SAILING IN SHALLOW WATER WAVES WITH THE DTC CONTAINER CARRIER: OPEN MODEL TEST DATA FOR VALIDATION PURPOSES

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SUMMARY

After successful conferences on bank effects, ship-ship interaction, ship behaviour in locks and ship-bottom interaction, the Fifth International Conference on Ship Manoeuvring in Shallow and Confined Water (MASHCON) has a non-exclusive focus on wind, waves and current action on manoeuvring ships. A clear understanding of the ship's manoeuvring characteristics in waves, wind and currents is essential in both everyday operations and ship safety in so-called adverse conditions. To open a joined research effort on the validation and verification of the different research methods, the Knowledge Centre Manoeuvring in Shallow and Confined Water has selected model test data which were obtained during the execution of seakeeping tests with the DTC container carrier in the framework of the European SHOPERA project. The benchmark data are both captive and free running model tests with the DTC at full draft in calm water and in waves.

NOMENCLATURE

a_0	[mm]	Mean Fourier series
a_i	[mm]	ith order cosine terms Fourier series
B	[m]	Breadth of the ship
b_i	[mm]	ith order sine terms Fourier series
C_B	[-]	Block coefficient
$\overline{GM}$	[m]	Transverse metacentric height
H	[mm]	Measured wave height
I_{xx}	[kg m²]	Mass moment of inertia about Ox-axis
I_{yy}	[kg m²]	Mass moment of inertia about Oy-axis
I_{zz}	[kg m²]	Mass moment of inertia about Oz-axis
L_{PP}	[m]	Length between perpendiculars
m	[kg]	Mass
n	[rps]	Propeller rate
n_{max}	[rps]	Maximum propeller rate
N_z	[-]	Population Z
O	[-]	Origin of the ship-bound axis system
O_0	[-]	Origin of the earth-bound axis system
$O_{0x0y0z0}$	[-]	Earth bound axis system
O_{xyz}	[-]	Ship bound axis system
T	[s]	Measured wave period
T_{design}	[m]	Design draft
$t_{acc,end}$	[s]	End time captive acceleration
$t_{acc,start}$	[s]	Start time captive acceleration
t_{dec}	[s]	Start time deceleration
$t_{reg,end}$	[s]	End time regime condition
$t_{reg,start}$	[s]	Start time regime condition
t_{wave}	[s]	Meeting between ship and waves
u	[m/s]	Longitudinal component of ship speed
v	[m/s]	Lateral component of ship speed
V	[m/s]	Ship speed
$x_{0acc,end}$	[m]	End position captive acceleration
$x_{0acc,start}$	[m]	Start position captive acceleration
x_{0dec}	[m]	Start position deceleration
x_G	[m]	Centre of gravity (longitudinal)
$x_{0reg,end}$	[m]	End position regime condition
$x_{0reg,start}$	[m]	Start position regime condition
x_{0wave}	[m]	Meeting between ship and waves
X	[N]	Longitudinal force
Y	[N]	Transversal force
Z	[-]	Random variable
z_G	[m]	Centre of gravity (vertical)
z_{VF}	[mm]	Running sinkage at fore perpendicular
z_{VA}	[mm]	Running sinkage at aft perpendicular
β	[°]	Hull drift angle
δ_R	[°]	Rudder angle
$\dot{\delta}_R$	[°/s]	Rudder rate
Δx_{0WM}	[mm]	Wave maker position
ζ	[mm]	Position of the free surface
ζ_i	[mm]	ith harmonic amplitude (Fourier)
η	[°]	Wave angle
λ_{theo}	[m]	Theoretical wave length
μ	[°]	Wave encounter angle
μ_z	[-]	Average value Z
σ_z	[-]	Standard deviation Z
ψ	[°]	Ship's heading
ω	[rad/s]	Wave frequency

