Wave Excitation Forces on a Sphere

Description of a Physical Testcase

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AALBORG UNIVERSITY

Wave Excitation Forces on a Sphere - Description for a Physical Testcase

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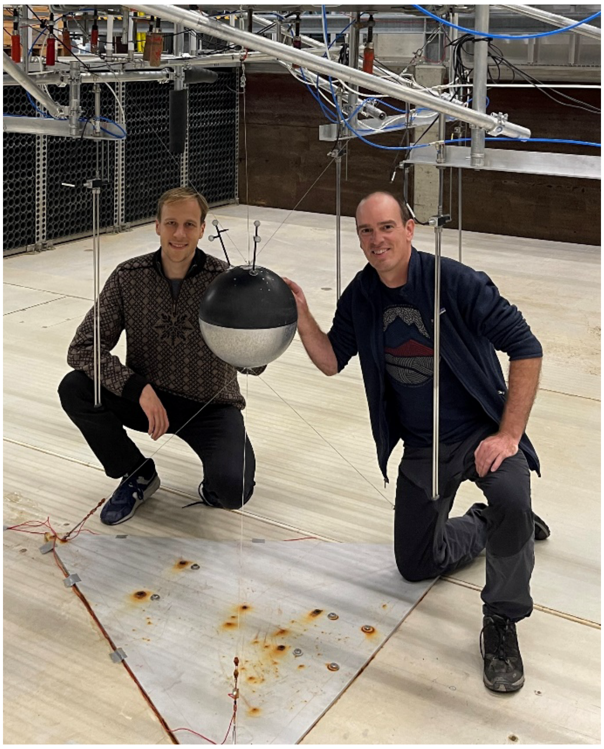
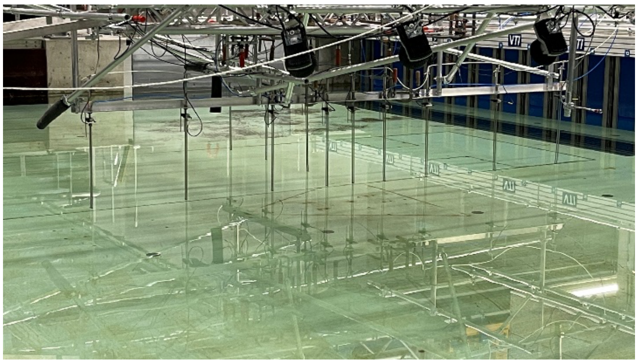
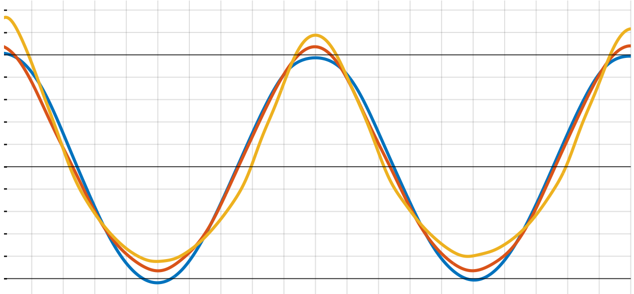
[1)]Aalborg University, [2)]Floating Power Plant







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by

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Contents

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Rev.	Date	Description of Change
1	2023 March	Initial issue
2	2023-05-12	Reference [1] updated to Revision 2

1 Introduction with Objective

Physical wave basin tests with a focus on uncertainty estimation have been conducted on a sphere subjected to wave loads at Aalborg University as part of the effort of the OES Wave Energy Converters Modelling Verification and Validation (formerly, OES Task 10) working group to increase credibility of numerical modelling of WECs. The tests are referred to as *the Kramer Sphere Cases*, and the present note is dealing with wave excitation force tests on a fixed model.

To enable simple numerical simulations an *idealized testcase* was formulated to accurately represent the physical tests in a simple way [1]. To allow further and more detailed numerical modelling of the physical tests, the present note is including further details to facilitate CFD models which replicates the physical setup in detail. In the idealized testcase the wave conditions are described simply by a wave height H and a wave period T, and the actual measured surface elevation time series is not part of the testcase. To facilitate CFD modelling of the actual wave conditions in the physical wave basin, this note is defining a *physical testcase* by providing details on the basin setup, and it includes the full time series of the measured wave generation paddle motion and also the wave probe measurements performed at specific positions in the basin without the model in place.

CFD simulations on the physical testcase will include effects of initial transient effects from the wave ramp-up and the evolution of the wave in the basin over time. In contrast, CFD simulations on the idealized testcase will not include these effects. Thereby comparisons of CFD simulations on the idealized testcase versus on the physical testcase will enable us to quantify the effects of the initial transients on the wave and on the response (i.e., the wave excitation force on the sphere).

Like the idealized testcase, the physical testcase consists of a fixed, rigid sphere half submerged in water subjected to regular waves of three different levels of linearity. The objective of the present note is to provide descriptions that allow for numerical tests of the physical testcase. Explanations for the structure and upload of numerical test outputs to a common SharePoint is also included. This allows partners in the OES WEC group to perform further comparative studies between the models and the physical test data.

If the reader is not familiar with the previous work on building benchmark datasets from fluid-structure-interaction tests on the sphere under OES Task 10 it is recommended to start out with the following:

1) Become familiar with the background and intention of the sphere studies of the OES working group. For the present study, a similar procedure as the decay tests completed as the first part of the *Kramer Sphere Cases* will be followed [2].
2) Become familiar with the status and plans of the work, e.g., by reading the presentations from the OES Task 10 Webinar on 2022-11-17 [3], 2023-01-26 [4], [5], and 2023-05-11 .
3) Study the idealized testcase [1].

2 Description of Numerical Tests and File Names for Numerical Test Datasets

The Excel sheet described in Section 2 of the idealized testcase [1] should be used. Likewise, the file-naming must follow the convention described in Section 3 of [1].

3 File Format for Uploaded Numerical Test Datasets

The dataset should follow a similar format as used for the idealized testcase, i.e., it must consist of time series of the surface elevation η and the resulting force $[F_x, F_y, F_z]$ (and potentially resulting moment $[M_x, M_y, M_z]$). Surface elevation is the incident, regular wave extracted from the simulations at the location of sphere centre (without the sphere). The format of the files must be ASCII with 8 columns having the contents described in Table 1. Samples are given in the rows.

In contrast to the idealized testcase the dataset must start with time 0 corresponding to the time when the wave generator starts. Data should be included for a sufficiently long time to cover the interval of analysis used for the idealized testcase, which depends on the type of wave, see details in the following Section. However, it is sufficient to simulate 12 s independent of the wave type, which is therefore recommended.

Table 1. Description of numerical data files.

time [s]	eta [m]	Fx [N]	Fy [N]	Fz [N]	Mx [Nm]	My [Nm]	Mz [Nm]
0							
…							

For further info and an example of a file, please see Section 4 of the description for the idealized testcase [1].

The CFD users may want to store further information from the output of their CFD simulation than required for the files described in Table 1 (such as waves extracted at the locations corresponding to the locations of the wave gauges in the physical tests,…). Such information may be included in separate files, which are named and described in an accompanying note or readme-file.

4 Details about the Required Length of the Simulations

The wave conditions with the specified heights used for the idealized testcase corresponds to specific time intervals in the time series, and the same intervals must be used for the physical testcase. The interval has been chosen as a compromise between influence of initial transients and reflections in the wave signal. The initial transients produce a non-steady wave profile as the wave is ramped up from calm conditions, which makes the first part of the signal far from steady state and thereby inappropriate to use. When wave reflections come back from the beach or other sides of the basin, it makes the later part of the signal inappropriate to use as the incident wave is contaminated by the reflections. The time window for analysis has been chosen based on this compromise. The time t_{peak} is selected for the wave crest to be used in the analysis, and the interval is given with reference to this time for two wave periods ($2T$), with the centre 1 period ($t_{peak} \pm ½T$) intended for the main comparison between data. The time intervals are given in Table 2 for the wave conditions R01, R05 and R12. Plots of the wave time series are given in Appendix C, which covers the first 20 s of the time series. In Appendix D plots for the selected time intervals are given, and in Appendix E plots for the selected intervals are given when using normalized axes.

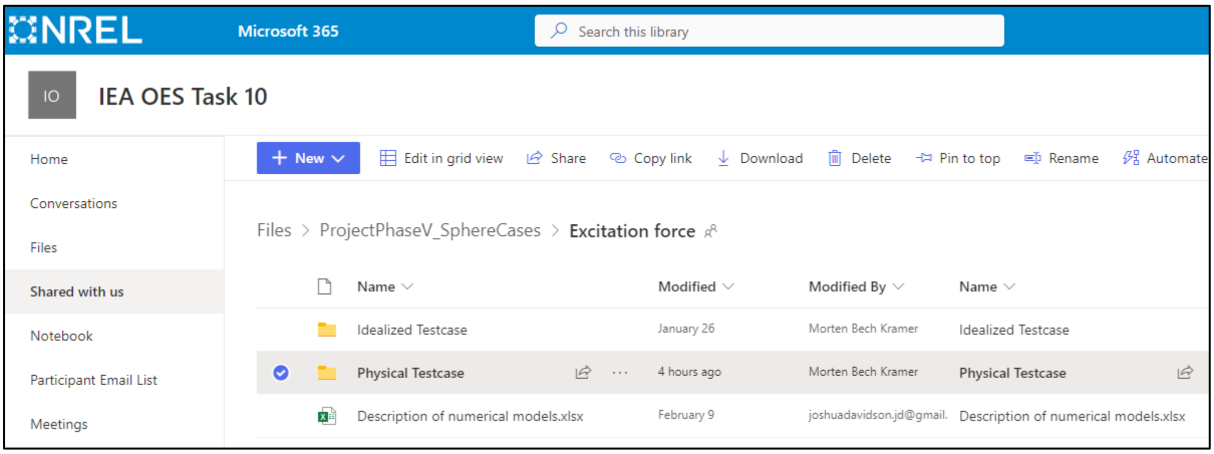
Table 2. Details regarding required length of simulations to cover the interval of analysis for R01, R05 and R12.

Wave specs			Time for central crest	Time interval	
Case	**T [s]**	**H [m]**	**t_{peak} [s]**	**$t_{start} = t_{peak} - T$ [s]**	**$t_{end} = t_{peak} + T$ [s]**
R01	1.14	0.0178	10.320	9.18	11.46
R05	0.88	0.0562	10.900	10.02	11.78
R12	1.42	0.2618	7.545	6.13	8.97

5 Procedure for Uploading Numerical Test Datasets

When uploading numerical test datasets, the following procedure must be used:

1) Complete the numerical tests using the inputs described in this note.
2) Generate output datasets from the numerical tests complying with Table 1.
3) Get access to the NREL share. To get access please ask the responsible person at NREL, who presently is Thanh Toan Tran, ThanhToan.Tran@nrel.gov
4) Browse the NREL fileshare to find the location for the numerical test datasets (Files -> ProjectV_SphereCases -> Excitation force -> Physical Testcase), see Figure 1.
5) Update the Excel file on the NREL fileshare (located under the *Excitation force* folder). Include a new line in the sheet with the information for your model.
6) Make a subfolder for your datasets within "Physical Testcase" and upload files to the subfolder. Make sure the model name given in the Excel file is the same as the name of the subfolder.



Name	Modified	Modified By	Name
Idealized Testcase	January 26	Morten Bech Kramer	Idealized Testcase
Physical Testcase	4 hours ago	Morten Bech Kramer	Physical Testcase
Description of numerical models.xlsx	February 9	joshuadavidson.jd@gmail.	Description of numerical models.xlsx

Figure 1. Screendump from NREL Sharepoint fileshare showing the folder used for the present data.

6 Wave Basin Layout and Position of Wave Gauges

Tests were performed in the wave basin at the Ocean and Coastal Engineering Laboratory of Aalborg University (AAU), Denmark, https://www.en.build.aau.dk/lab/ocean-and-coastal-engineering [7] and additional details are given in Appendix A. Details about the basin and the present setup with the sphere are given in the following.

The wave basin is 14.6 m x 19.3 m x 1.5 m (internal length x width x wall height) with an active test area of 8.44 m x 13.00 m (length x width, basin is wide). The basin is equipped with long-stroke segmented piston wavemakers for accurate short-crested (3-dimensional) random wave generation with active absorption. Only 2D waves were generated in the present sphere tests, and active absorption was not included to have as good repeatability as possible. A photo of the wave basin is given in Figure 2.

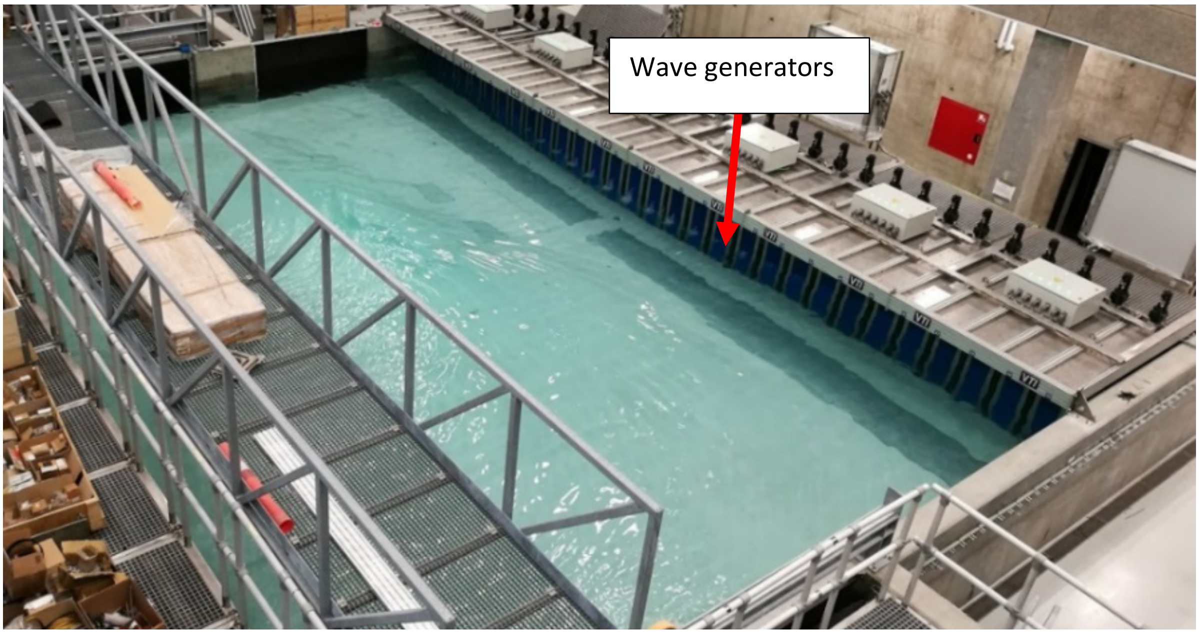


Figure 2. Wave basin at Aalborg University.

The sphere model was placed in the centre of the basin along the width, i.e., with the same distance to the basin sidewalls. Along the length, the model was placed at the centre between the mean paddle position and the start of the vertical beach. A drawing of the setup with the model in place is given in Figure 3 and Figure 4.

As shown in Figure 4 and the left part of Figure 5, nine wave gauges were placed in the tests which included the model; WG1-3 were placed along $y = 0$ at the wave generator side of the model with WG1 closest to the wave generator, WG4-6 were placed along $y = 0$ behind the model with WG6 closest to the beach, and WG7-9 were placed along $x = 0$ with WG7 closest to the model.

