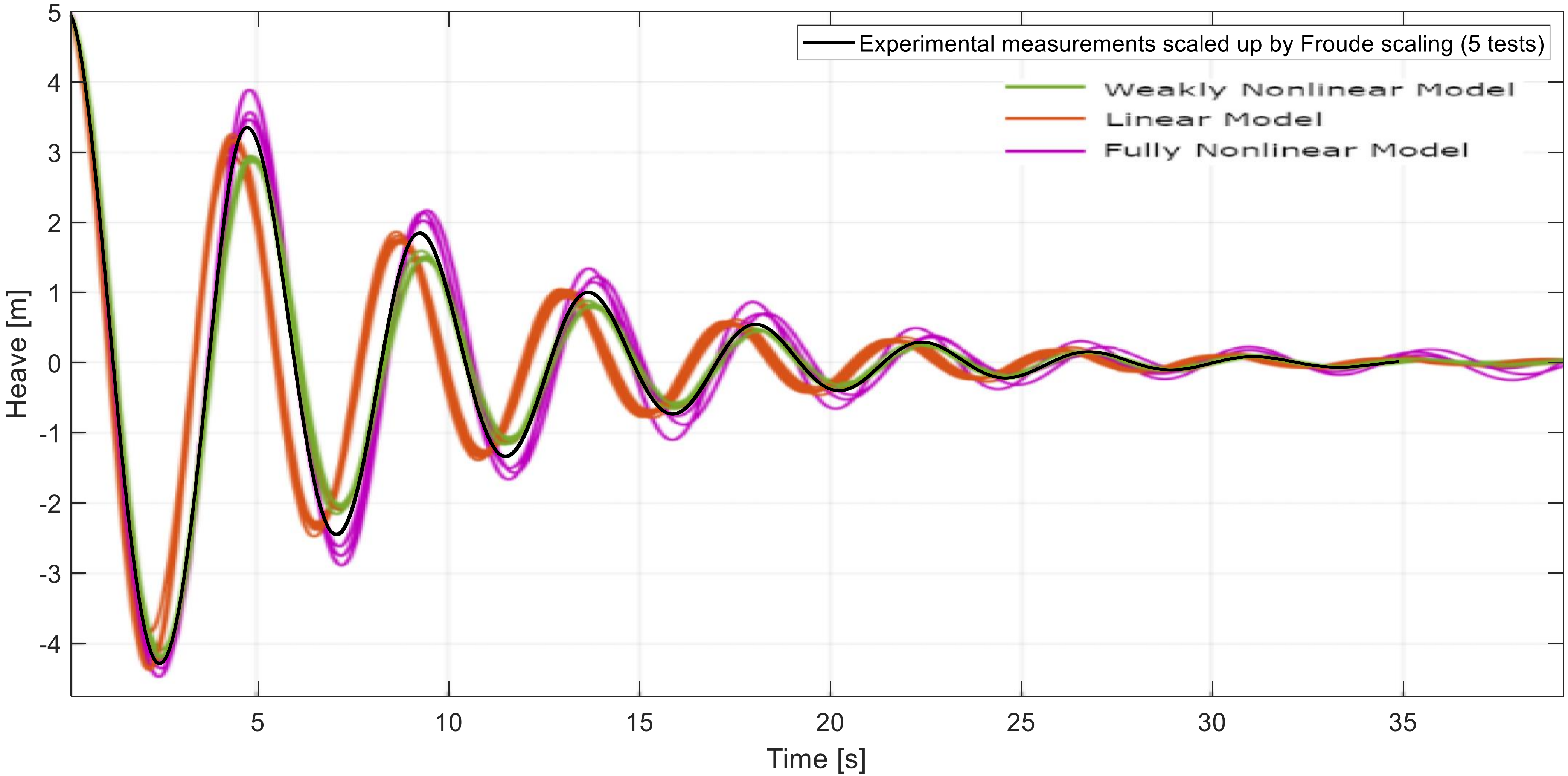




- Measured phase is not perfectly in line with the potential model with non-linear hydrostatics
- Measured amplitude is remarkably higher than both of the potential models.

Comparison to CFD models

- As described in the introduction CFD calculations have been performed. The lower plot shows how the experimental results fits with results presented in [1].



Remaining issues with existing setup

Issue	Solution
To make accurate PTO tests, the controller needs to be faster and more robust	Some preliminary trials and experimental measurements performed at AAU on the system indicates that it is indeed possible to improve the controller by using current control using a combined feed forward and closed loop force controller.
6 DoF real-time rigid body motion measure of the sphere is by now runing on a stand-alone system. In the future the data should be included in the real-time control-system	The Qualisys system contains possibilities for real-time UDP streaming of rigid body motion data to the controller, so this issue can be solved with some dedicated legwork.
The complete mass matrix of the sphere is not established yet (i.e. including inertia moments)	The 2D drawings have been validated by measurements of dimensions and masses, so it is relatively easy to draw up the sphere in 3D with the correct densities, and extract the mass matrix from the CAD software.