C1-3	Captive calm water model tests 1-3
G	Centre of Gravity
CM	Clamping mechanism
CW1-5	Captive wave model tests 1-5
P1-4	Potentiometers 1-4
DTC	Duisburg Test Case
EEDI	Energy Efficiency Design Index
FHR	Flanders Hydraulics Research
FW1-2	Free running wave model tests 1-2
LC1-2	Load cells 1-2
PID	Proportional integral derivative
R1-4	Reflector plates 1-4
H1-2	Height meters 1-2
MASHCON	Manoeuvring in shallow and confined water
S1-4	Lasers 1-4
SHOPERA	Energy Efficient Safe Ship operation
UKC	Under keel clearance
VLIZ	Flanders Marine Institute
WG1-4	Wave gauges 1-4

1 INTRODUCTION

The Fifth International Conference on Ship Manoeuvring in Shallow and Confined Water (MASHCON) is held at the seaside city of Ostend, Belgium, from May 20th until May 22nd 2019 and is organised by Flanders Hydraulics Research (FHR), Ghent University (UGent) and Flanders Marine Institute (VLIZ). The venue of Ostend not only offers the opportunity to organise a morning walk/run along the picturesque coastline, it also provides the opportunity of visiting the shallow water towing tank (currently under construction) at the Flanders Maritime Laboratory. The main, non-exclusive, topic of the conference is manoeuvring in wind, waves and current, three important factors when sailing in shallow and confined waters. This conference is the successor to previous editions with non-exclusive focus on bank effects (Vantorre and Eloot, 2009) (Antwerp, May 2009), ship-ship interaction (Pettersen et al., 2011) (Trondheim, May 2011), ship behaviour in locks (Vantorre et al., 2013) (Ghent, May 2013) and ship-bottom interaction (Uliczka et al., 2016) (Hamburg, May 2016). These topics fit within the scope of the Knowledge Centre Manoeuvring in Shallow and Confined water, which aims to consolidate, extend and disseminate knowledge on the behaviour of ships in navigation areas with major vertical and horizontal restrictions.

A clear understanding of the ship's manoeuvring characteristics in waves, wind and currents is essential in both everyday operations and ship safety in so-called adverse conditions. Sailing in confined waterways adds to the complexity of the problems, forcing the ship to have non-favourable headings towards the main wind and current directions. The restriction of engine power (EEDI regulations) to reduce emissions emphasises the importance of a good understanding of the behaviour of ships in adverse conditions, which could limit the possible power reduction from the viewpoint of the ship's safety. These concerns have led to the establishment of the EU funded project 'Energy efficient safe SHip OPERAtion' (SHOPERA) (Papanikolaou et al., 2015). In the framework of this project, a substantial amount of model tests have been performed by four leading European institutes (SINTEF Ocean, FHR, TU Berlin and CEHIPAR). The Knowledge Centre has made a selection of the tests performed with the DTC (Duisburg Test Case container ship) in shallow water, in order to stimulate validation and verification of different research methods.

2 MODEL TEST SET-UP

The tests were executed using a scale model of the DTC in the Towing Tank for Manoeuvres in Shallow Water (cooperation FHR and UGent). The dimensions and layout of the tank define the range of wave climates which can be generated.