In tests, where the waves were measured without the model, three additional wave gauges were included numbered WG10-12. WG11 was placed at the centre of the sphere location, see the sketch in the right part of Figure 5.

The position of the wave gauges allows for studies such as the reflection characteristics. However, such details are beyond the scope of this note and is a part of the test reporting about wave conditions and uncertainties.

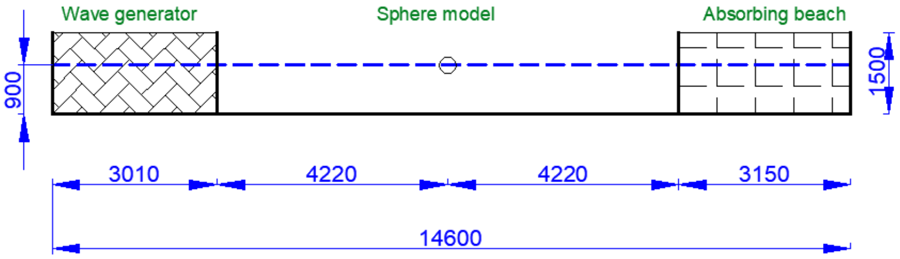


Figure 3. Side view of the setup. The dashed line at 900 mm above the floor indicates the water level. Measures in mm.

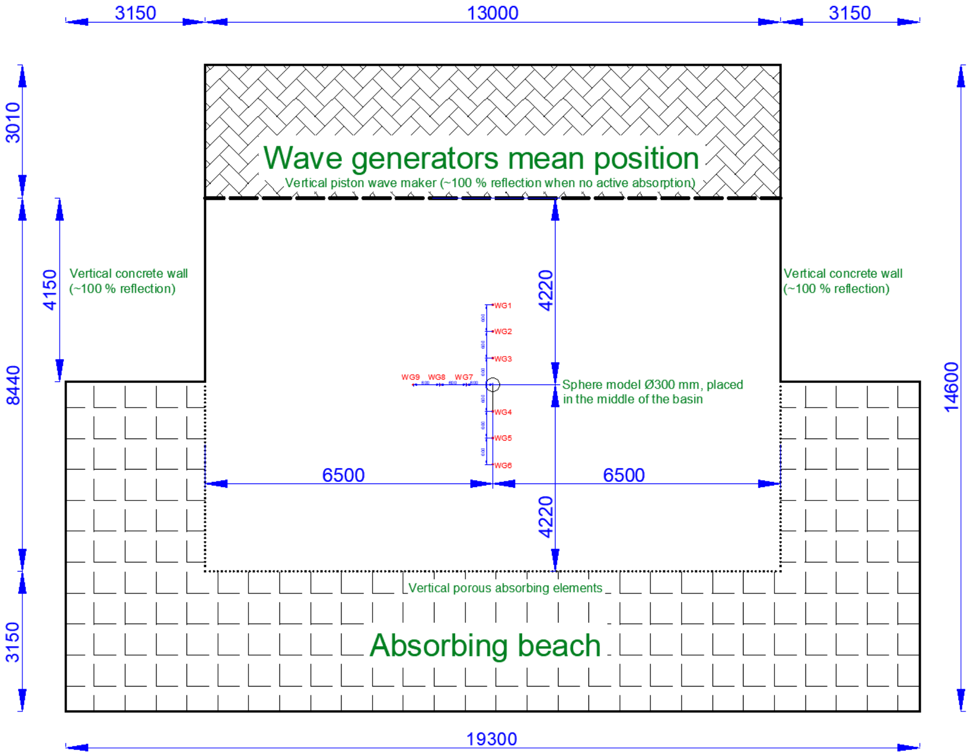


Figure 4. Top view of the setup. Measures in mm.

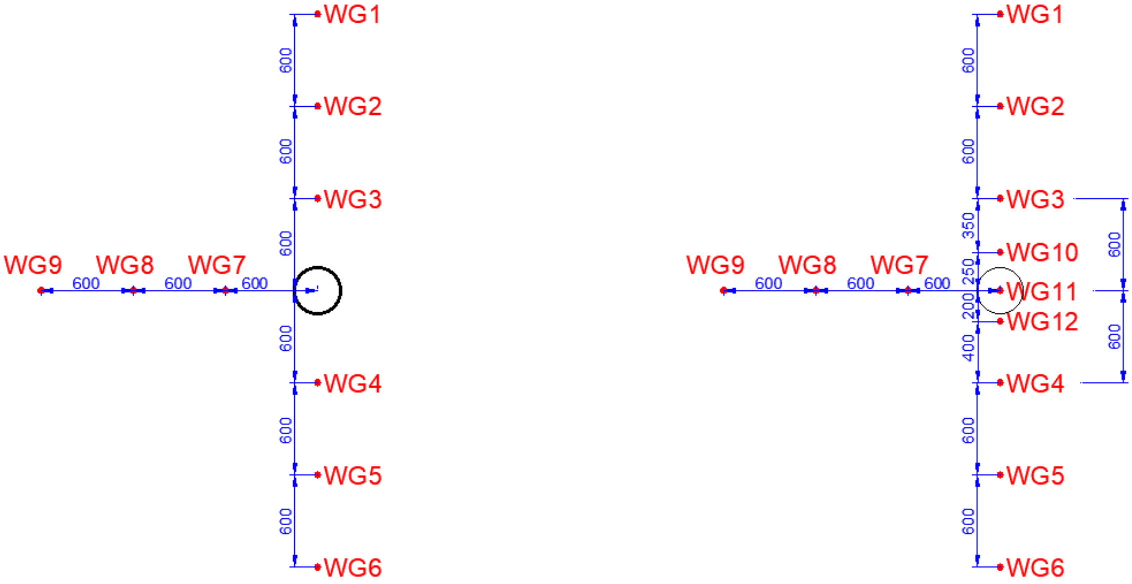


Figure 5. Details of wave gauges (WG). Left: Setup with model in place (9 WGs), right: Setup without the model (12 WGs). WG numbers are shown with red font, the distances between the gauges are shown with blue front with numbers in mm.

7 Physical Data Files from Wave Generator

Two sets of data are provided; raw data files from the wave generator are described in Section 7.1, and processed files which contains estimated uncertainty bounds are described in Section 7.2.

7.1 Raw data files from wave generator

The software used to generate waves is AwaSys7 which is described in the manual [8] using the theory given in [9]. The files stored by AwaSys7 are described Section 3.1 of the manual, but the details needed to use the files are given in Table 3. The raw files generated by AwaSys7 are in binary format, but they have been converted to ASCII and stored with ".conv" appended to the filenames. Each of the 30 pistons have individual control signals. Only one paddle motion signal is stored (Channel 31 of the AWD-file), but as 2D waves are generated in the present tests, this is sufficient as all wave paddle motion signals are identical.

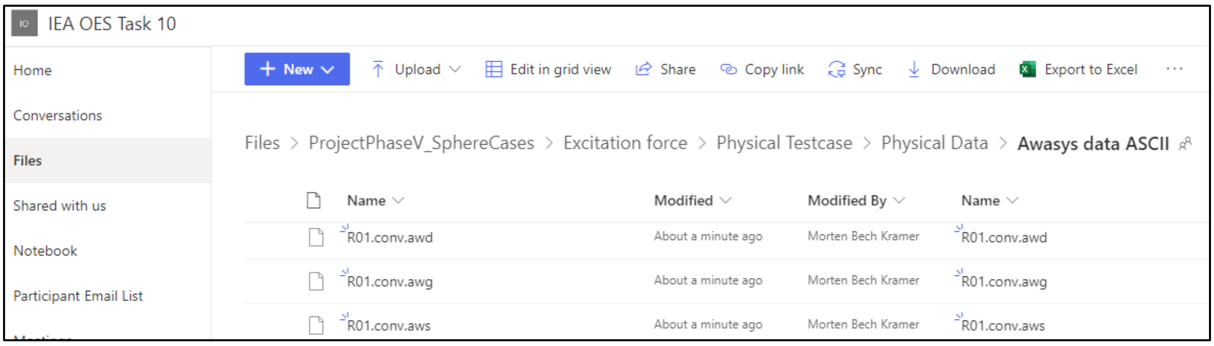
Table 3. Description of files stored by the wave generator software.

File	Description	Signal column contents
AWS	File is generated before the actual waves are tested in the basin. All contents are targets and calculated. Top of file: Explanations, inputs to wave generator Bottom of file: 90 signals, 3 signals for each paddle.	1) Paddle 1, Paddle position* [m] 2) Paddle 1, Nearfield wave [m] 3) Paddle 1, Farfield wave [m] 4) Paddle 2, …
AWD	Top of file: Explanations Bottom of file: 31 signals, 1 signal for each paddle and 1 additional (see description on right)	1-30) Modified position signal for paddle 1-30 [m] 31) Measured position of a paddle [m]
AWG	Top of file: Explanations Bottom of file: 30 signals, 1 signal for each wave gauge mounted on paddles	1-30) Measured wave by paddles [m]

*) Stored paddle position in AWS are before clipping and before active absorption.

The generator has a delay of about 58 ms as described in the detailed investigation in Appendix B. For this reason, it is important that the measured paddle position is used as inputs to CFD models, i.e., Channel 31 of the AWD-file. As described in the files the sampling frequency is 50 Hz.

Files are located at the NREL drive (Files -> ProjectV_SphereCases -> Excitation force -> Physical Testcase -> Physical Data -> Awasys data ASCII), see Figure 6.



Files > ProjectPhaseV_SphereCases > Excitation force > Physical Testcase > Physical Data > Awasys data ASCII

Name	Modified	Modified By	Name
R01.conv.awd	About a minute ago	Morten Bech Kramer	R01.conv.awd
R01.conv.awg	About a minute ago	Morten Bech Kramer	R01.conv.awg
R01.conv.aws	About a minute ago	Morten Bech Kramer	R01.conv.aws

Figure 6. Screenshot from NREL Sharepoint fileshare showing the folder used for the Awasys wave generator data.

Here follows some elaboration on why the nearfield and farfield waves are interesting. The sphere is located 4.22 m from the wave generator, which is 4.7**h* (*h* being the water depth). For positions larger than ~3**h* the nearfield effects (piston wave maker velocity profile to wave velocity profile) is negligible, i.e., at the sphere location the waves are farfield (influence of wave generator velocity profile is negligible). The farfield wave can therefore be propagated to the sphere location (e.g., by use of linear wave theory) to get an estimate of the transient effects of the ramping up of the wave.

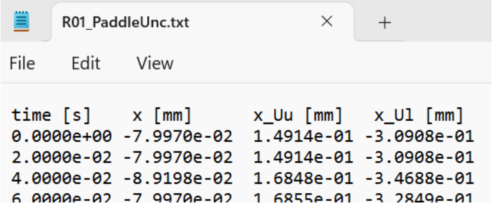
7.2 Processed Data Files from Wave Generator

The wave generator is considered very accurate, and the measured motion can be assumed to be exact. However, for detailed studies the files described in this section can be used. The uncertainty on the measured paddle motion reported in [11] is used to generate a dataset which includes the confidence interval for the paddle motion. Five repetitions with recorded paddle motions were completed, and the mean value of these tests are provided as part of the present dataset. The system for the variable names is described in Table 4.

Table 4. Description of variables in paddle motion data files.

Description	Variable name	Variable name in ASCII	Column no	Unit
Time stamp	t	time	1	s
Mean value of paddle motion	$\bar{x}$	x	2	mm
Upper bound for expanded uncertainty interval for paddle motion	$\bar{x} + U_{\bar{x}}$	x_Uu	3	mm
Lower bound for expanded uncertainty interval for paddle motion	$\bar{x} - U_{\bar{x}}$	x_Ul	4	mm

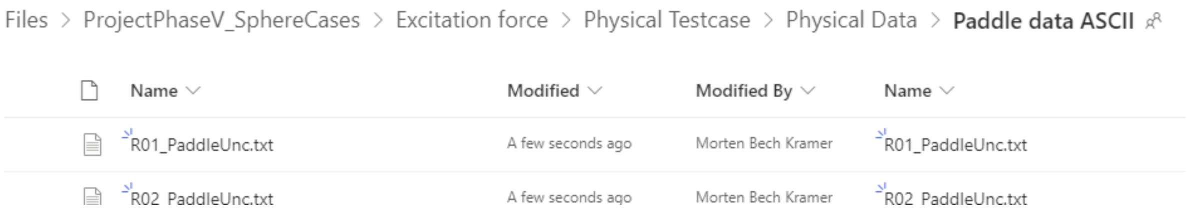
Sampling frequency is 50 Hz. The layout of the files is further shown in the screenshot in Figure 7. It is seen that the first time stamp is zero (the time corresponding to the start of the wave generator), and the second time stamp is a sample time later, i.e., a value of 1/50 = 0.02 = 2.0000e-2.



```
time [s]    x [mm]      x_Uu [mm]   x_Ul [mm]
0.0000e+00 -7.9970e-02  1.4914e-01 -3.0908e-01
2.0000e-02 -7.9970e-02  1.4914e-01 -3.0908e-01
4.0000e-02 -8.9198e-02  1.6848e-01 -3.4688e-01
6.0000e-02 -7.9970e-02  1.6855e-01 -3.2849e-01
```

Figure 7. Screenshot showing first part of a paddle motion datafile.

Files are located at the NREL drive (Files -> ProjectV_SphereCases -> Excitation force -> Physical Testcase -> Physical Data -> Paddle data ASCII), see Figure 8.



Name	Modified	Modified By	Name
R01_PaddleUnc.txt	A few seconds ago	Morten Bech Kramer	R01_PaddleUnc.txt
R02_PaddleUnc.txt	A few seconds ago	Morten Bech Kramer	R02_PaddleUnc.txt

Figure 8. Screenshot from NREL Sharepoint fileshare showing the folder used for the paddle motion data.

If wave case and time dependence is not considered, the average expanded uncertainty for the measured paddle position can be taken as 0.8 % of the paddle motion range x_H, see Table 5.

Table 5. Time averaged uncertainties for paddle motion [11].

						Average uncertainty on paddle motion					
Wave specs			Paddle target motion			Repeatability	Calibration	Total	Expanded total		
Case	T [s]	H [mm]	x_{Max} [mm]	x_{Min} [mm]	$x_H = x_{Max} - x_{Min}$ [mm]	$\bar{u}_{rep}$ [mm]	$\bar{u}_{cal}$ [mm]	$\bar{u}_x$ [mm]	$\bar{U}_x$ [mm]	$\bar{U}_x/x_H$ [%]	$\bar{U}_x/H$ [%]
R01	1.14	18.1	5.21	-5.27	10.48	0.03	0.01	0.03	0.09	0.8%	0.5%
R05	0.88	56.1	14.61	-15.44	30.05	0.10	0.01	0.10	0.27	0.9%	0.5%
R12	1.42	261.1	95.22	-95.10	190.32	0.37	0.01	0.37	1.04	0.5%	0.4%
									Average	0.8%	0.5%

The expanded uncertainties are based on a coverage factor of 2.8.

8 Physical Data Files from Wave Gauges

Measurements of waves from the basin tests without the model in place are provided. The actual testing included five repetitions of all sea states, and the mean value of these tests are provided as part of the present dataset to enable comparison with the simulated waves. The time dependent expanded uncertainty interval for the wave elevation is also included in the dataset as described in further detail in Appendix F and [11]. To give an idea of the magnitude of the uncertainties, the time averaged uncertainties for WG11 are given in Table 6. It is seen that the average expanded uncertainty varies from 0.75 mm for the low wave R01 to 6.53 mm for the high wave R12, corresponding to 4.2 % and 2.5 % of the wave height, respectively. The main source of error is repeatability.