Conclusions on heave decay tests

- The model and release mechanisms are performing well
- Repeatability is very good
- High quality motion data has been acquired suitable for further numerical model validation

Outstanding tasks:

- Make the data and descriptions public available (subject for discussion how to do that)

Part 3:
Future possible validation tests with moving WEC & power absorption

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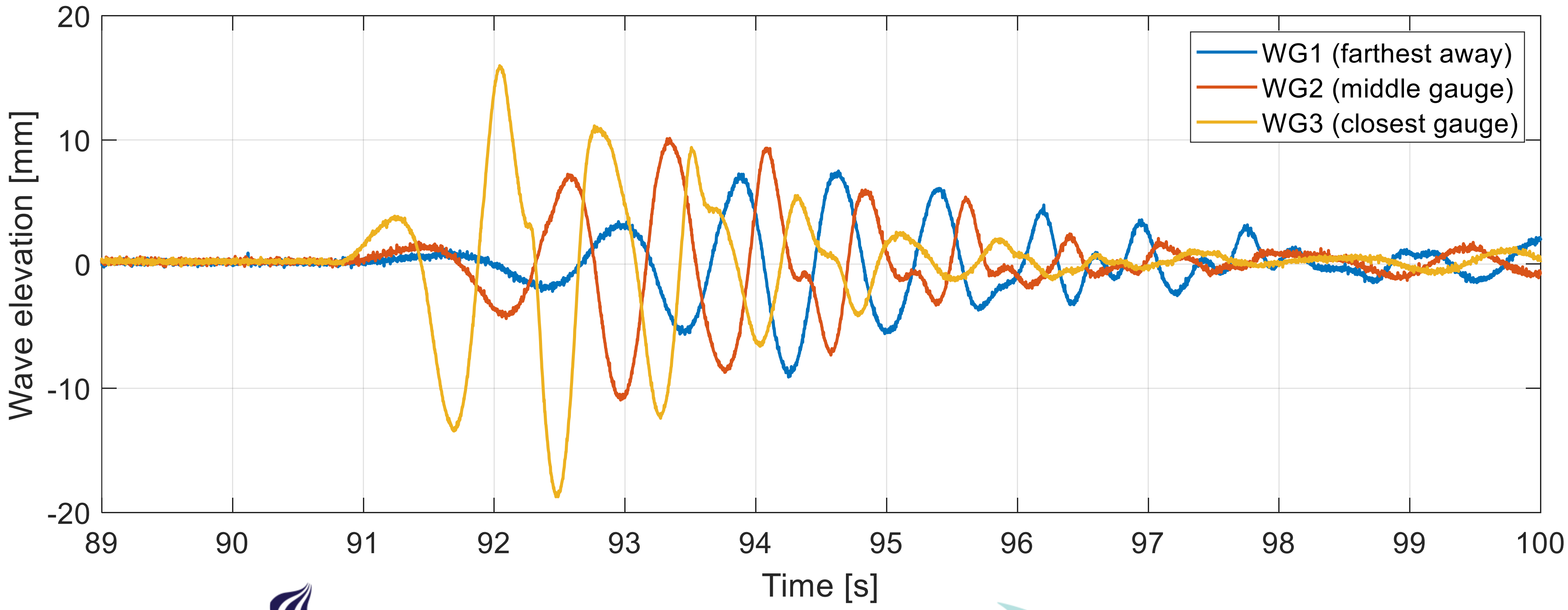
Some further initial tests have been performed

1. Wave measurements
2. Decay with drop from higher positions
3. Decay with release from submerged positions
4. Freefloat
5. PTO tests with a regular wave and linear damping control

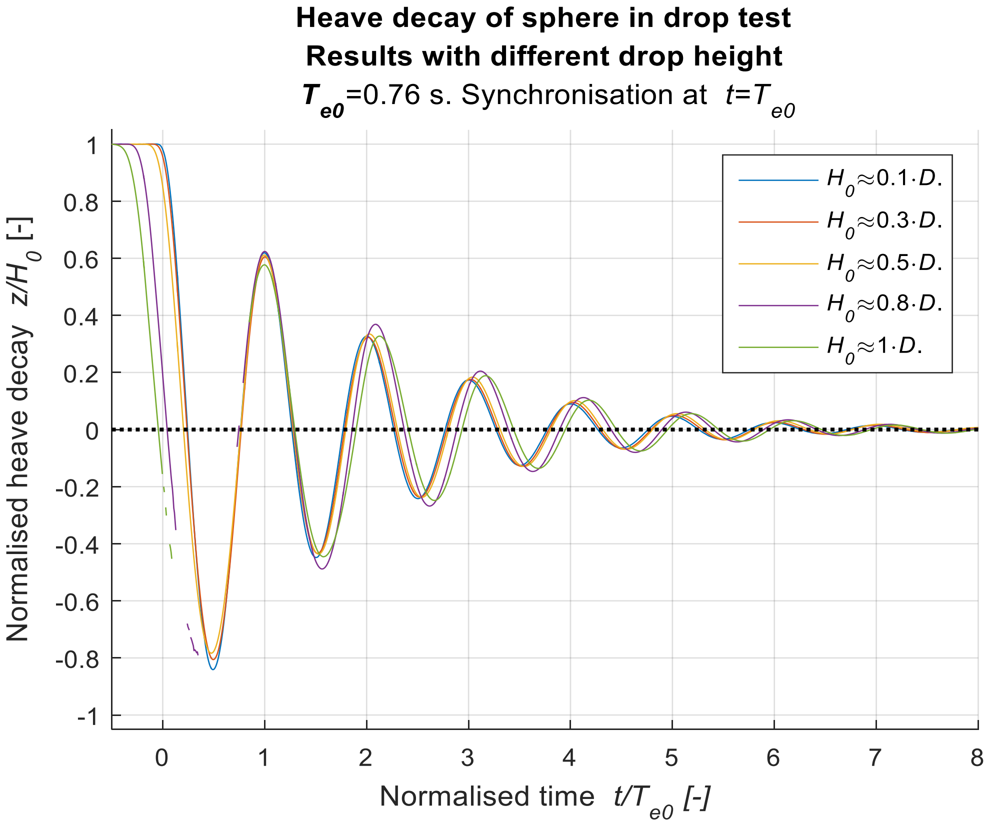
Some info about these tests are given in the following