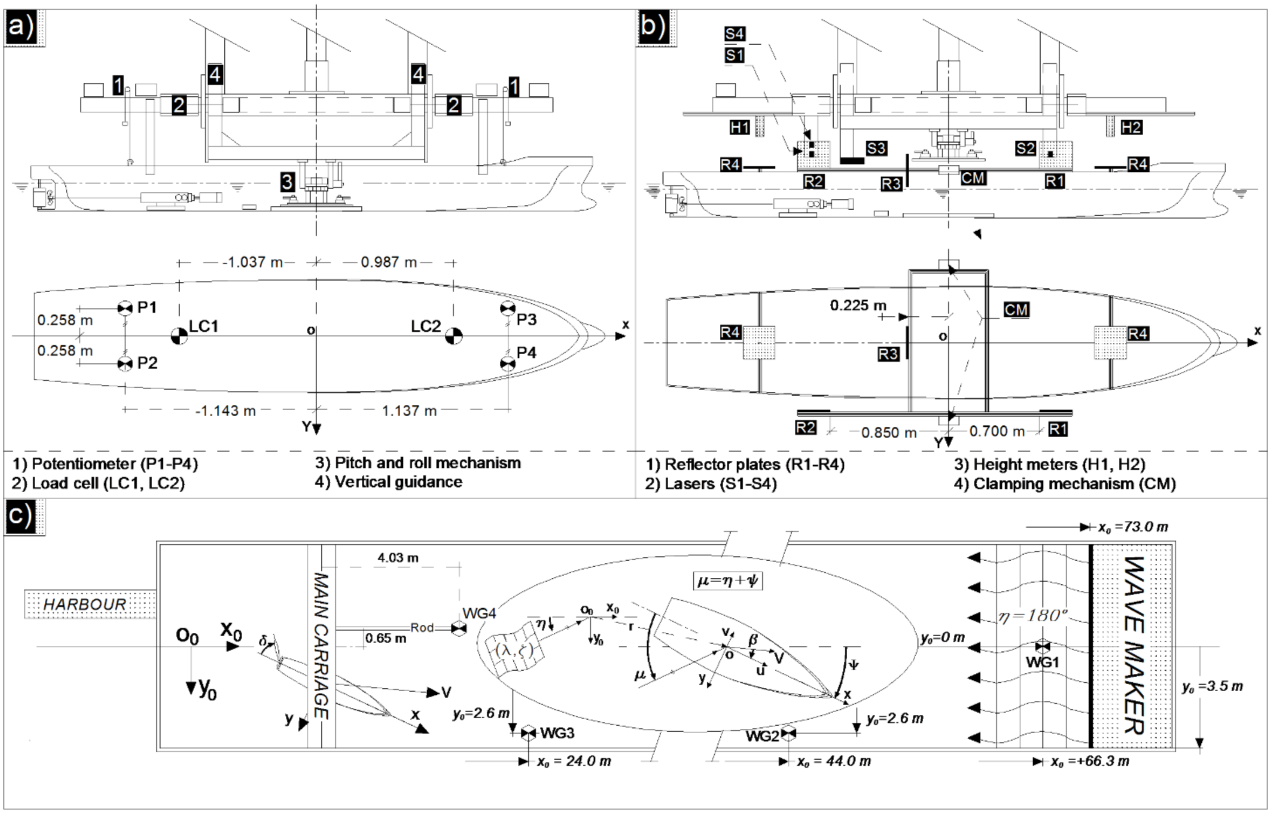

Figure 1. Towing tank at FHR, (a) set-up for captive test, (b) set-up for free running test, and (c) general configuration in the towing tank. ±1 mm uncertainty of dimensions.

2.1 TOWING TANK

The towing tank at FHR has a total length of 87.5 m, a width of 7.0 m and a maximum water depth of 0.5 m. Because of the presence of the harbour and the wave maker, the useful towing tank length is limited to 68.0 m. The towing tank mechanism consists of a main carriage and a lateral carriage, combined with a yawing table, allowing all possible movements in the horizontal plane. The carriage mechanism allows the execution of both captive and free running tests by using two different set-ups (Delefortrie et al., 2016). The towing tank's general configuration, the captive and free running setups are shown in Figure 1.

During captive tests the ship is fixed in the horizontal plane (surge, sway and yaw), allowing roll, pitch and heave (during the calm water tests, roll is fixed and then the moment is measured). The hull forces are measured using load cells LC1 (separate measurement of X and Y force) and LC2. The ship's heave, trim and roll are measured by using four potentiometers P1 to P4 (see Figure 1a). In the case of free running tests, the vessel uses its own propeller and rudder to sail through the towing tank, while the carriage mechanism follows the ship minutely, recording its trajectory through the tank. The ship's relative position with respect to the carriage is measured in six degrees of freedom by a combination of four lasers S1 to S4 (see Figure 1b).