Table 6. Time averaged uncertainties for η within interval for WG11. Average results for all WG's are provided in [11].

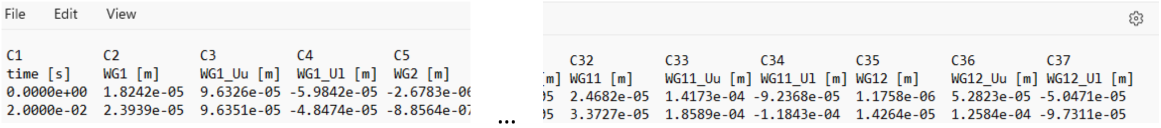
Wave specs			**Average uncertainty on η for *WG11***				
Case	**T [s]**	**H [mm]**	**$\bar{u}_{rep}$ [mm]**	**$\bar{u}_{cal}$ [mm]**	**$\bar{u}_{\eta}$ [mm]**	**$\bar{U}_{\eta}$ [mm]**	**$\bar{U}_{\eta}/H$ [%]**
R01	1.140	18.1	0.27	0.03	0.27	0.75	4.2%
R05	0.880	56.1	0.40	0.08	0.41	1.14	2.0%
R12	1.420	261.1	2.28	0.37	2.33	6.53	2.5%

The system for the variable names is described in Table 7. The timestamp is stored in the first column as "time", second column is the mean of the wave gauge number 1 as "WG1", followed by the third and fourth column containing the upper bound "WG1_Uu" and lower bound "WG1_Ul" for the expanded uncertainty. The subsequent columns contain the three signals from the remainder of wave gauges. As 12 wave gauges were applied each files have 12 times 3 columns plus 1 time column, thus the total number of columns is: 12*3+1 = 37 columns.

Table 7. Description of variables in wave gauge data files.

Description	**Variable name**	**Variable name in ASCII**	**Column no**	**Unit**
Time stamp	t	time	1	s
Mean value of WG number *i*	$\bar{\eta}_{\mathrm{i}}$	WGi	2+3*(i-1)	m
Upper bound for expanded uncertainty interval for WG number *i*	$\bar{\eta}_{\mathrm{i}} + U_{\bar{\eta}_{\mathrm{i}}}$	WGi_Uu	3+3*(i-1)	m
Lower bound for expanded uncertainty interval for WG number *i*	$\bar{\eta}_{\mathrm{i}} - U_{\bar{\eta}_{\mathrm{i}}}$	WGi_Ul	4+3*(i-1)	m

The wave signals have been downsampled from 200 Hz to 50 Hz before storage. The layout of the files is further shown in the screenshot in Figure 9, where it is seen that the files have two header lines. The first line is describing the column number "Ci", with "i" being the column number, and the second line describes the contents. It is seen that the first time stamp is zero (the time corresponding to the start of the wave generator), and the second time stamp is a sample time later, i.e., a value of 1/50 = 0.02 = 2.0000e-2. As an example, consider that you would like to read the mean wave signal at the location corresponding to centre of the sphere, i.e., WG11, the file first row shows you to use column "C32", see Figure 9.



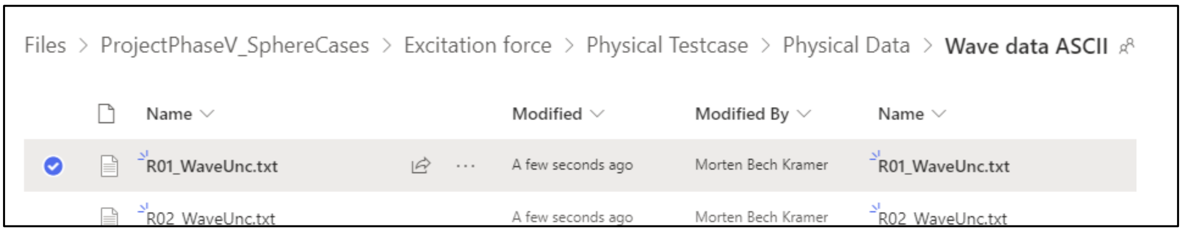
```
C1          C2          C3          C4          C5
time [s]    WG1 [m]     WG1_Uu [m]  WG1_Ul [m]  WG2 [m]
0.0000e+00  1.8242e-05  9.6326e-05 -5.9842e-05 -2.6783e-06
2.0000e-02  2.3939e-05  9.6351e-05 -4.8474e-05 -8.8564e-07
```

…

```
   C32         C33         C34         C35         C36         C37
m] WG11 [m]    WG11_Uu [m] WG11_Ul [m] WG12 [m]    WG12_Uu [m] WG12_Ul [m]
5  2.4682e-05  1.4173e-04 -9.2368e-05  1.1758e-06  5.2823e-05 -5.0471e-05
5  3.3727e-05  1.8589e-04 -1.1843e-04  1.4264e-05  1.2584e-04 -9.7311e-05
```

Figure 9. Screenshot showing part of a wave datafile.

Files are located at the NREL drive (Files -> ProjectV_SphereCases -> Excitation force -> Physical Testcase -> Physical Data -> Wave data ASCII), see Figure 10.



Files > ProjectPhaseV_SphereCases > Excitation force > Physical Testcase > Physical Data > Wave data ASCII

Name	Modified	Modified By	Name
R01_WaveUnc.txt	A few seconds ago	Morten Bech Kramer	R01_WaveUnc.txt
R02_WaveUnc.txt	A few seconds ago	Morten Bech Kramer	R02_WaveUnc.txt

Figure 10. Screenshot from NREL Sharepoint fileshare showing the folder used for the measured wave data.

In Appendix G an example Matlab script is given, which demonstrates how to load and plot the signals for a selected wave gauge.

9 Timing of Recorded Paddle Motion and Waves

As described in the uncertainty report [11], the trigger signal from the wave generator has a rather high uncertainty, especially for the low waves. The paddle motion has been stored separately from the wave measurements with an uncertainty on the timing given by the accuracy of the trigger. The trigger uncertainty is not part of the uncertainties included in the uncertainty interval for the wave signal provided with this report.

As seen in the last column of Table 8, the standard deviation (std) of the trigger for R01 is 27.8 ms (milli seconds), whereas it is only 6.7 ms for R12. This error in timing may be used to evaluate possible inconsistences in timing of the waves coming out of the CFD analysis when comparing to the measured waves.

Table 8. Accuracy of trigger timing for R01, R05 and R12 as given in the uncertainty report [11]. "T" is wave period, "H" is wave height, and "std" is standard deviation.

Wave			**Trigger accuracy**
Case	***T* [s]**	***H* [m]**	**std [ms]**
R01	1.14	0.0181	27.8
R05	0.88	0.0561	8.2
R12	1.42	0.2611	6.7

Other sources of uncertainty on the timing when comparing CFD calculated waves based on paddle motion as input is that the waves take some time to propagate from the wave generator to the location of the wave gauges. The accuracy in the distance from the wave generator to the wave gauges is therefore important as well as the velocity of the wave propagation. As the velocity of the wave depends on the water depth and other characteristics such as the water density (see a comprehensive list in Table 3 in [1], where the uncertainty on some of the testcase characteristics are given), the uncertainties on a variety of physical environmental characteristics influences the timing accuracy. It is beyond the scope of this report to evaluate the total accuracy in the timing to be used when comparing CFD calculated waves based on paddle motion and the wave measurements provided with the present testcase.

Cross correlation the measured wave signals to the output from the CFD analysis could be done to evaluate the difference in the timing. To compensate for the difference, the calculated waves and forces should be shifted by the time difference before the data are compared to the experimentally measured forces.

10 References

[1] Kramer, M. B., Andersen, J., Nielsen, K. (2023). *Wave Excitation Forces on a Sphere - Description of an Idealized Testcase.* Department of the Built Environment, Aalborg University. ISSN 1901-726X. DCE Technical Report No. 307, Rev2.

[2] Kramer, M. B., Andersen, J., Thomas, S., Bendixen, F., Bingham, H., Read, R., Holk, N., Ransley, E., Brown, S., Yu, Y-H., Tran, T. T., Davidson, J., Horvath, C., Janson, C. E., Nielsen, K., & Eskilsson, C. (2021). *Highly Accurate Experimental Heave Decay Tests with a Floating Sphere: A Public Benchmark Dataset for Model Validation of Fluid-Structure Interaction*. Energies, 14(2), [269]. https://doi.org/10.3390/en14020269

[3] Kramer, M. B., Andersen, J. (2022). *Sphere Excitation Tests*. Presentation from OES Task 10 Webinar, 2022-11-17.

[4] Kramer, M. B., Andersen, J. (2023). *Definition of an Idealized Testcase for the Sphere Excitation Tests*. Presentation from OES Task 10 Webinar, 2023-01-26.

[5] Nielsen, K. (2023). *Minutes Of Meeting - OES Task 10 Wave Energy Modelling - Webinar 2022-11-17*.

[6] Kramer, M. B., Andersen, J. (2023). *Update on the Sphere Excitation Test Cases*. Presentation from OES Task 10 Webinar, 2023-05-11.

[7] AAU (2023). Ocean and Coastal Engineering Laboratory, Department of the Built Environment, Aalborg University. https://www.en.build.aau.dk/lab/ocean-and-coastal-engineering

[8] Andersen, T.L., Meinert, P., Frigaard, P. (2022). *AwaSys 7 user manual*. Ocean and Coastal Engineering Laboratory, Aalborg University, Dept. of the Built Environment

[9] Andersen, T.L., Frigaard, P. (2014). *Wave Generation in Physical Models – Technical documentation for AwaSys 6*. Aalborg University, Dept. of Civil Engineering, Water and Soil. ISSN 1901-7286, DCE Lecture Notes No. 34.

[10]ISO/IEC, 2008. *Guide 98-3 Uncertainty of Measurement—Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995)*, 1st ed.; ISO/IEC: Geneve, Switzerland.

[11] Kramer, M. B., Andersen, J. (2023). *Wave Excitation Forces on a Sphere - Uncertainty.* Department of the Built Environment, Aalborg University. ISSN 1901-726X. DCE Technical Report No. 311.

Appendix A: AAU Wave basin – A General Description

Welcome to the Ocean and Coastal Engineering Laboratory

- an integrated part of the research and teaching at the
Department of the Built Environment, Aalborg University

At the Ocean and Coastal Engineering Laboratory, we have created a modern, flexible laboratory with state-of-the-art equipment. We are located on the ground floor of the Department of Civil Engineering and are visible from several locations in the building. The research group has more than 30 years of research experience related to physical model testing and have developed advanced model testing techniques to test ports, coastal structures, offshore structure, wave energy converters etc.

The wave basin is 14.6 m x 19.3 m x 1.5 m (length x width x depth) with an active test area of 13 x 8 m. A deep water pit with size 6.5 m x 2.0 m with up to 6 m extra depth is available. The basin holds up to approximately 400 m3 water (400.000 liters) and accommodates testing on deep and shallow water. The basin is equipped with long-stroke segmented piston wavemaker for accurate short-crested (3-dimensional) random wave generation with active absorption and pumps for currents.

The wave flume is 22.1 m x 1.5 m x 1.5 m (length x width x depth) and equipped with long-stroke piston wavemaker for random wave generation and active absorption.

The wavemakers are powered by electric motors, which allows for less acoustic noise, no oil pollution in the basin and more accurate waves. Our water treatment system in the basement enables us to reuse the water from one test to the next. This makes a more operational/efficient laboratory and minimizes the environmental impact.

The equipment

Wave and current generation system for basin

- 13 x 1.5 m (width and height).
- 30 individually controlled wave paddles (snake type configuration) powered by electric motors.
- Accurate generation of 3D waves due to narrow vertically hinged paddles (0.43 m segment width).
- Maximum wave height up to 45 cm (at 3 s period).
- Typical maximum significant wave height in the range of 0.25-0.30 m
- Built with stainless steel and fibreglass for minimum maintenance.
- Pumps with a total maximum flow of 3500 m3/h for generation of strong current in the basin (up to 0.15 m/s at 0.5 m water depth). Structures can be tested in combined waves and current (following or opposing).

Wave and current generation system for flume

- 1.5 x 1.5 m (width and height).
- Single-element wave generator powered by electric motors.
- Exact generation of 2D waves.
- Maximum wave height up to 65 cm (at 3 s period).
- Built with stainless steel and fibreglass for minimum maintenance.
- Pumps with a total maximum flow of 1100 m3/h for generation of strong current in the flume (up to 0.4 m/s at 0.5 m water depth). Structures can be tested in combined waves and current (following or opposing).

Passive wave absorber elements

- For absorption of waves in the wave basin and wave flume.
- Built with stainless steel and hot galvanized stretch metal sheets for minimum maintenance.

Water treatment system

- Contains sand filters and UV filters.
- Reuses the water in the reservoir.
- Automatic fast filling to specified water depth and fast emptying of the facilities (adjustable speed)

Wave generation software

- In-house deigned AwaSys software utilizing state-of-the-art wave generation principles (used by more than 25 labs)
- Generation of regular, irregular, solitary waves
- 2-D and 3-D active wave absorption (reflection compensation)
- 2^{nd} order irregular unidirectional and multidirectional wave generation

Wave analysis software

- In-house deigned WaveLab software for data acquisition and wave analysis (used by more than 20 labs)
- Data acquisition system that support simultaneous sampling of 80 channels at more than 1 kHz sampling rate
- Reflection separation of linear and nonlinear 2-D waves
- Directional wave analysis of short-crested waves using BDM and MLM methods

Other equipment

- More than 40 resistance type wave gauges including electronics
- Large selection of pressure transducers and load cells
- Various equipment for measurement of flow velocities (lasers, ADV, etc.)
- Laser profiler for automatic profiling of scour holes and surfaces of rubble mound structures
- Qualisys Mocap Oqus 700+ 4 camera motion capturing system
- OptiTrack Flex 13 object tracking system
- Step gauge for run-up measurement
- Large selection of breakwater armour units

Special requirements

Operation of the laboratory requires participation of technicians or scientific personnel from the facility.