Wave measurements

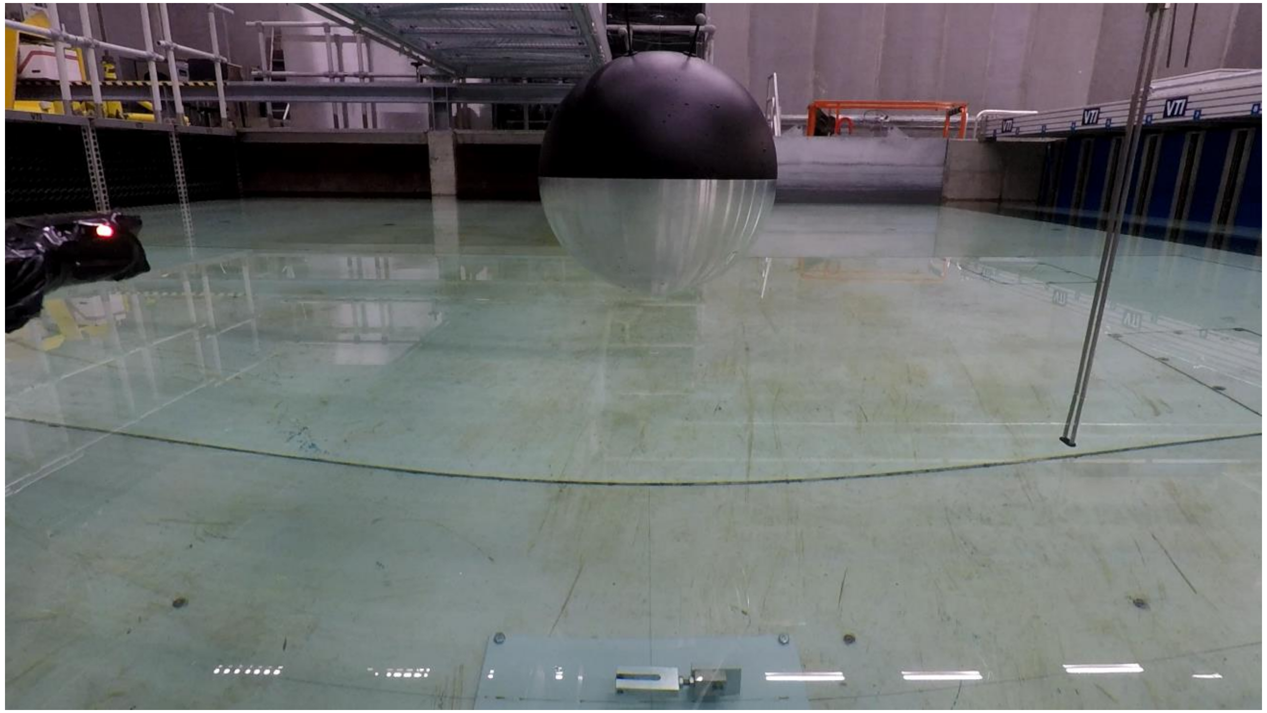
- Wave measurements from 3 wave gauges are part of the dataset, but the measurements have not yet been analysed. Below is an example from a decay test with drop height of 150 mm.



Decay with manual drop from higher position



Example with drop height = 1*D = 300 mm.