To define the ship's position and orientation along the tank two coordinate systems are used, $O_{0x0y0z0}$ is the earth-bound axis system, and O_{xyz} is the ship fixed axis system, with its origin amidships on the water plane. Both systems have the $z_{(0)}$ axis defined positive downwards. The ship's position/orientation during tests is defined by the wave encounter angle (μ), hull drift angle (β) and ship's heading (ψ), as shown in Figure 1c.

The wave profile along the tank was measured by using four wave gauges WG1 to WG4. Three of them, WG1 to WG3, were at a fixed position in the towing tank while the fourth wave gauge WG4 was attached to the carriage (see Figure 1c). In the $O_{0x0y0z0}$ axis system, its lateral position is constant (y_{WG4} = -0.65). It moves along the x0-axis along with the carriage, being located 4.03 m in front of midship ($x_{WG4} = x_0 + 4.03$)

2.2 DTC.

The DTC is a hull design of a 14,000 TEU container ship, developed at the Institute of Ship Technology, Ocean Engineering and Transport Systems (Duisburg-Essen, Germany), for benchmarking and validation of numerical methods (el Moctar et al., 2012). The DTC is a single screw vessel with a bulbous bow and a large bow flare. The captive tests are performed bare hull (absence of movable part of the rudder and propeller). For the appended free running tests the model is equipped with a fixed-pitch five-bladed propeller with right rotation and a twisted rudder with a Costa bulb. The first set of parameters is hull form specific (Table 1), the second set is a function of the loading condition of the ship (Table 2).

Table 1. Ship particulars: general.

Particular	Full scale	Model scale
Scale [-]	1	1:89.11
L_{PP} [m]	355.0	3.984 ± 0.001
B [m]	51.0	0.572 ± 0.001
T_{design} [m]	14.5	0.163 ± 0.001
C_B [-]	0.661	0.661

Table 2. Ship particulars: loading specific parameters.

Particular	Captive	Free-running
m [kg]	242.8 ± 0.2	243.5 ± 0.2
x_G [m]	-0.052 ± 0.002	-0.049 ± 0.002
z_G [m]	-0.059 ± 0.003	-0.059 ± 0.003
I_{xx} [kgm²]	12 ± 1	16 ± 1
I_{yy} [kgm²]	221 ± 1	273 ± 2
I_{zz} [kgm²]	230 ± 1	356 ± 2
$\overline{GM}$ [m]	0.058 ± 0.003	0.055 ± 0.003

3 BENCHMARK TESTS

Ten model tests have been selected: eight captive model tests and two tests in free running mode. The captive model tests, which were all performed with the bare hull only, can be subdivided into three calm water tests and five tests in waves. The three captive model tests in calm water are presented in Table 3. Appendix 1 presents the time series of all measured variables during these captive tests.

Table 3. Benchmark tests: captive tests with the bare hull in calm water.

	Velocity		
Test ID	Model scale [m/s]	Full scale [kts]	UKC [%]
C1; C2	0.327 ; 0.872	6 ; 16	100
C3	0.327	6	20

A description of the captive tests in waves is given in Table 4. The free running tests in waves are given in Table 5. The variables logged during the free running tests are given in Appendix 2. The wave height and wave period are function of time and position in the towing tank. This is discussed in Section 4.

Table 4. Benchmark tests: Captive tests with the bare hull in waves.

	Velocity		Environment	
Test ID	Model scale [m/s]	Full scale [kts]	UKC [%]	λ_{theo}/L_{PP} [-]
CW1; CW2 ; CW3	0 ; 0.327 0.872	0; 6; 16	100	0.55
CW4; CW5	0 ; 0.327	0; 6	20	0.55

Table 5. Benchmark tests: Free running wave tests.