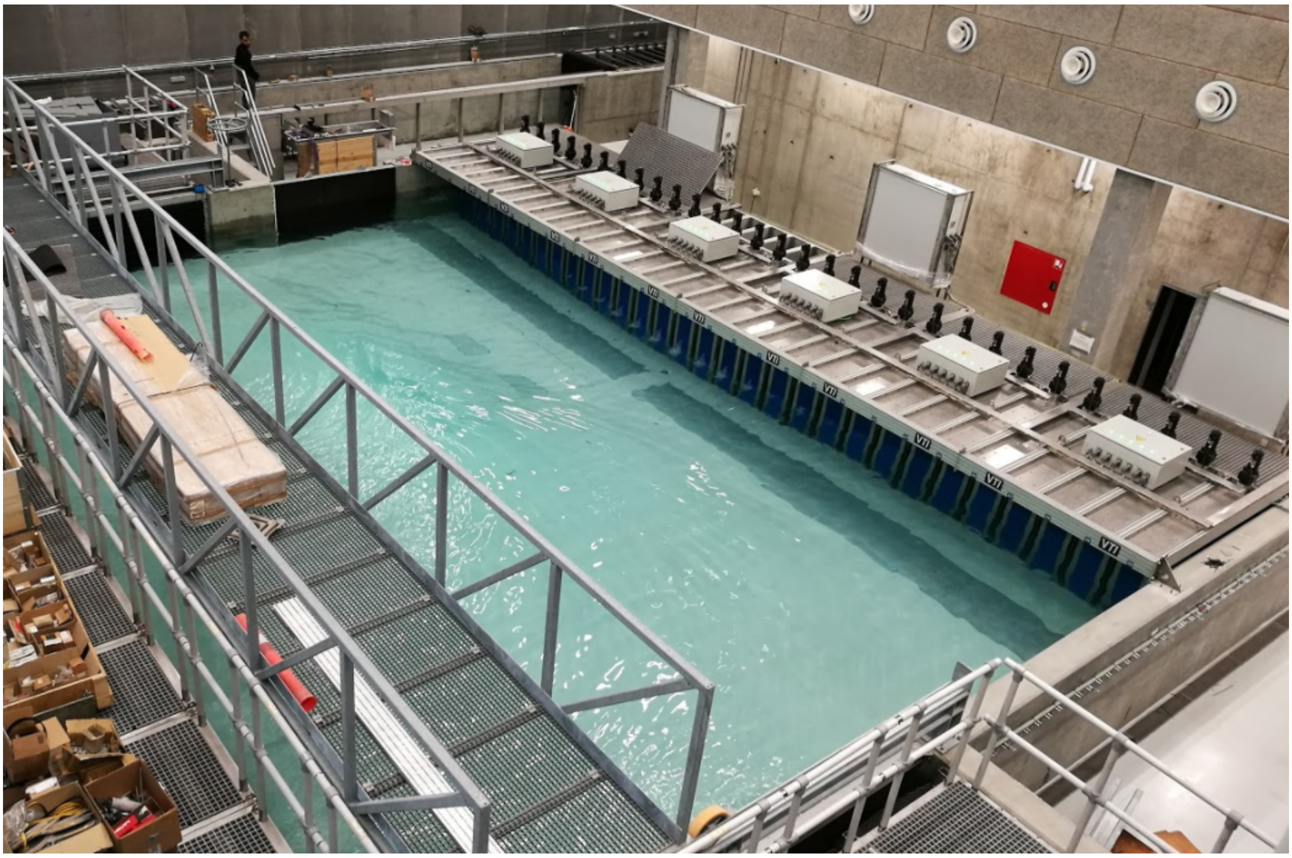
Staff

Leader of laboratory/Contact Person

Thomas Lykke Andersen, +45 9940 8486, tla@build.aau.dk

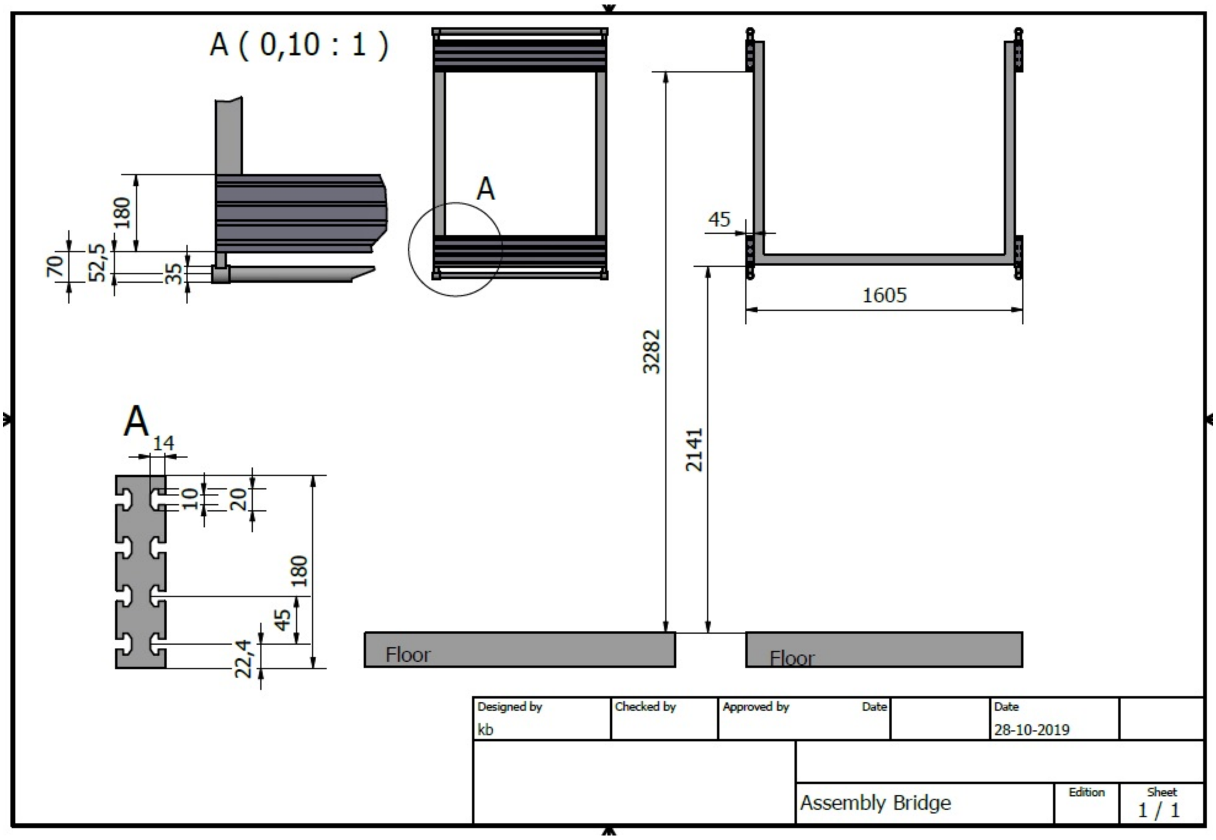
Other key staff

Nikolaj Holk, +45 9940 8558, nh@build.aau.dk



The lab getting ready (01.06.2017).

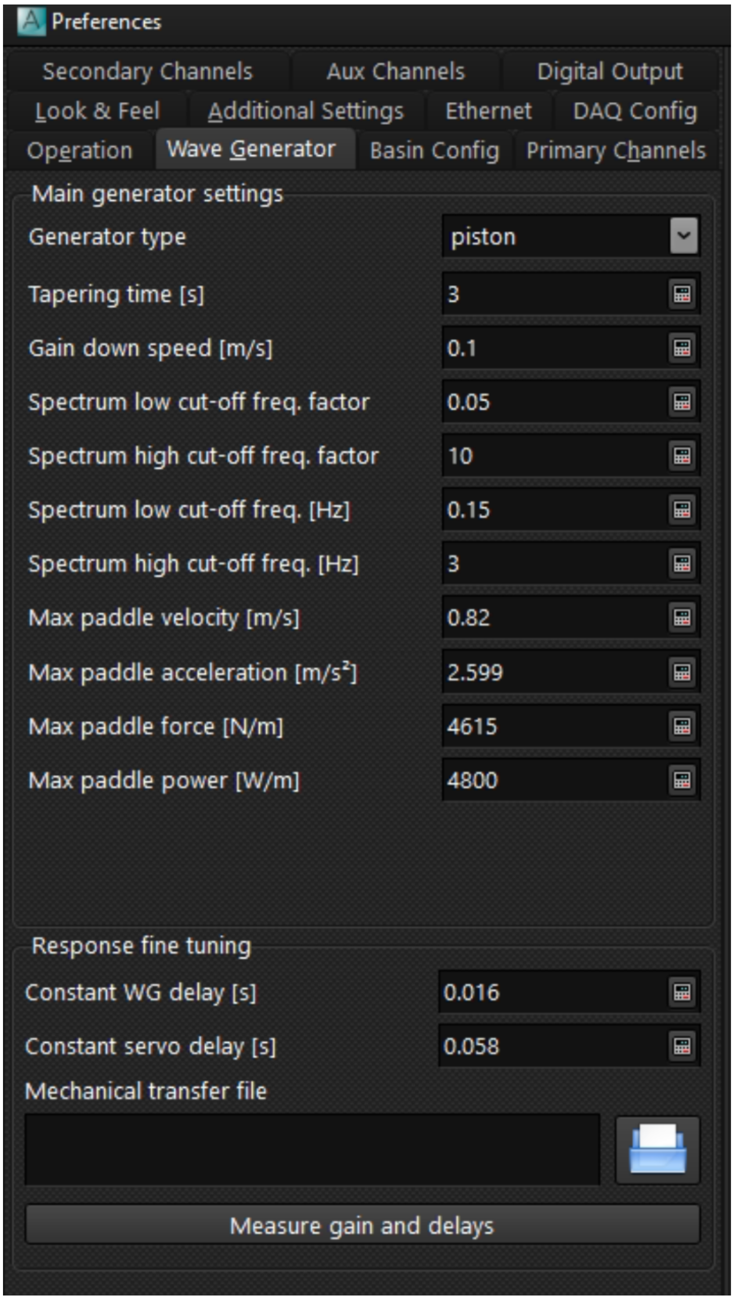
Testing of breakwater for Port of Hanstholm (19.01.2018).



Mounting details and dimensions

Appendix B: Details on Wave Generator Performance and Delay

The wave generator has a delay of about 58 ms, which is included in the wave generator software as seen in Figure 11. Further it is seen that the wave measurements from this system have a delay of 16 ms.



Main generator settings

Generator type	piston
Tapering time [s]	3
Gain down speed [m/s]	0.1
Spectrum low cut-off freq. factor	0.05
Spectrum high cut-off freq. factor	10
Spectrum low cut-off freq. [Hz]	0.15
Spectrum high cut-off freq. [Hz]	3
Max paddle velocity [m/s]	0.82
Max paddle acceleration [m/s²]	2.599
Max paddle force [N/m]	4615
Max paddle power [W/m]	4800

Response fine tuning

Constant WG delay [s]	0.016
Constant servo delay [s]	0.058
Mechanical transfer file	

Figure 11. Screendump from AwaSys wave generator software, showing the setting of a servo delay of 0.058 s (58 ms).

Ramp-up time (tapering time given in Figure 11) was fixed at 3 s, independent of wave condition. This very short ramp-up time was chosen as it was problematic to get a long enough window without significant reflections from the beach. The drawback is that the wave group generated during ramp-up will propagate slower than the main component, which will therefore have larger influence/contamination on the initial transients compared to longer ramp times. The shape of the applied ramp-up function for the wave generator is given in Figure 12.

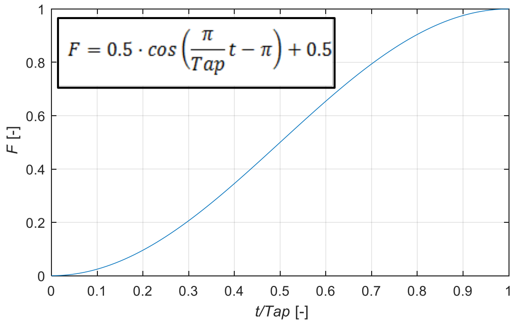


Figure 12. Function used for ramping up the wave generation.

The delays of the paddle signals in the present tests are investigated further in the following by comparing the target paddle motion signal to the measured paddle motion for the R01 and R12 waves (i.e., the two extremes of the tested regular wave conditions in the R-series). Time series are given in Figure 13 for the R01 wave and in Figure 14 for the R12 wave. Visual reading from graphs can be performed from the lower subplot giving approximately a 60 ms delay of actual motion.

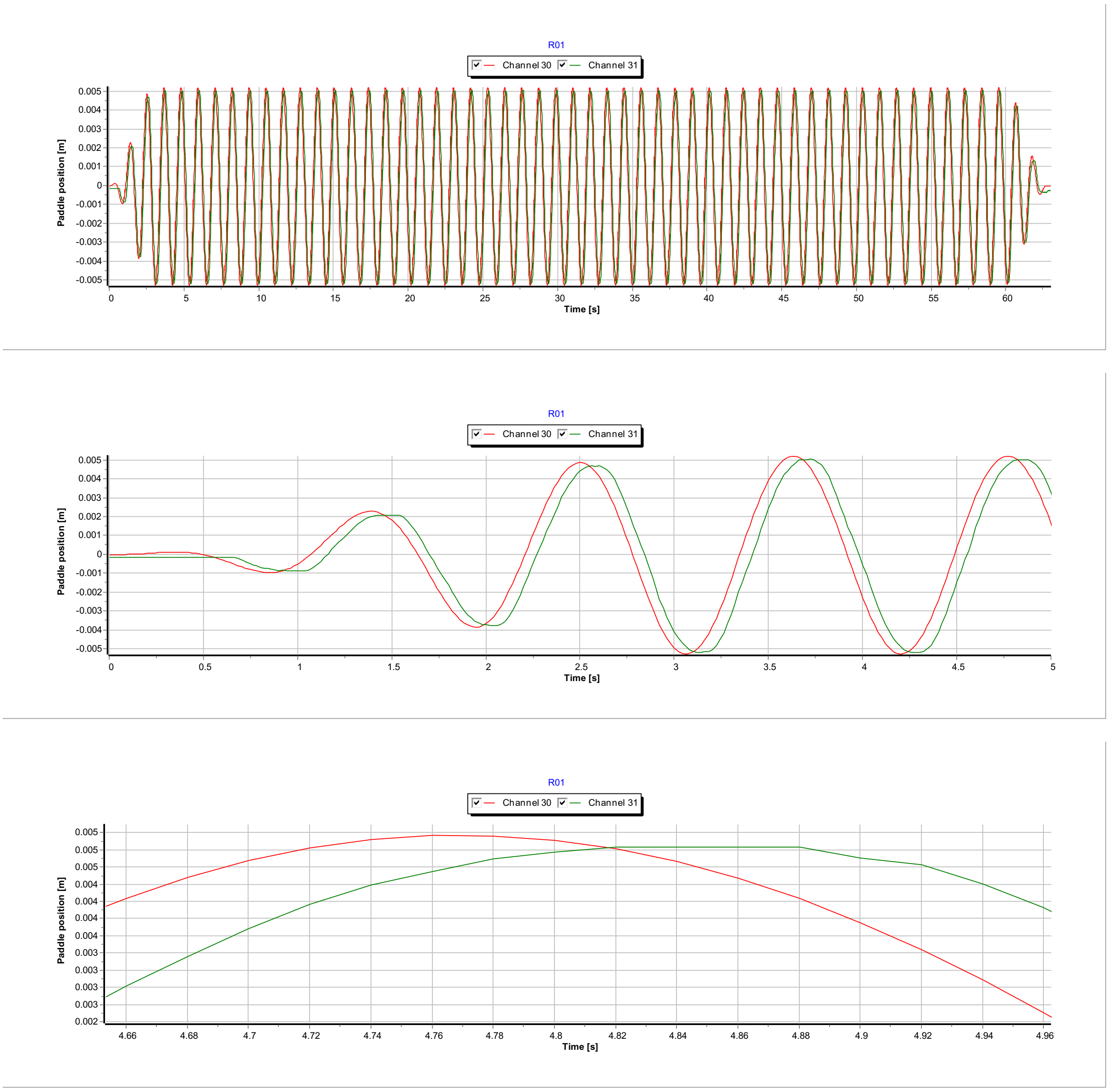


Figure 13. Time series for target (Channel 30) VS actually measured (Channel 31) paddle motion for wave no R01. Upper plot: Full time series, Middle plot: Zoom on first part of signal, Lower plot: Zoom on signal crest at t = ~4.8 s.