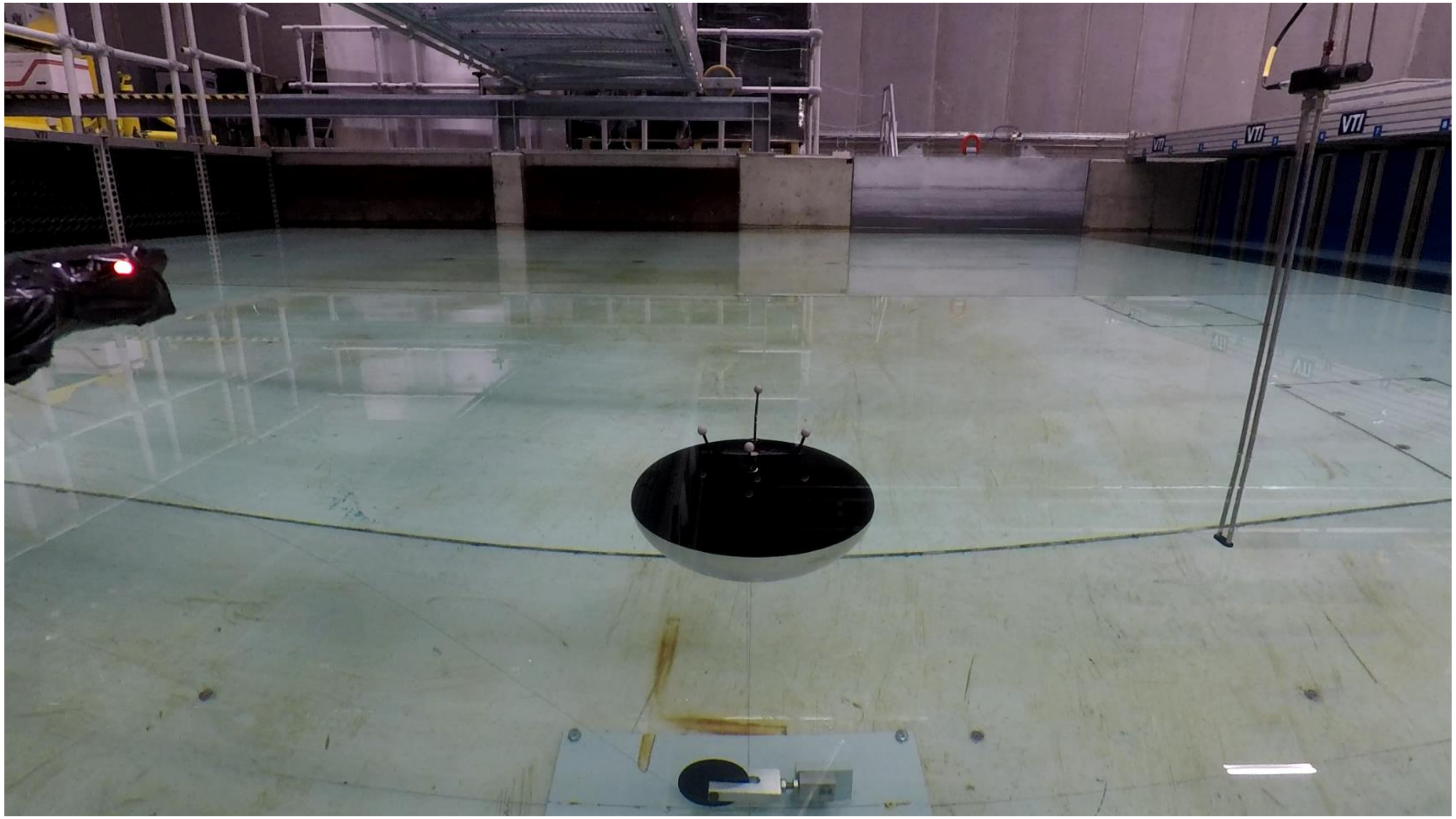


Actual tests are not useful due to two reasons:

- Wrong initial conditions due to the manual drop
- A large part of the signal is missing due to the markers coming under water

Decay with manual release from submerged positions

Example with release position = -0.5*D = -150 mm.



Actual tests are not useful due to the wong initial conditions caused by the manual drop

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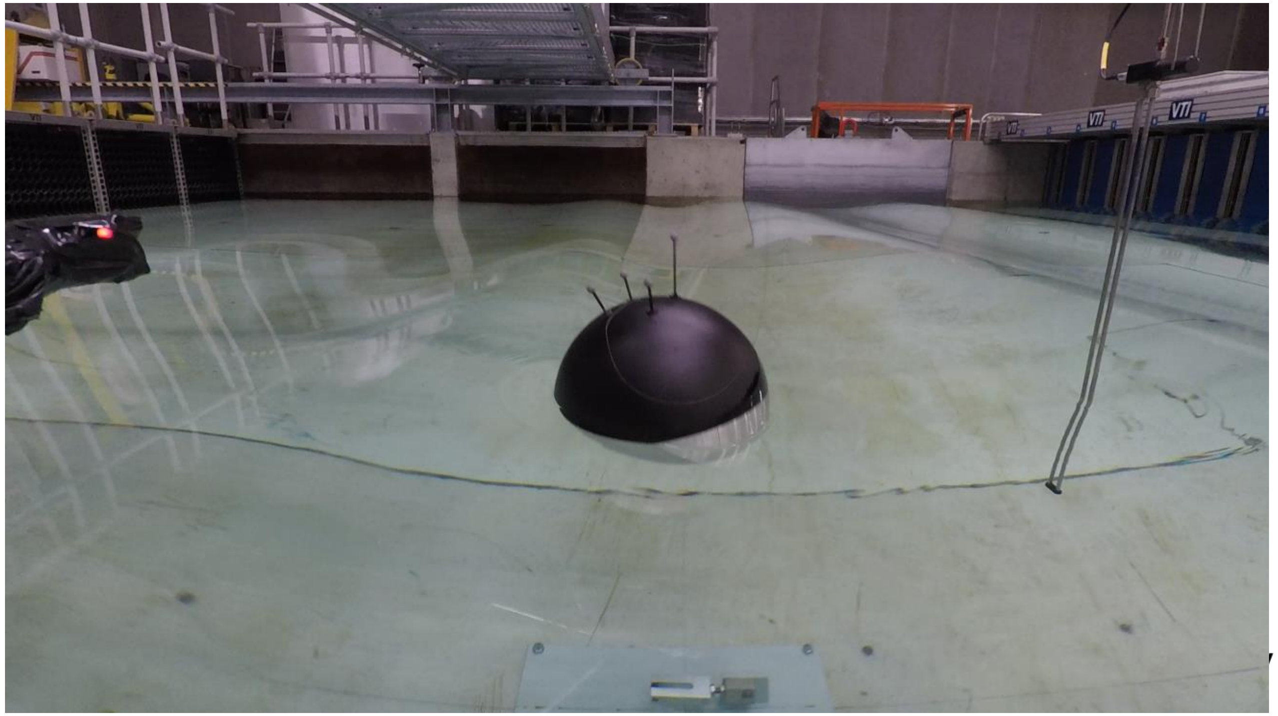
Example of free float cases with regular waves