	Velocity		Environment	
Test ID	Model scale [m/s]	Full scale [kts]	UKC [%]	$\lambda_{\mathrm{theo}}/L_{\mathrm{PP}}$ [-]
FW1	0.327	6	100	0.55
FW2	0.872	16	100	0.40

4 WAVE PROPAGATION IN THE TANK.

Performing model tests in waves requires a thorough investigation of the wave propagation through the tank. The steadiness of the wave pattern as a function of position and time is deemed important.

4.1 WAVE CLIMATE AS A FUNCTION OF POSITION

To verify the main wave characteristics along the tank, the wave profiles obtained at WG1 and WG2 have been further investigated by fitting a Fourier series up to the third order with the eight parameters a_0, a_1, a_2, a_3, b_1, b_2, b_3, and ω.

$$\zeta = a_0 + \sum_{j=1}^{3} \left[a_j \cos(j\omega t) + b_j \sin(j\omega t) \right] \qquad (1)$$

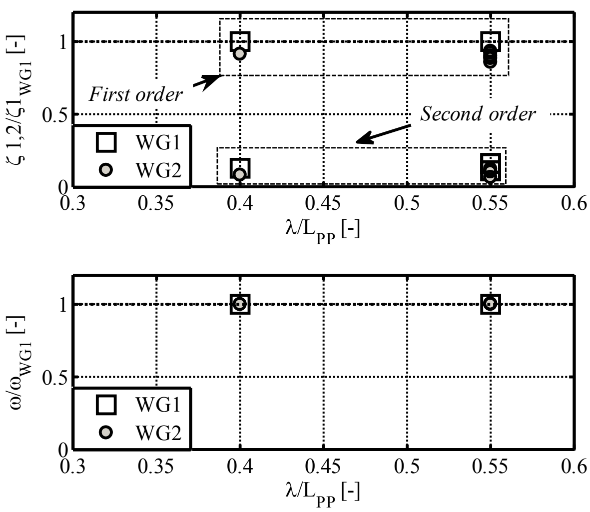

Figure 2. Regular waves at WG1 and WG2. Non-dimensional first and second order harmonics (top) and wave frequency (bottom).

The results shown in Figure 2 are presented dimensionless. For the wave amplitudes, the first and second order amplitudes (ζ_1 and ζ_2) are divided by the first order amplitude at WG1. The wave frequency (ω) is divided by the wave frequency measured at WG1. Third order magnitudes (ζ_3) have been excluded because they are relatively small. It is worth mentioning that from the regression analysis, a relative high R^2 has been found for all tests, with a lowest value of $\mathrm{R}^2 = 0.98$ obtained at WG2 for the CW5 test.

From the results presented in Figure 2, it can be observed that the wave amplitudes for both the first and the second order harmonics present slightly different magnitudes at WG1 and WG2 (see Figure 2 top), while the wave frequencies (see Figure 2 bottom) show a better agreement and remain approximately the same along the tank. Thus, the limited discrepancies observed in the wave parameters at WG1 and WG2 guarantee that the wave along the tank can be considered as steady and regular.

4.2 WAVE CLIMATE AS A FUNCTION OF TIME

The variability in wave heights measured at one gauge is investigated using the readings at WG2, as they are the most representative for the wave climate which the ship encounters during the regime condition (see Section 5). For all the wave tests, the wave height, calculated based on maximum and minimum surface elevations, and zero up-crossing period, are determined. The mean and standard deviation are calculated based on 15 wave cycles, using equation 2.

$$\mu_z = \sum_{i}^{N} Z_i \quad ; \quad \sigma_z = \sqrt{\sum_{i}^{N} \frac{(Z_i - \mu_z)^2}{N_z - 1}} \qquad (2)$$

Table 6 shows that the deviation of the wave height as a function of time is limited. The period of the measured wave can be seen as invariant. The wave climate for CW4 and CW5 is moderate, as larger waves cause bottom touch at 20% UKC.