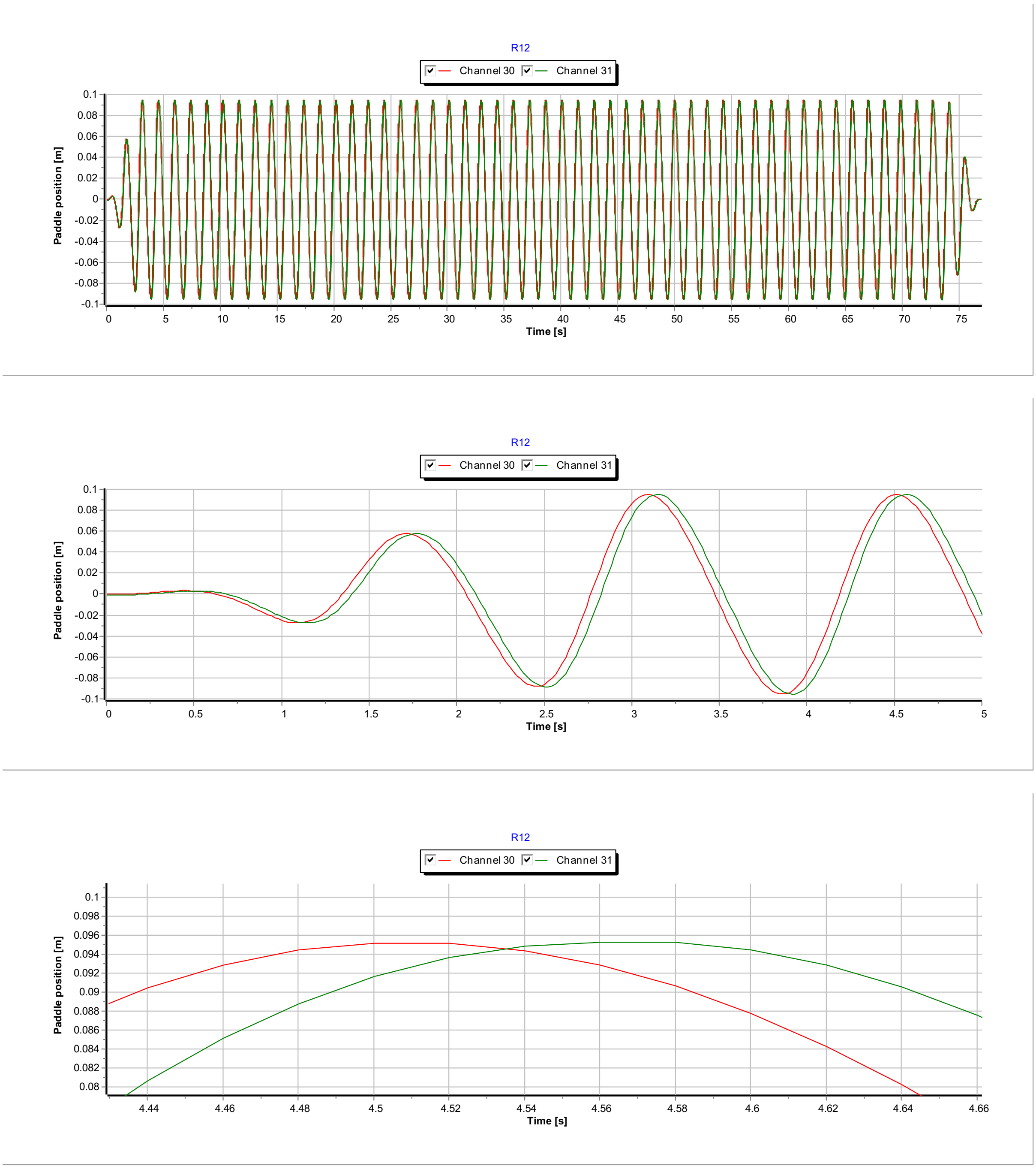
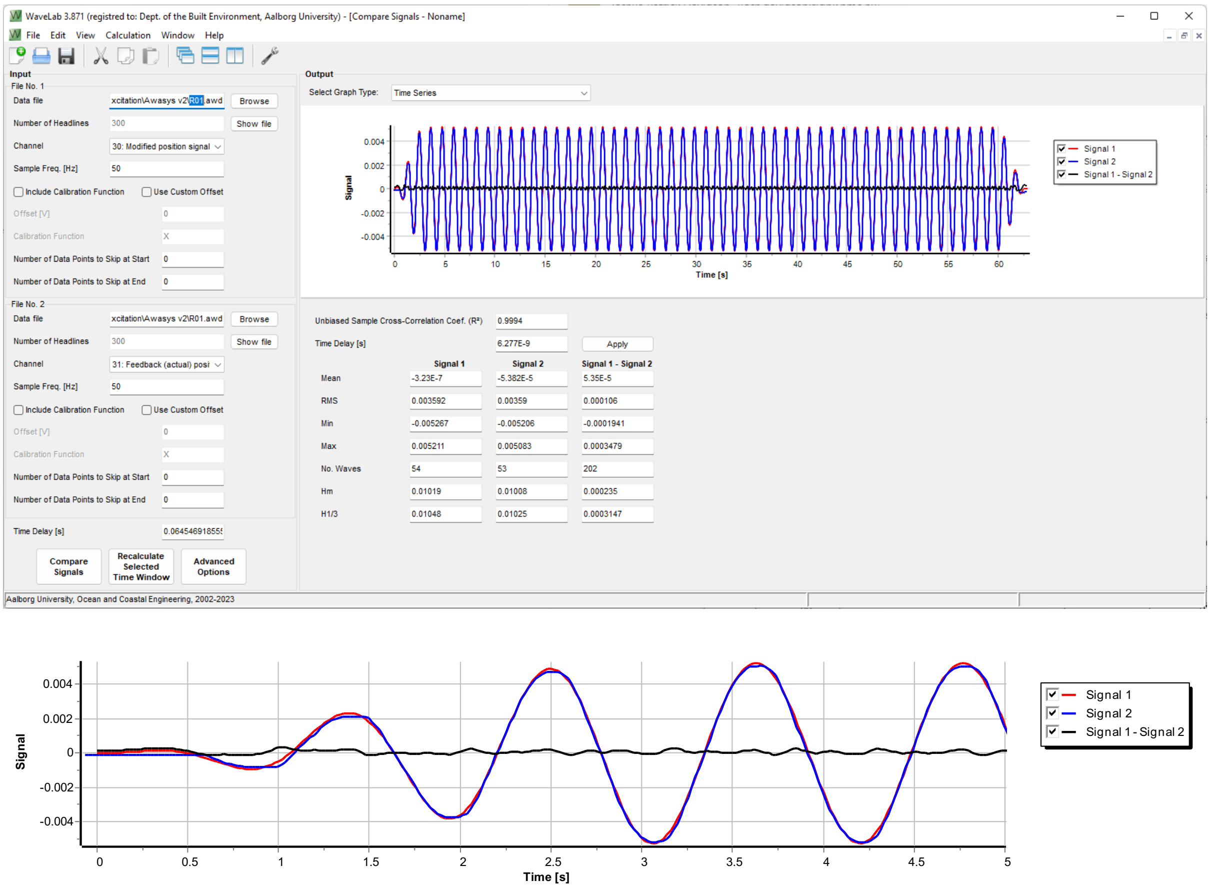


Figure 14. Time series for target (Channel 30) VS actually measured (Channel 31) paddle motion for wave no R12. Upper plot: Full time series, Middle plot: Zoom on first part of signal, Lower plot: Zoom on signal crest at t = ~4.5 s.

The delays are investigated further by cross correlating the target and the actual motion signals, see Figure 15 and Figure 16 for info regarding R01 and R12, respectively. As seen the analysis reveals that the delay is 65 ms for R01 and 54 ms for R12. By visual inspection of the two signals, it is seen that the error is merely a constant delay (no error in gain).

As a further investigation to check if the conclusions are general, the same study is performed for the irregular wave IR04, see Figure 17. The delay is found to be constant at 55 ms, which is in agreement with the findings for the regular waves.

The conclusion is that the wave generator is accurately reproducing the target motion. As the wave generator has a (small) delay, it is recommended that the actual measured motion is used as inputs to the models.



WaveLab 3.871 (registred to: Dept. of the Built Environment, Aalborg University) - [Compare Signals - Noname]

Input

File No. 1

Data file: xcitation\Awasys v2\R01.awd

Number of Headlines: 300

Channel: 30: Modified position signal

Sample Freq. [Hz]: 50

☐ Include Calibration Function ☐ Use Custom Offset

Offset [V]: 0

Calibration Function: X

Number of Data Points to Skip at Start: 0

Number of Data Points to Skip at End: 0

File No. 2

Data file: xcitation\Awasys v2\R01.awd

Number of Headlines: 300

Channel: 31: Feedback (actual) posi

Sample Freq. [Hz]: 50

☐ Include Calibration Function ☐ Use Custom Offset

Offset [V]: 0

Calibration Function: X

Number of Data Points to Skip at Start: 0

Number of Data Points to Skip at End: 0

Time Delay [s]: 0.06454691855

Output

Select Graph Type: Time Series

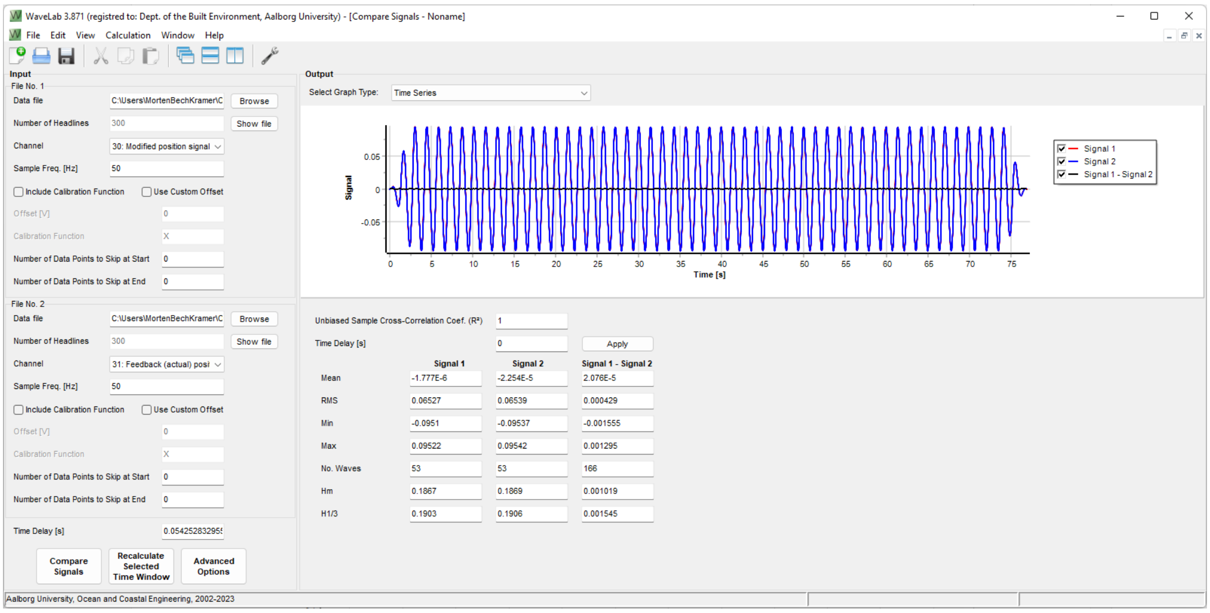
Unbiased Sample Cross-Correlation Coef. (R²): 0.9994

Time Delay [s]: 6.277E-9

	Signal 1	Signal 2	Signal 1 - Signal 2
Mean	-3.23E-7	-5.382E-5	5.35E-5
RMS	0.003592	0.00359	0.000106
Min	-0.005267	-0.005206	-0.0001941
Max	0.005211	0.005083	0.0003479
No. Waves	54	53	202
Hm	0.01019	0.01008	0.000235
H1/3	0.01048	0.01025	0.0003147

Aalborg University, Ocean and Coastal Engineering, 2002-2023

Figure 15. Correlation study for target (Channel 30) VS actually measured (Channel 31) paddle motion for wave no R012. Upper plot: Full time series, Lower plot: Zoom on first part of time series. Time series are shown after correlation adjustment.



WaveLab 3.871 (registred to: Dept. of the Built Environment, Aalborg University) - [Compare Signals - Noname]

Input

File No. 1

Data file: C:\Users\MortenBechKramer\C

Number of Headlines: 300

Channel: 30: Modified position signal

Sample Freq. [Hz]: 50

☐ Include Calibration Function ☐ Use Custom Offset

Offset [V]: 0

Calibration Function: X

Number of Data Points to Skip at Start: 0

Number of Data Points to Skip at End: 0

File No. 2

Data file: C:\Users\MortenBechKramer\C

Number of Headlines: 300

Channel: 31: Feedback (actual) posi

Sample Freq. [Hz]: 50

☐ Include Calibration Function ☐ Use Custom Offset

Offset [V]: 0

Calibration Function: X

Number of Data Points to Skip at Start: 0

Number of Data Points to Skip at End: 0

Time Delay [s]: 0.05425283295

Output

Select Graph Type: Time Series

Unbiased Sample Cross-Correlation Coef. (R²): 1

Time Delay [s]: 0

	Signal 1	**Signal 2**	**Signal 1 - Signal 2**
Mean	-1.777E-6	-2.254E-5	2.076E-5
RMS	0.06527	0.06539	0.000429
Min	-0.0951	-0.09537	-0.001555
Max	0.09522	0.09542	0.001295
No. Waves	53	53	166
Hm	0.1867	0.1869	0.001019
H1/3	0.1903	0.1906	0.001545