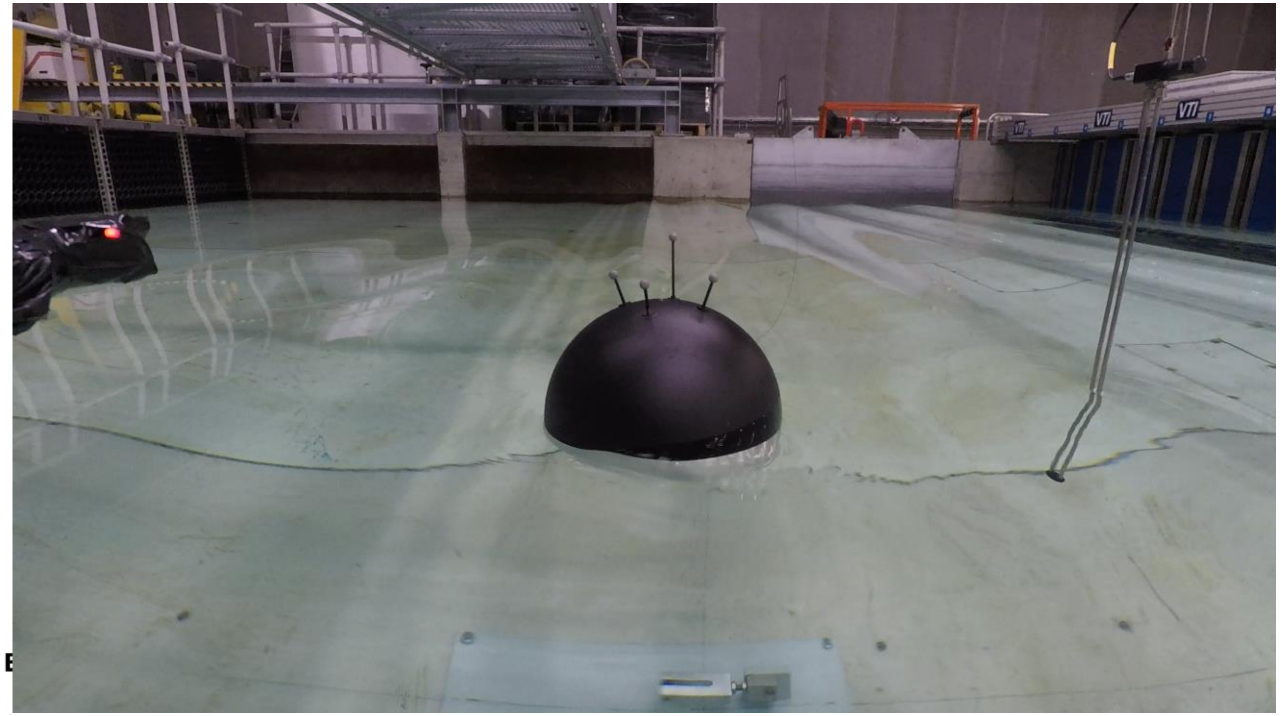
Te	0.758	s		
fe	1.319261	Hz		
fe-factor	f	T	Wave length L1 [m]	Wave length L0 [m]
0.8	1.055	0.948	1.402	1.403
1.0	1.319	0.758	0.898	0.898
1.2	1.583	0.632	0.623	0.624
All waves are deep water!				

Name	S0 = H/L0	T (s)	L0 (m)	H (m)
R1	0.025	0.948	1.403	0.035
R2	0.025	0.758	0.898	0.022
R3	0.025	0.632	0.624	0.016
R4	0.050	0.948	1.403	0.070
R5	0.050	0.758	0.898	0.045
R6	0.050	0.632	0.624	0.031
R7	0.100	0.948	1.403	0.140
R8	0.100	0.758	0.898	0.090
R9	0.100	0.632	0.624	0.062

Video from R4 test



Video from R6 test

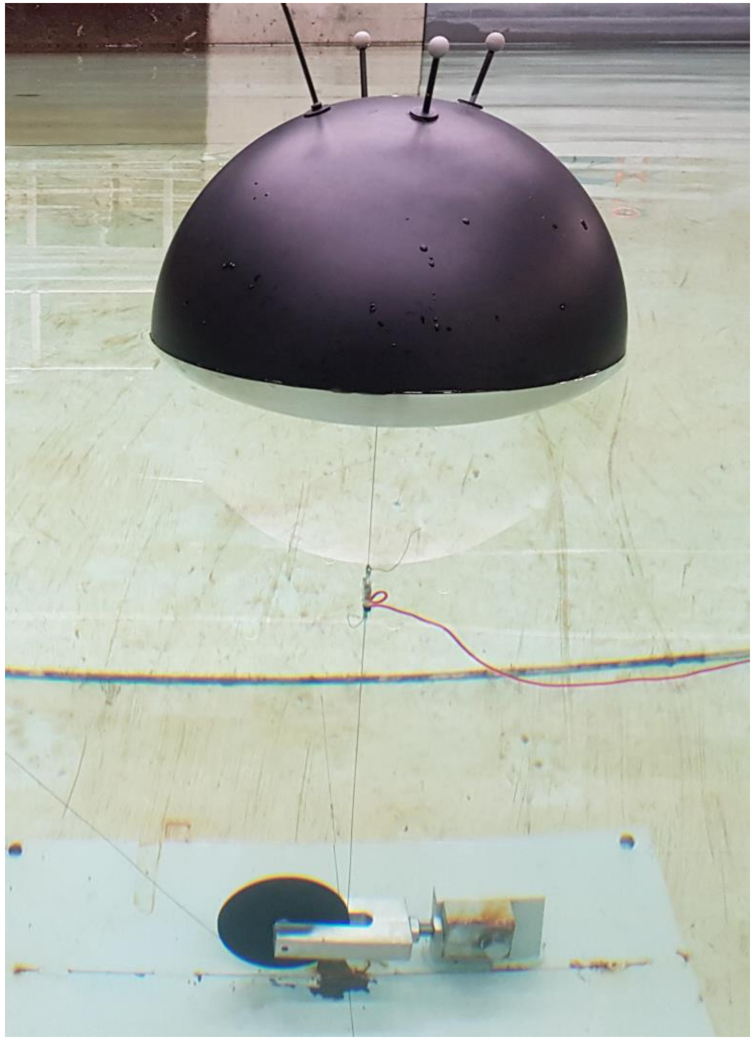


PTO tests

- To allow for PTO tests the mooring line must always be with tension (not go slack)
- A lighter absorber and pre-tension in the mooring line is therefore needed. As shown in slide 18 the following condition was chosen