Table 6. Measured wave height (*H*) and wave period (*T*) at gauge 2, based on 15 cycles.

ID	$\mu_H \pm \sigma_H$ [mm]	$\mu_T \pm \sigma_T$ [s]
CW1	54.49 ± 1.96	1.38 ± 0.01
CW2	62.31 ± 0.95	1.38 ± 0.01
CW3	62.35 ± 0.64	1.38 ± 0.01
CW4	22.21 ± 0.33	1.66 ± 0.02
CW5	21.26 ± 0.31	1.66 ± 0.03
FW1	56.92 ± 0.51	1.39 ± 0.01
FW2	60.72 ± 1.12	1.09 ± 0.01

5 CAPTIVE WAVE MODEL TESTS (CW)

5.1 MEASURED TIME SERIES.

The logged data, at 40 Hz, is available on request for all captive tests, except for the semi-blind captive wave tests at 6 knots (i.e. CW2 and CW5), for which only the carriage position, wave gauge readings and the wave maker position as a function of time are given. Appendix 1 gives an overview of the time series which are delivered. Appendix 3 shows the time series, averaged over 0.25 s for visualization purposes.

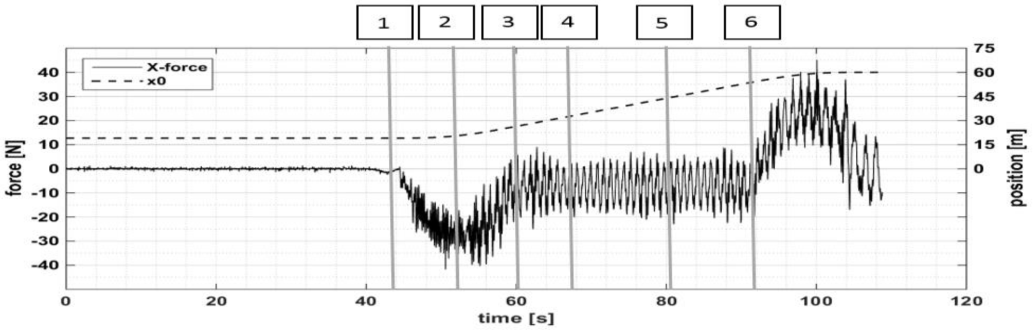

Figure 3. Time series X-force (sum two load cells LC1 and LC2) and longitudinal ship position as a function of time [test CW3, see Table 3].

Testing the ship in waves complicates the post-processing of the times series. Figure 3 shows the logged X-force and longitudinal ship position in the tank, as a function of time, during the execution of a captive wave test. Six vertical lines denote key moments during the execution of the test. For these six transitions, the longitudinal tank position (x_0) and the corresponding time (t) are also included in Appendix 1.

Vertical line 1 indicates the start of the acceleration phase, at position $x_{0acc,start}$ and time $t_{acc,start}$. The meeting between ship and the initial waves is indicated by line 2 (x_{0wave}, t_{wave}). The end of the acceleration phase is denoted by line 3 ($x_{0acc,end}$, $t_{acc,end}$). The meeting with the first waves can be during the acceleration phase (as in Figure 3) or after sailing in calm water for a certain time (Figure 4). This depends on the optimal parameter selection in order to obtain the longest steady interval for sailing in waves (Section 5.3). When the ship meets the waves, a transition zone exists before the ship shows a steady behaviour ($x_{0reg,start}$, $t_{reg,start}$) (line 4). Due to the presence of the beach and the wave maker, the intended regular wave pattern is disturbed because of reflections ($x_{0reg,end}$, $t_{reg,end}$) (line 5). Line 6 shows the start of the deceleration phase of the vessel (x_{0dec}, t_{dec}).