Aalborg University, Ocean and Coastal Engineering, 2002-2023

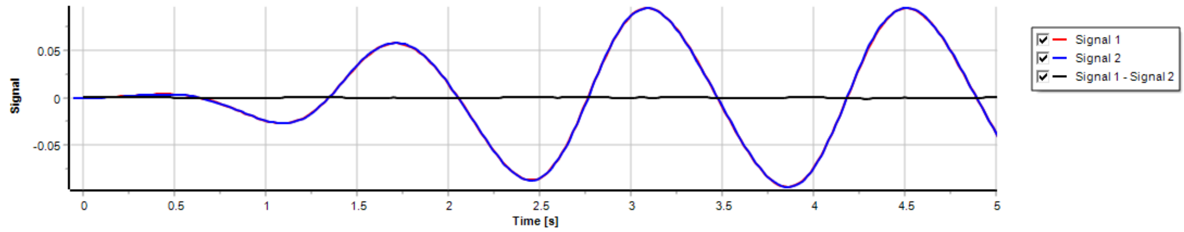
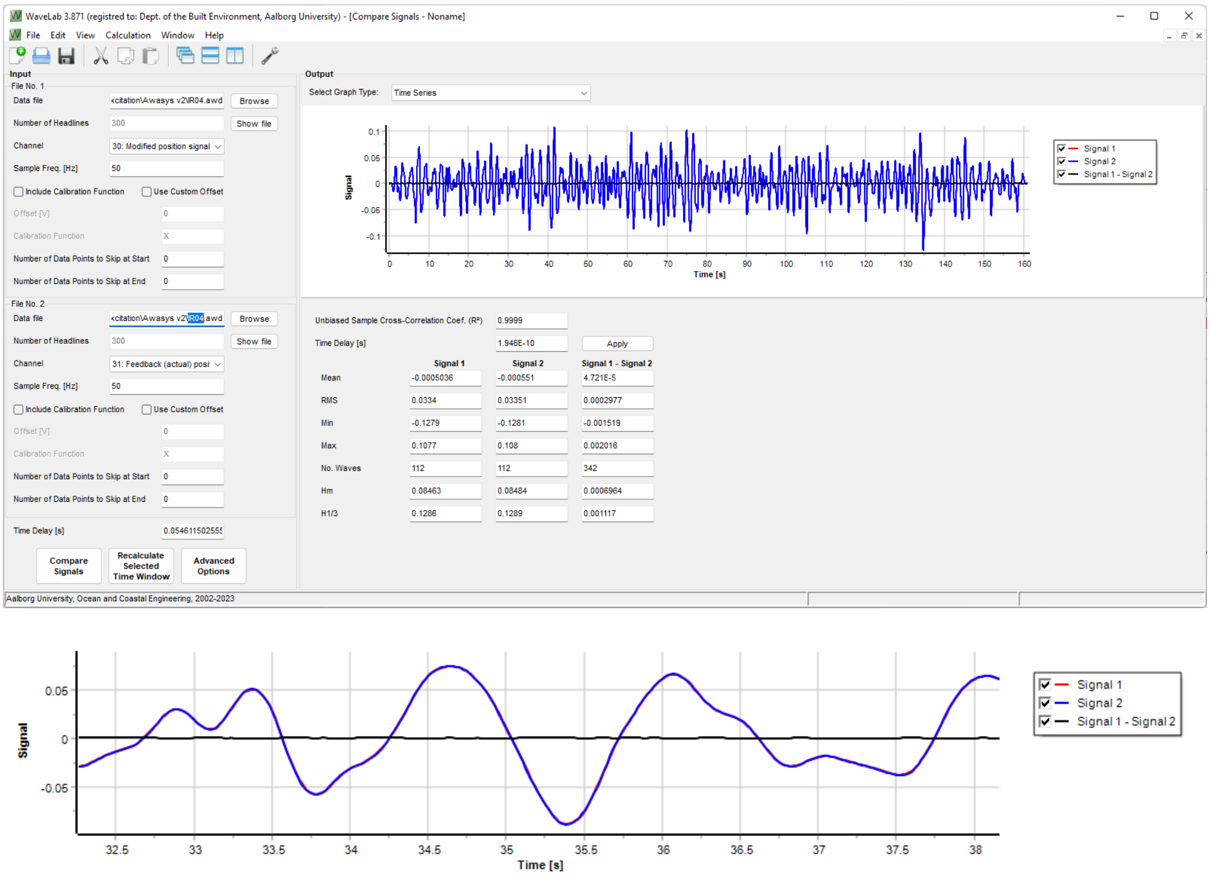


Figure 16. Correlation study for target (Channel 30) VS actually measured (Channel 31) paddle motion for wave no R12. Upper plot: Full time series, Lower plot: Zoom on first part. Time series are shown after correlation adjustment.



File No. 1

Data file: kcitation\Awasys v2\IR04.awd
Number of Headlines: 300
Channel: 30: Modified position signal
Sample Freq. [Hz]: 50
☐ Include Calibration Function ☐ Use Custom Offset
Offset [V]: 0
Calibration Function: X
Number of Data Points to Skip at Start: 0
Number of Data Points to Skip at End: 0

File No. 2

Data file: kcitation\Awasys v2\IR04.awd
Number of Headlines: 300
Channel: 31: Feedback (actual) posi
Sample Freq. [Hz]: 50
☐ Include Calibration Function ☐ Use Custom Offset
Offset [V]: 0
Calibration Function: X
Number of Data Points to Skip at Start: 0
Number of Data Points to Skip at End: 0

Time Delay [s]: 0.054611502555

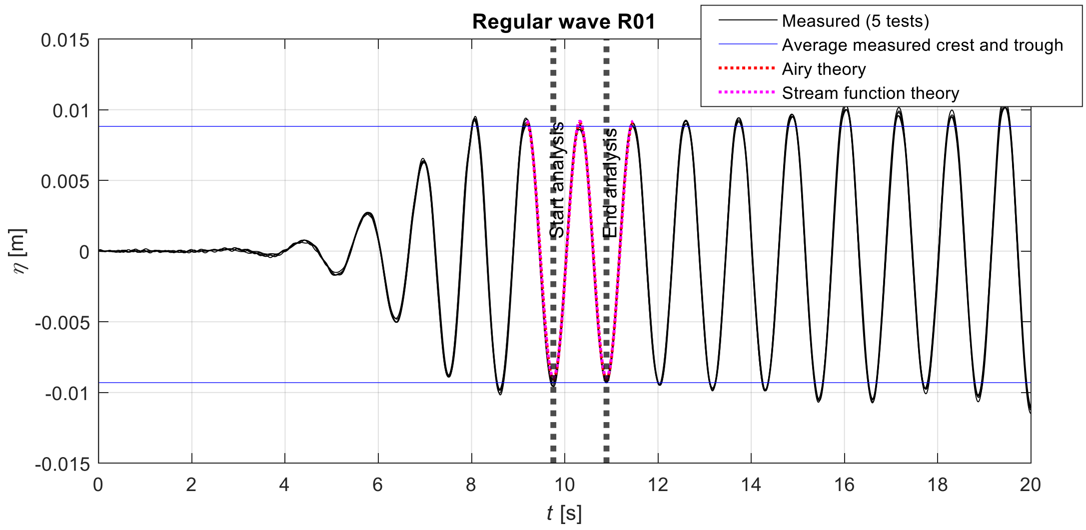
Select Graph Type: Time Series

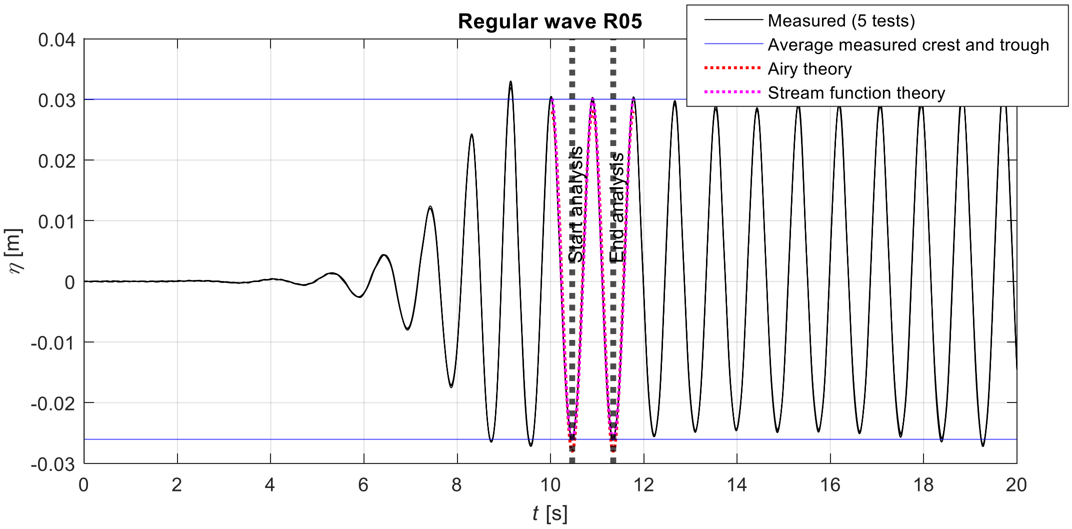
Unbiased Sample Cross-Correlation Coef. (R²): 0.9999
Time Delay [s]: 1.946E-10

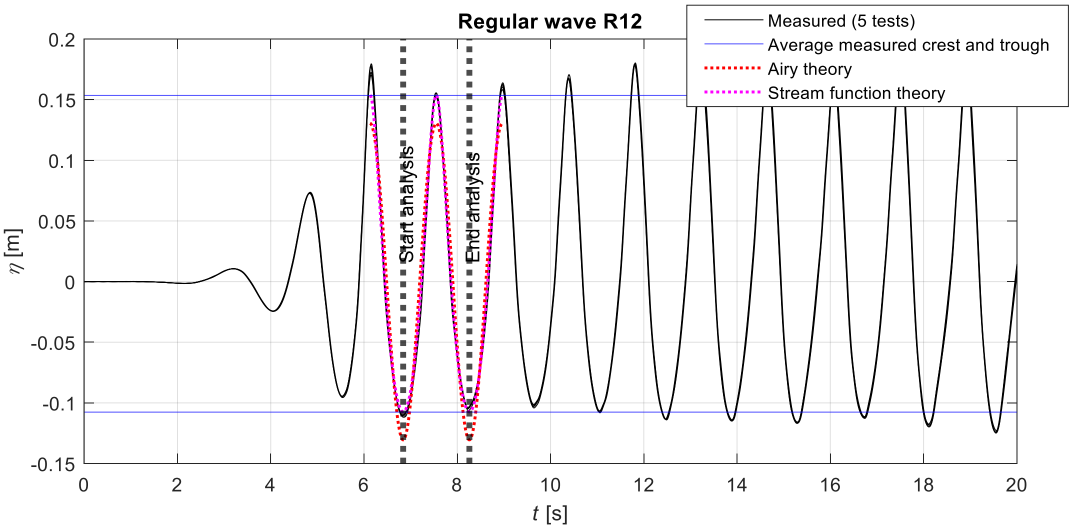
	Signal 1	Signal 2	Signal 1 - Signal 2
Mean	-0.0005036	-0.000551	4.721E-5
RMS	0.0334	0.03351	0.0002977
Min	-0.1279	-0.1281	-0.001519
Max	0.1077	0.108	0.002016
No. Waves	112	112	342
Hm	0.08463	0.08484	0.0006964
H1/3	0.1286	0.1289	0.001117

Figure 17. Correlation study for target (Channel 30) VS actually measured (Channel 31) paddle motion for irregular wave no IR04. Upper plot: Full time series, Lower plot: Zoom on a random part. Time series are shown after correlation adjustment.

Appendix C: Figures for Time Interval, 20 s Length

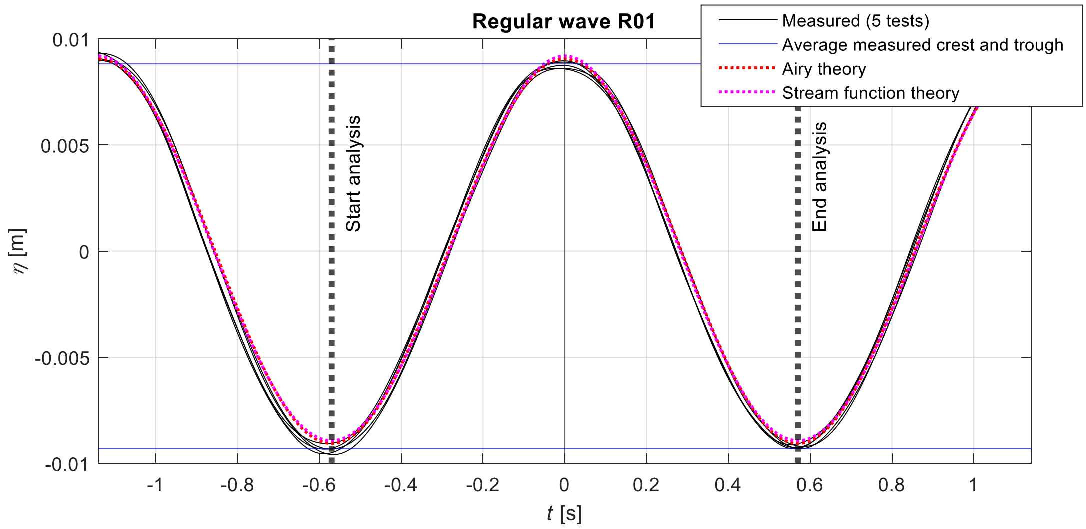


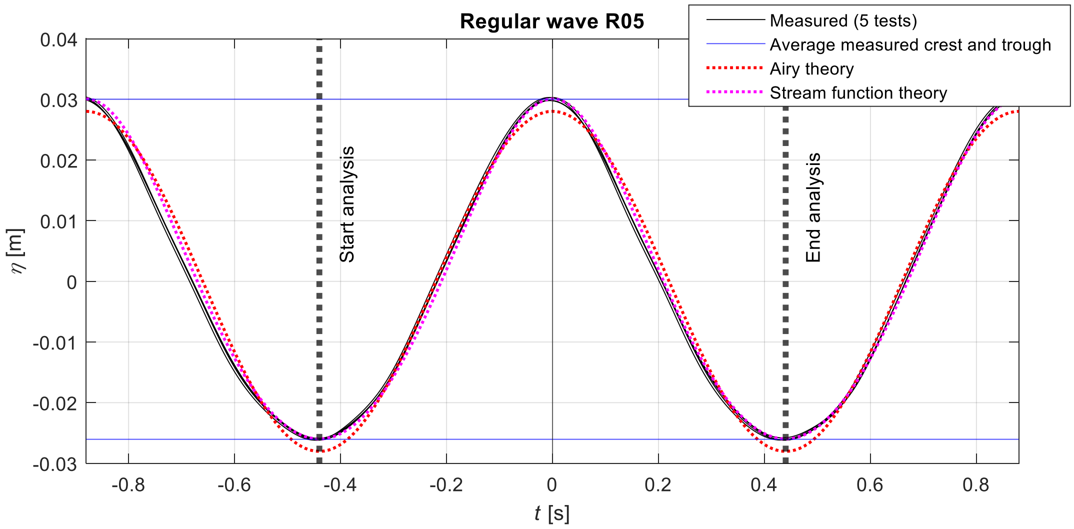


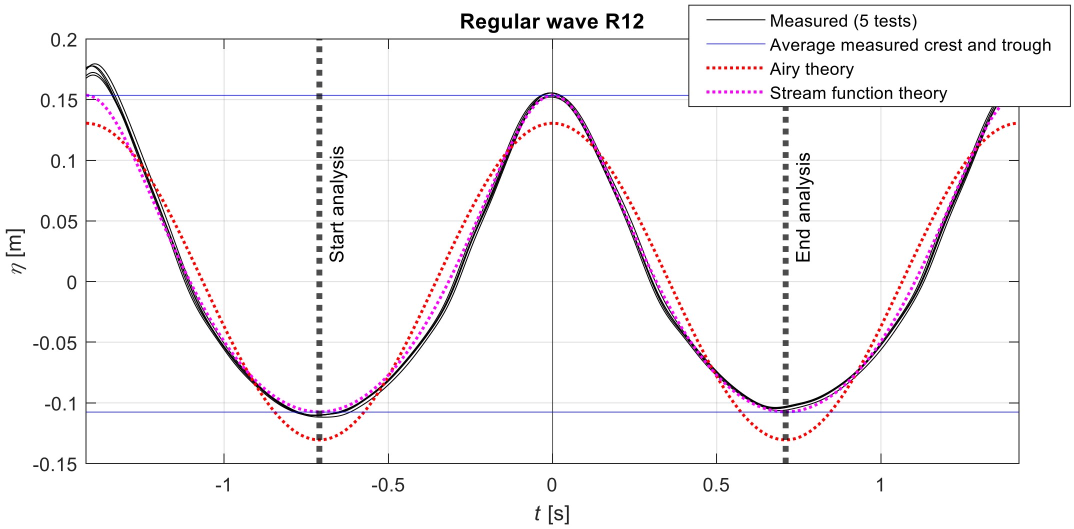


Appendix D: Figures for Time Interval, Two Wave Periods

Time on the following figures is given with reference to the peak time.