Lightest condition		
Total mass	5.327	kg (excluding the centre rod, which is not needed)
Pre-tension	16.98	N (to submerge the sphere to equator)

Setup in PTO test



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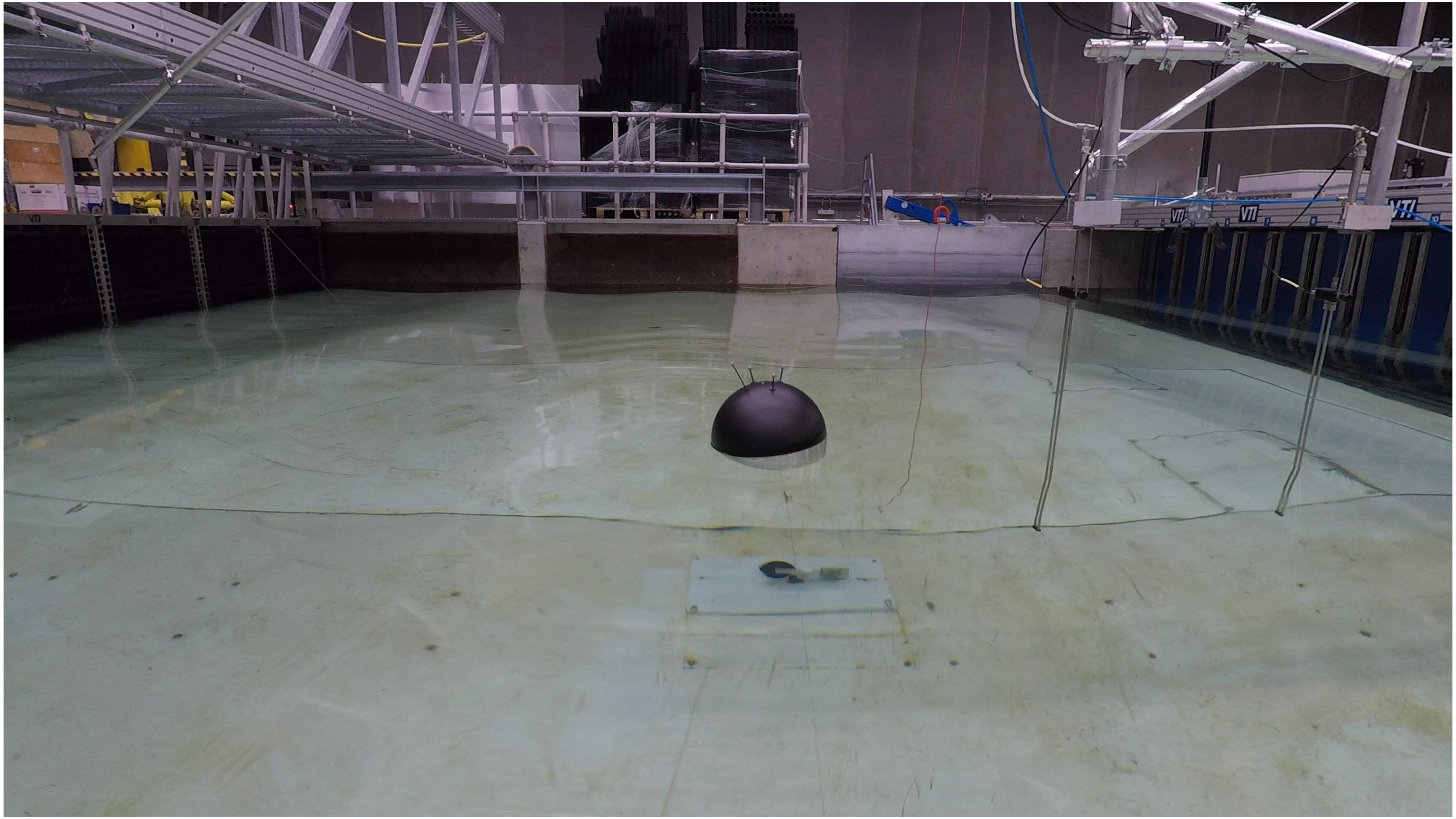
Video from PTO test with T = 1.0 s