5.2 UNCERTAINTY IN THE TIME SERIES.

The uncertainty of the measured time series has to be known to achieve a good interpretation of the model tests. Forces and motions are registered during the execution of captive model tests, using eight measuring devices (see Figure 1). Four loads cells measure the forces in the horizontal plane (X and Y at two positions) and four potentiometers (Figure 1a) measure the vertical motion of the vessel.

The contribution to the uncertainty due to the precision of the load cells and potentiometers is determined based on the output of 26 model tests, performed with the DTC corresponding to 6 knots full scale at 100% and 20% UKC. Although the ship model encounters waves during these tests, there is a sufficiently long time window present during which the ship sails at a steady state in calm water before encountering any waves. The selection of this time window is shown in Figure 4. The average of the load cell readings is calculated within the calm water condition for each of the 26 model tests. Equation 2 is used to calculate the mean μ and standard deviation σ of the sample.

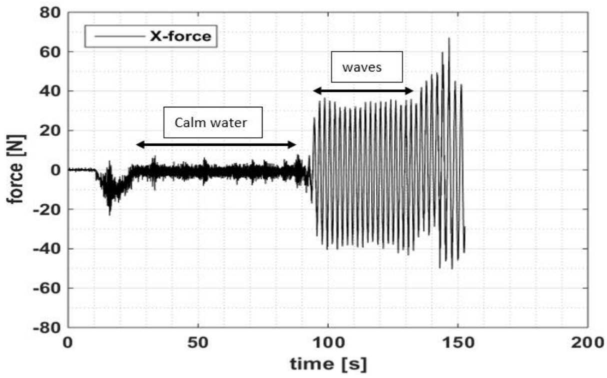

Figure 4. X-force (sum two load cells LC1 and LC2) during captive, bare hull wave test with the DTC at 6 knots, 100% UKC (λ/L_{PP} = 1.00).

Both X-force load cells are mounted on the same beam which connects the ship model with the carriage. This means that both X-force load cells influence each other (due to a hyperstatic configuration). Not only does it cause noise in the signal, it also means that the individual cell readings have no physical meaning. Only the mean and standard deviation of the sum of both readings are thus relevant. As the tests are performed in head waves, the lateral forces are primarily caused by waves reflecting off the tank's side walls (see also Section 5.3). These forces are not discussed here. Table 7 gives the results for the two series of model tests.

Table 7. Mean load cell and potentiometer readings with associated standard deviation, based on model tests performed with the DTC at 6 knots, 26 tests at 100% UKC and 26 tests at 20% UKC.

	100% UKC		20% UKC	
Variable	$\mu_z \pm \sigma_z$	σ_z/μ_z	$\mu_z \pm \sigma_z$	σ_z/μ_z
X	-0.86 ± 0.02 N	0.02	-1.05 ± 0.05 N	0.05
P1	0.79 ± 0.04 mm	0.05	1.53 ± 0.08 mm	0.05
P2	0.75 ± 0.03 mm	0.04	1.48 ± 0.08 mm	0.05
P3	0.69 ± 0.03 mm	0.04	1.45 ± 0.06 mm	0.04
P4	0.69 ± 0.03 mm	0.04	1.41 ± 0.06 mm	0.04

Table 8. Mean value and standard deviation for motions, derived from the individual potentiometer readings P1 to P4, based on model tests performed with the DTC at 6 knots, 26 tests at 100% UKC and 26 tests at 20% UKC.