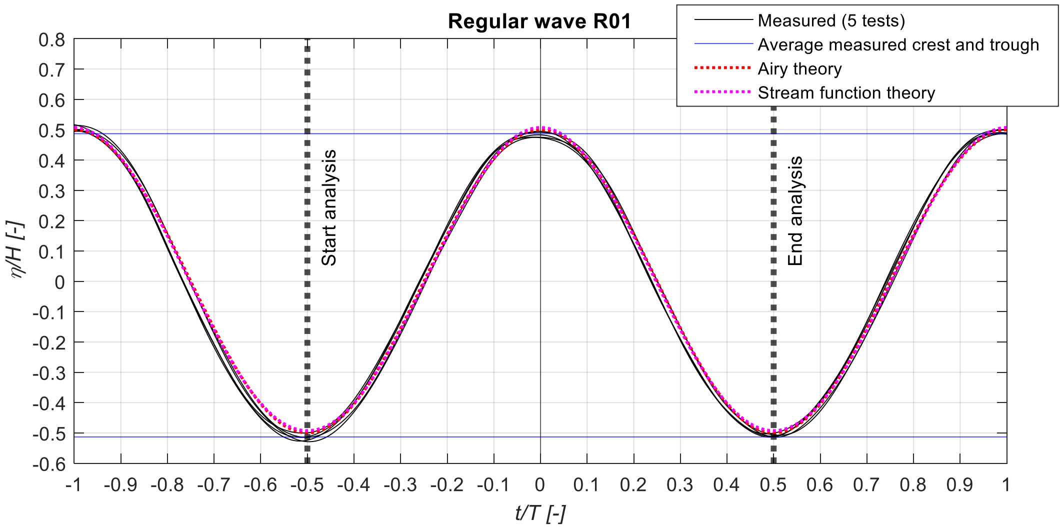


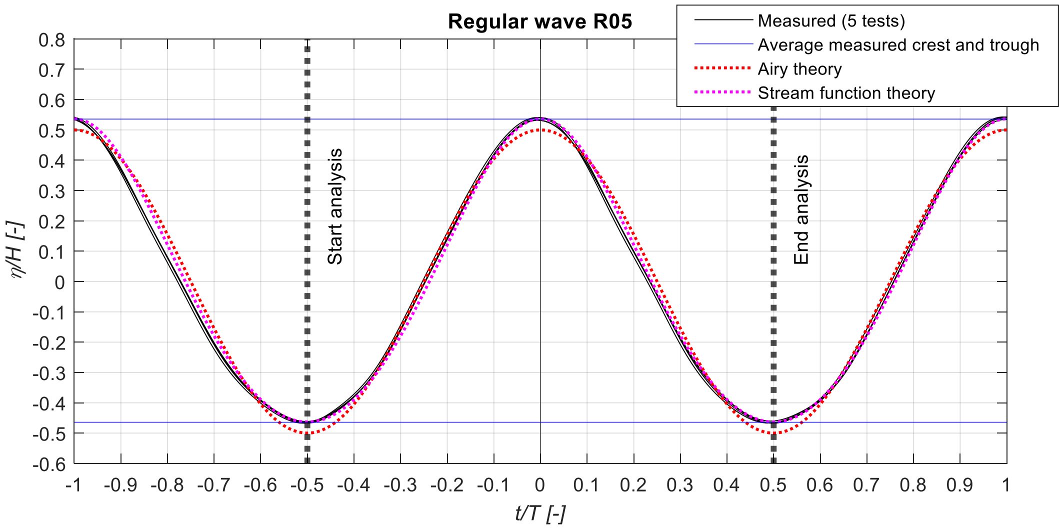


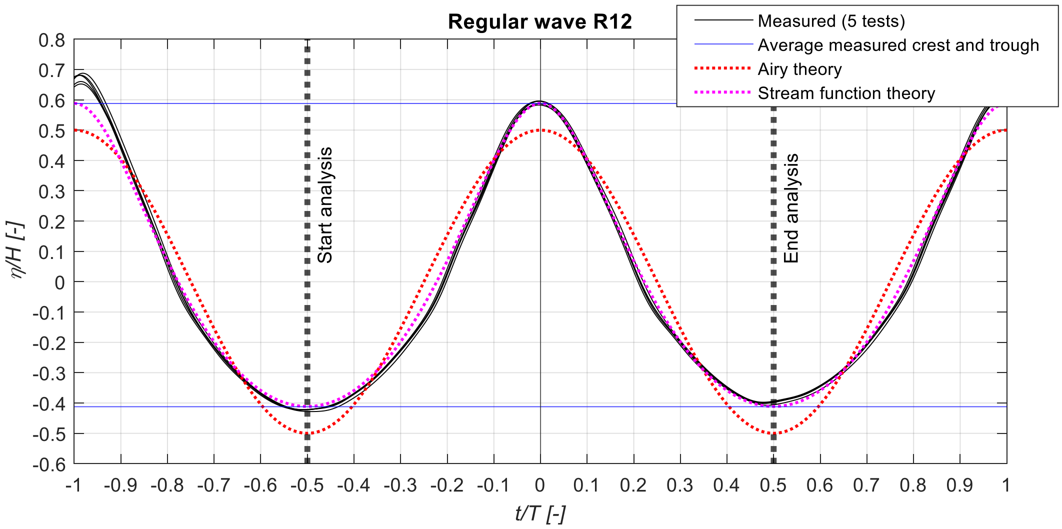


Appendix E: Figures for Time Interval, Two Wave Periods, Normalized

Time on the following figures is given with reference to the peak time, i.e., *t* = 0 is the time for the peak at the centre of the interval.







Appendix F: Figures for the Wave Uncertainty

An investigation of uncertainties related to the surface elevation measurements has been performed in a report describing the uncertainties [11]. The total expanded uncertainty (repeatability + calibration uncertainty) was evaluated using a coverage factor of 2.8, which was chosen based on 5 repetitions (4 degrees of freedom) corresponding to a 2-sided 95 % confidence interval.

The results for the WG11 measurements of the time dependency of the uncertainty is shown in the following figures for R01, R05 and R12. Figure 18, Figure 19, and Figure 20 are showing the non-normalised time series for the time interval 0 to 20 s. Figure 21, Figure 22 and Figure 23 are showing the same data, but in a normalised version for the interval for analysis.

The data files are containing results for all the 12 wave gauges.

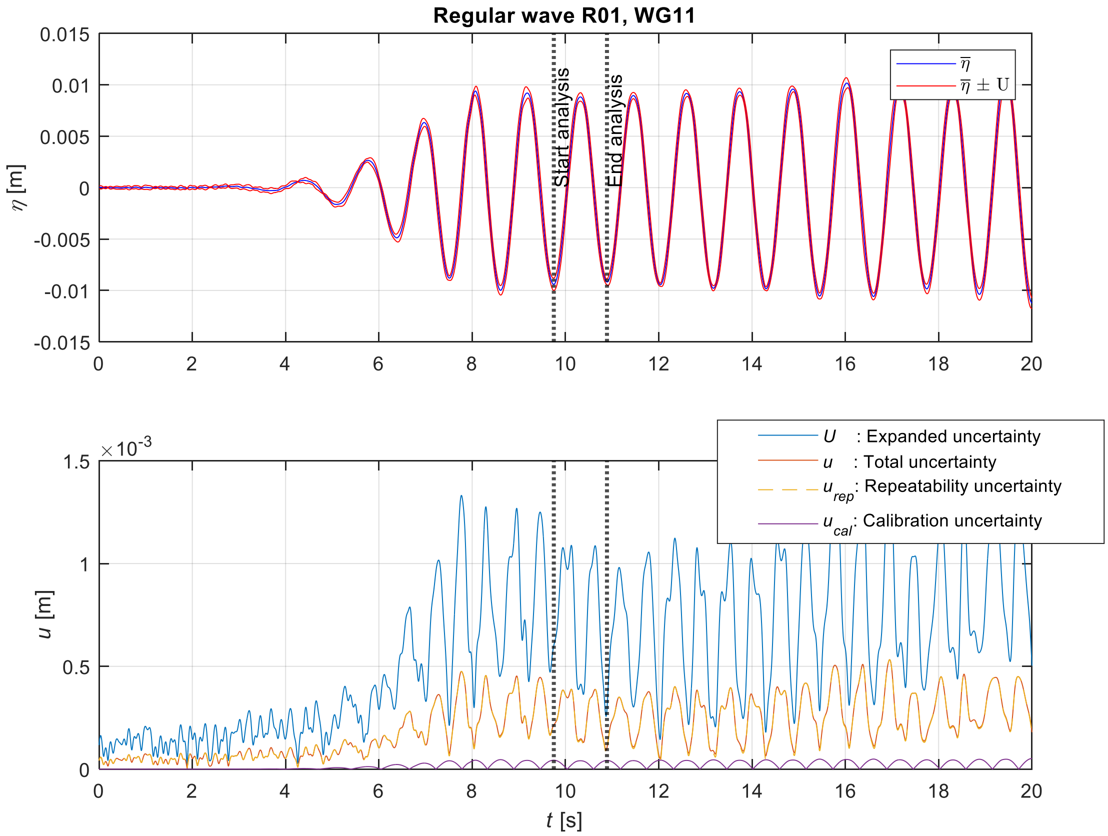


Figure 18. R01, wave and time dependency of uncertainty. Non-normalised time series of 20 s length.

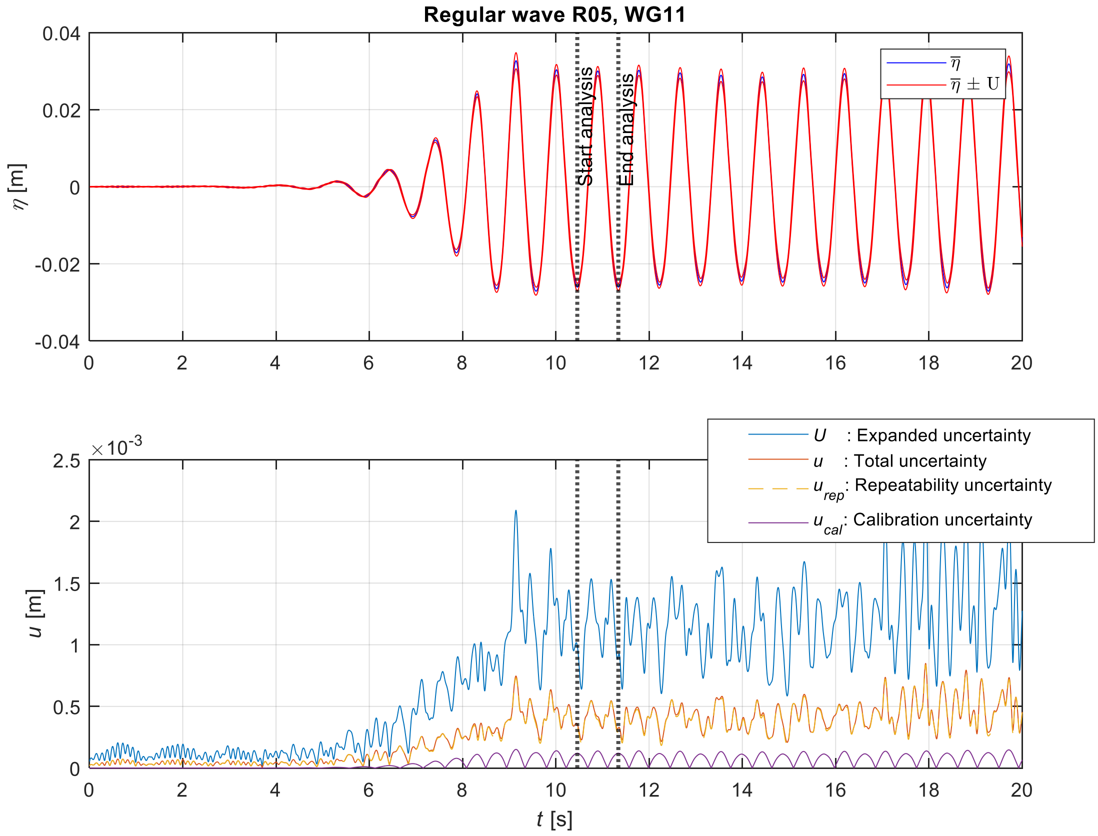


Figure 19. R05, wave and time dependency of uncertainty. Non-normalised time series of 20 s length.

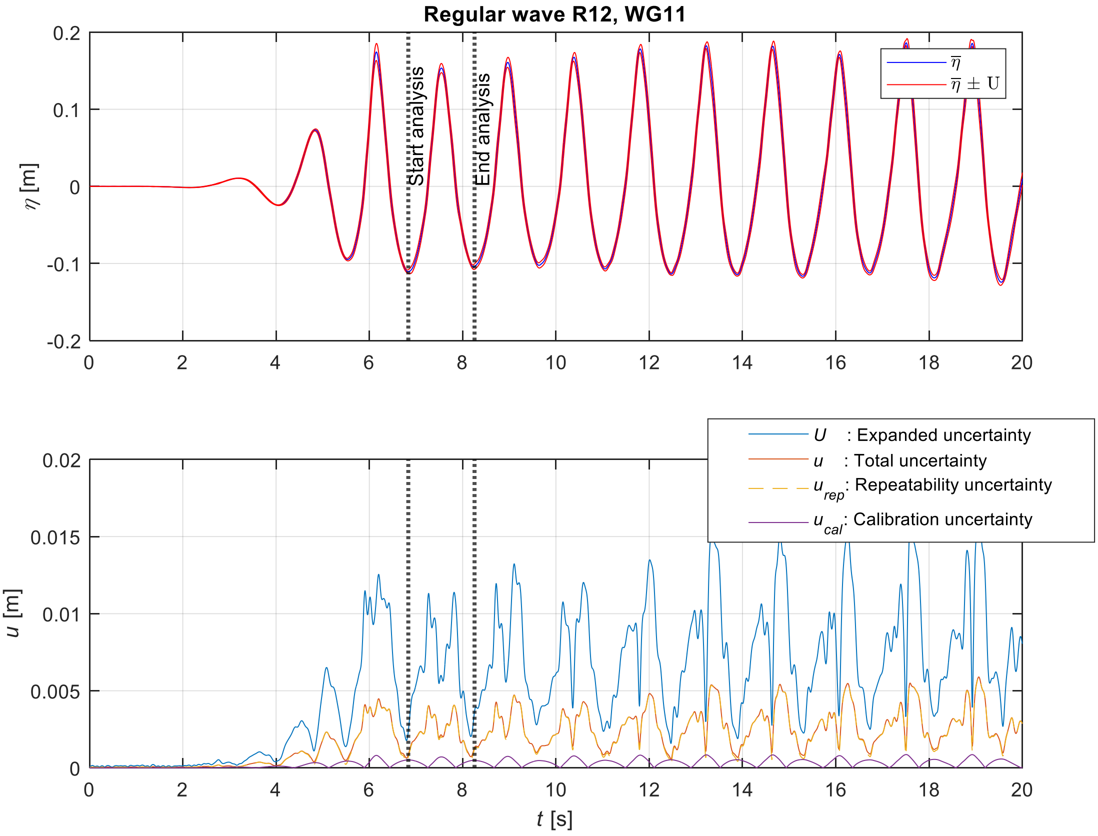


Figure 20. R12, wave and time dependency of uncertainty. Non-normalised time series of 20 s length.