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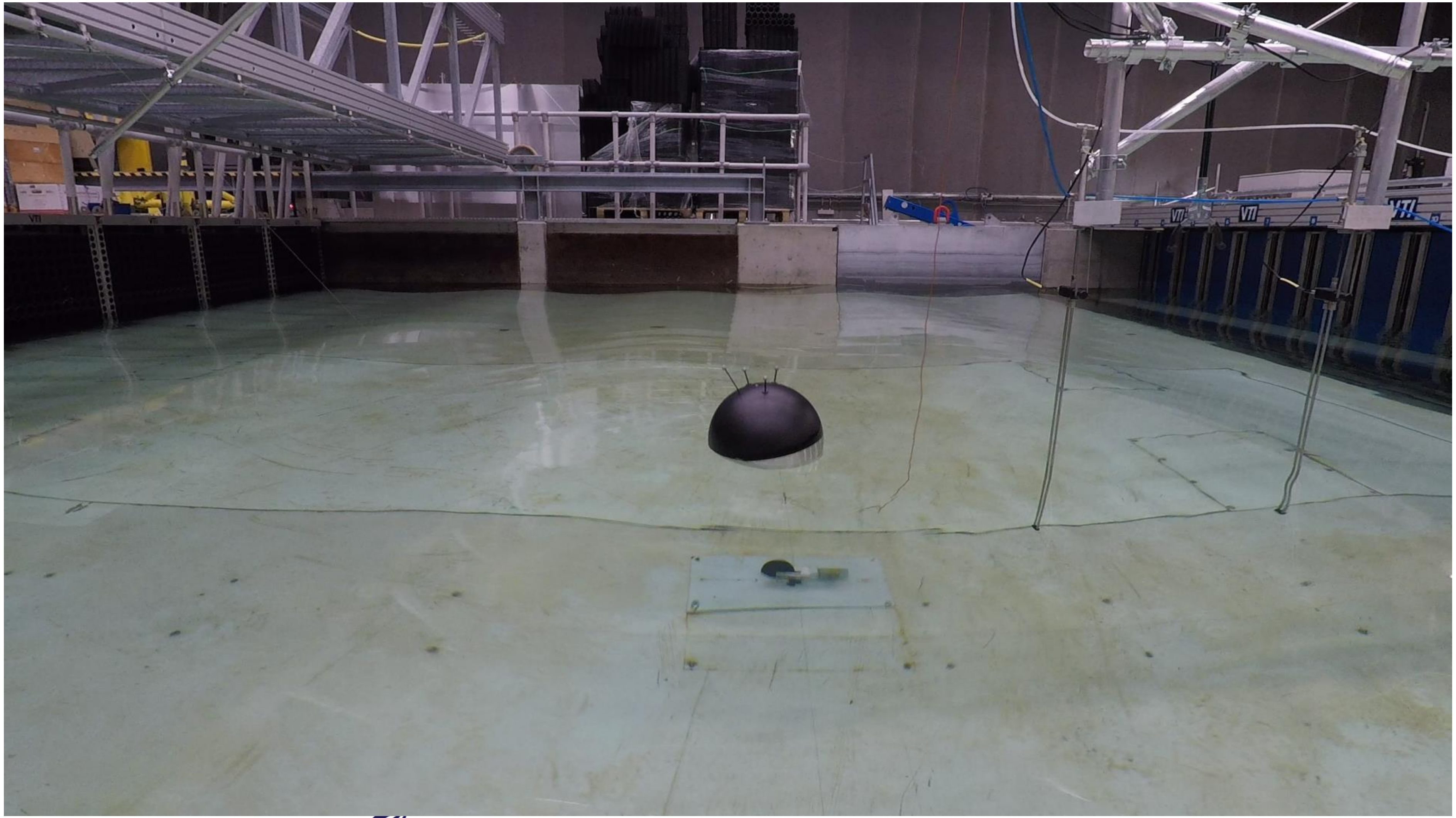
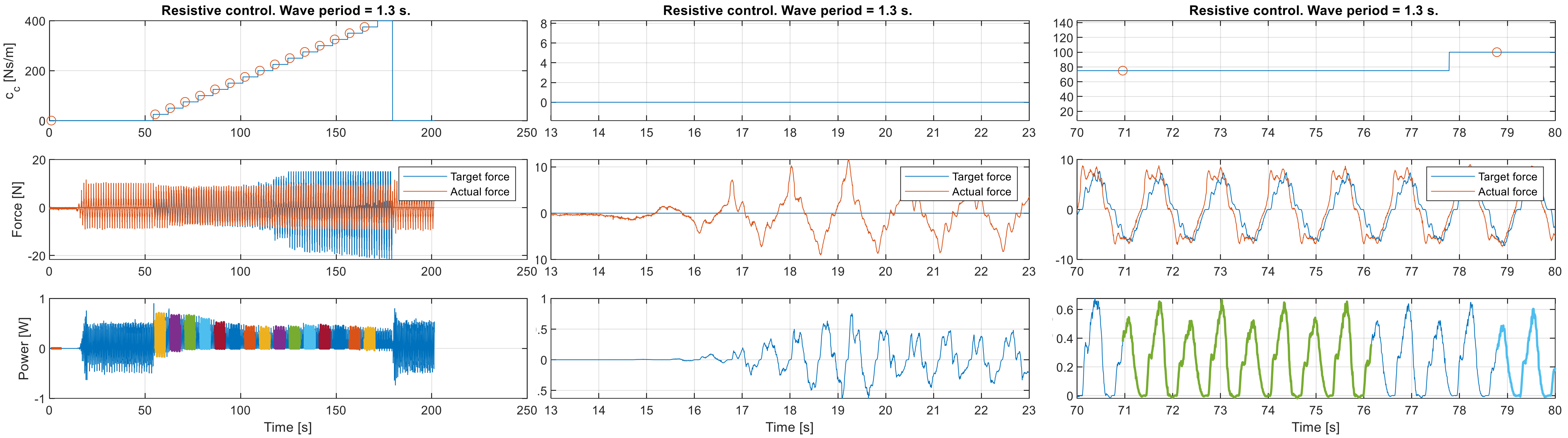
Video from PTO test with T = 1.3 s



Some results from test with T = 1.3 s



- When the PTO damping is low the controller struggles to follow the target force, i.e. the performance is very poor (middle graph).
- When producing power the performance is better (right graph).

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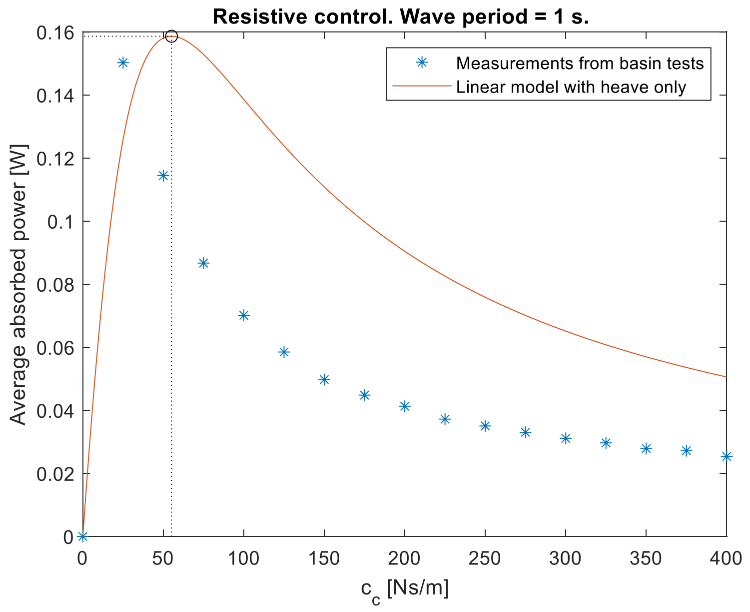
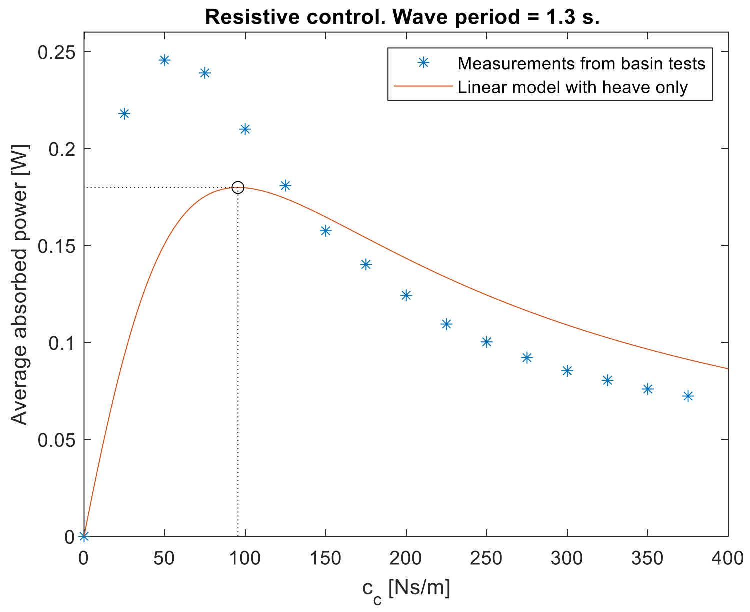
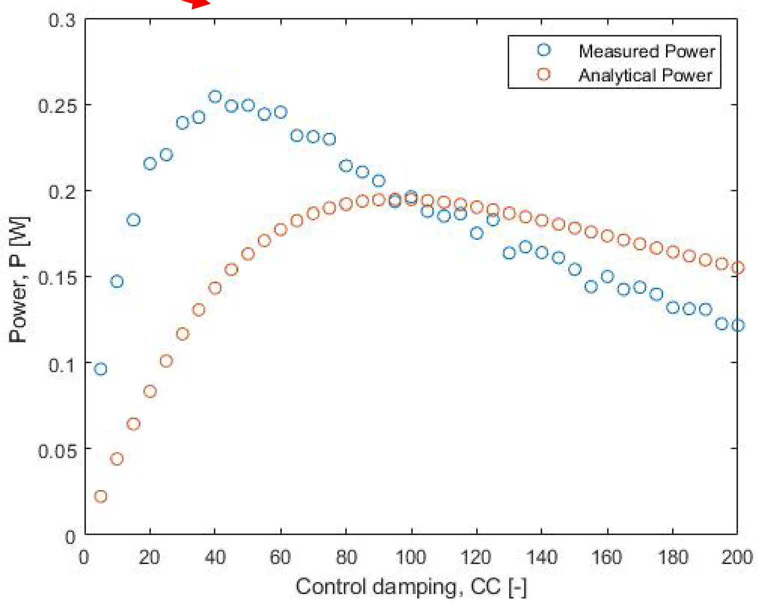
Average power in PTO tests

Same type of test, but plot on right below is from a 9th semester mini project at AAU [4]







- Clearly the linear model with "heave only" is not fitting the data well. As seen on the videos the model is moving in surge, heave & pitch, so a model that takes into account motion in all DoF's is needed.

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Conclusions

- The sphere model seems appropriate for further scientific simple validation cases, e.g. PTO tests.
- The model is appropriate for courses and lecturing in wave energy. The model has been used with success as a test case in a 9th semester civil engineering course about WEC control at Aalborg University.
- Further work and laboratory time is needed if validation tests with PTO control are to be completed with success.
- Initially the issues pointed out must be solved, i.e. a faster PTO controller & real-time rigid body motion data.
- Numerical multi-DoF-modelling prior to a new testing campaign should also be completed.

- The continuation of the work with the sphere in the Danish group depends on future funding, which is unknown at the moment.

- Ideas for further work is very welcome!

Thank you for your attention ☺

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