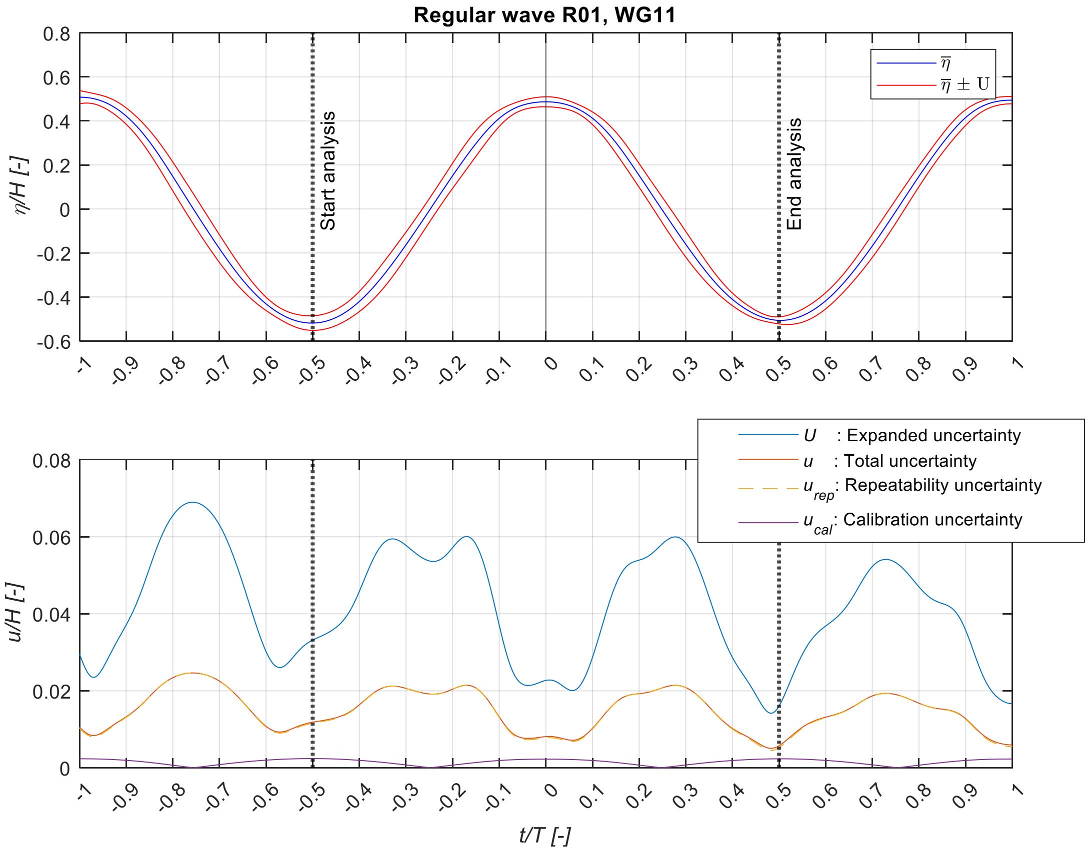


Figure 21. R01, wave and time dependency of uncertainty. Normalised time series for interval.

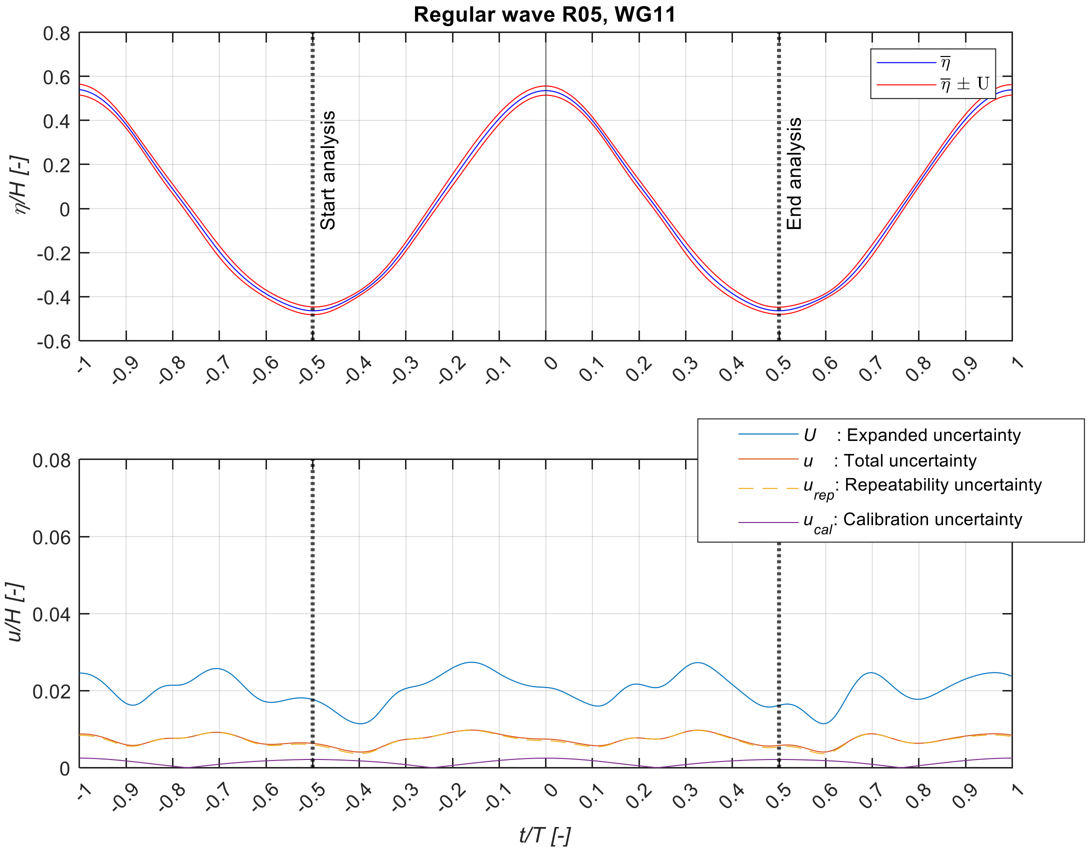


Figure 22. R05, wave and time dependency of uncertainty. Normalised time series for interval.

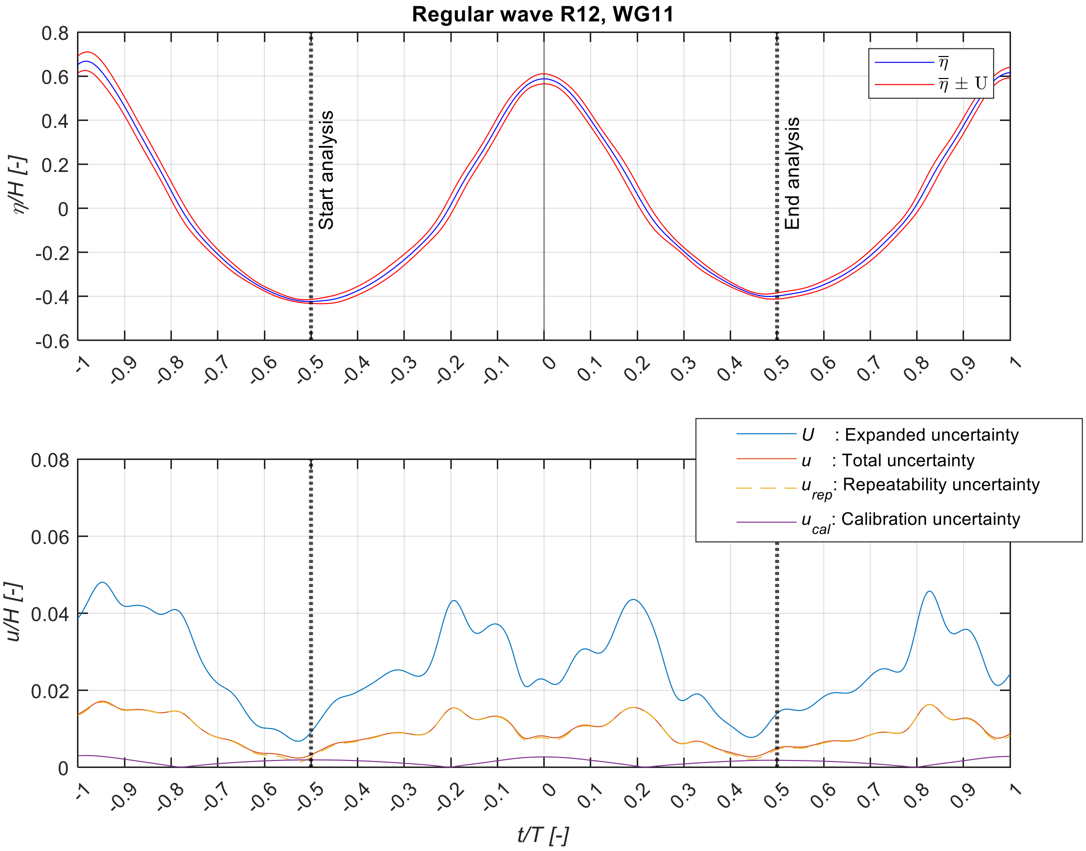
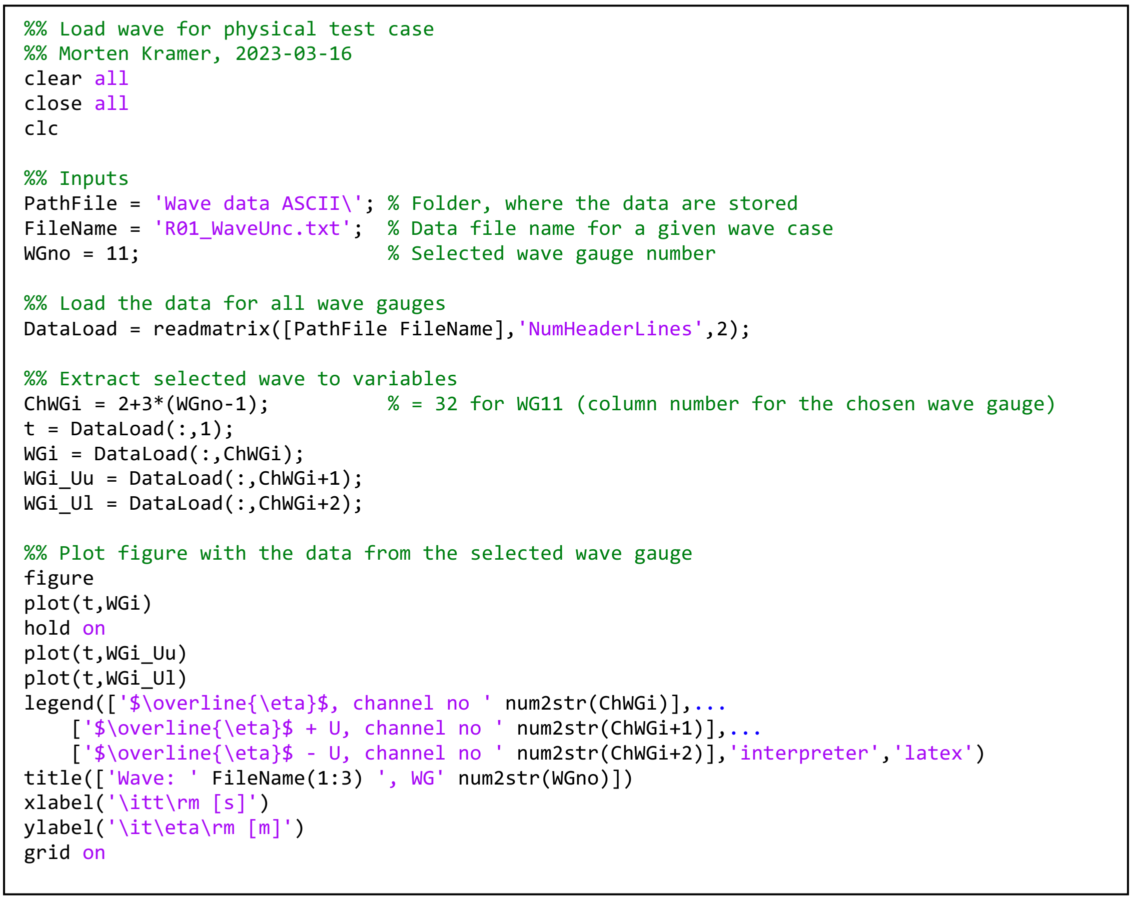


Figure 23. R12, wave and time dependency of uncertainty. Normalised time series for interval.

Appendix G: Example Matlab Script to Load and Plot a Wave File

An example of how to load the data into Matlab, and plot the data for a specific wave gauge is given in Figure 24 with the output figure shown in Figure 25.



```matlab
%% Load wave for physical test case
%% Morten Kramer, 2023-03-16
clear all
close all
clc

%% Inputs
PathFile = 'Wave data ASCII\'; % Folder, where the data are stored
FileName = 'R01_WaveUnc.txt';  % Data file name for a given wave case
WGno = 11;                     % Selected wave gauge number

%% Load the data for all wave gauges
DataLoad = readmatrix([PathFile FileName],'NumHeaderLines',2);

%% Extract selected wave to variables
ChWGi = 2+3*(WGno-1);          % = 32 for WG11 (column number for the chosen wave gauge)
t = DataLoad(:,1);
WGi = DataLoad(:,ChWGi);
WGi_Uu = DataLoad(:,ChWGi+1);
WGi_Ul = DataLoad(:,ChWGi+2);

%% Plot figure with the data from the selected wave gauge
figure
plot(t,WGi)
hold on
plot(t,WGi_Uu)
plot(t,WGi_Ul)
legend(['$\overline{\eta}$, channel no ' num2str(ChWGi)],...
    ['$\overline{\eta}$ + U, channel no ' num2str(ChWGi+1)],...
    ['$\overline{\eta}$ - U, channel no ' num2str(ChWGi+2)],'interpreter','latex')
title(['Wave: ' FileName(1:3) ', WG' num2str(WGno)])
xlabel('\itt\rm [s]')
ylabel('\it\eta\rm [m]')
grid on
```

Figure 24. Example Matlab script to load and plot a given wave signal.

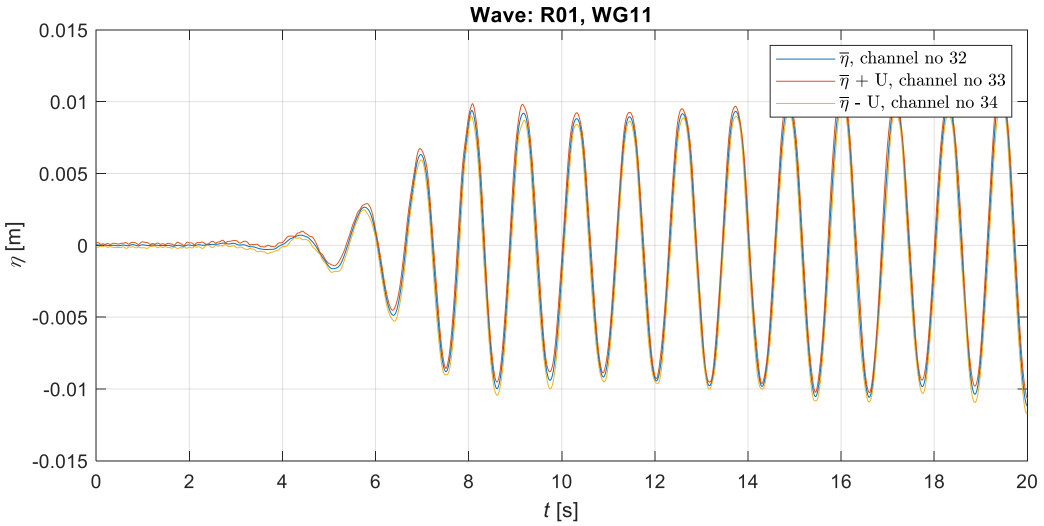


Figure 25. Plot produced by the example Matlab script.