	100% UKC		20% UKC	
	$\mu_f \pm \sigma_f$	σ_f/μ_f	$\mu_f \pm \sigma_f$	σ_f/μ_f
heave	0.73 ± 0.02 mm	0.03	1.47 ± 0.03 mm	0.02
trim	-0.04 ± 0.01 mm/m	0.25	-0.03 ± 0.03 mm/m	1.00
roll	-2.43E-03 ± 5.93E-05°	0.02	-4.34E-03 ± 1.19E-05°	0.00
z_{VF}	0.80 ± 0.04 mm	0.05	1.53 ± 0.08 mm	0.05
z_{VA}	0.66 ± 0.03 mm	0.05	1.40 ± 0.06 mm	0.04

The uncertainty on the mean of the X-force reading is important to evaluate the added wave resistance. For tests at 100% UKC, the average measured calm water resistance is 0.86 N. In waves, for a ratio $\lambda_{\text{theo}}/L_{PP}$ equal to 0.90 (not included as benchmark), the total average resistance measured during the steady state condition (region between line 4 and 5 in Figure 3) is 2.06 N. Thus, the added resistance due to wave action is 1.20 N ± 0.03 N, assuming the deviation is constant. The obtained value of added resistance can thus be seen as significant with regard to the standard deviation on the load cell readings.

The tests at 20% UKC, however, have been performed with smaller wave heights, which leads to smaller magnitudes for the added wave resistance. The calm water resistance is 1.05 N ± 0.05 N, whereas the added resistance in waves is 0.15 N ± 0.07 N ($\lambda_{\text{theo}}/L_{PP}$ = 0.75). The obtained value for the added resistance is only twice the standard deviation.

Based on the potentiometers (P1 to P4), the uncertainty on the derived heave, trim, roll and the running sinkages at fore and aft perpendicular (z_{VF} and z_{VA}) (see delivered time series), can be calculated. The trim is defined in equation 3 (positive bow up)

$$\text{trim} = \frac{z_{VA} - z_{VF}}{L_{\text{PP}}} \left[\frac{\text{mm}}{\text{m}}\right] \tag{3}$$

Because of uncertainty in the position of the potentiometers and length of the vessel (see Table 1), the standard deviation is calculated with the uncertainty propagation method, using equation 4. Cross correlation between the variables is neglected. The lateral as well as the longitudinal position of the potentiometers comes with an uncertainty of ± 1 mm, as does the length of the vessel. The results are given in Table 8.

$$\begin{aligned} \text{f} &= \text{f}(\text{x}_1, \dots, \text{x}_i, \dots, \text{x}_n) \\ \mu_\text{f} &= \text{f}(\mu_1, \dots, \mu_i, \dots, \mu_n) \\ \sigma_\text{f} &= \sqrt{\sum_{i=1}^{n} \left(\frac{\partial \text{f}}{\partial \text{x}_i}\right)^2 \cdot \sigma_{\text{x}i}{}^2} \end{aligned} \tag{4}$$

5.3 SELECTION OF THE STEADY STATE TIME WINDOW.

ITTC (2014) recommends performing model tests with a ship model in waves in absence of wave reflection and tank side wall interaction. It is advised to reach a minimum of 10 oscillation cycles at steady condition, where the amplitude and period of oscillations are constant. Transition zones in the time records should be avoided.
The above general recommendations are mostly suited for deep water tanks, where solutions to the problem of tank side wall interaction in wave tests can be simply achieved by choosing realistic ship forward speeds higher than a critical one defined in the ITTC recommendations (ITTC, 2014). In contrast with deep water, tests in shallow water are additionally restrained by problems such as bow wave generation, and squat effects which increase significantly the bottom touch probability.

Testing the ship in a restrained scenario is then a challenging task to achieve. At FHR, studies have been conducted to limit these problems (Tello Ruiz et al., 2015; Tello Ruiz et al., 2016). The ship tests in waves have been designed to obtain a time window characterised by:

- steady forward speed of the ship;
- absence of reflections from the beach;
- steady wave climate;
- minimised tank side wall reflection.

From all the complications mentioned above, the tank side wall interaction is the most challenging. Waves radiated by the ship are reflected by the tank side wall back to the ship, hence, altering the desired wave exciting condition. By selecting wave frequencies that lie outside the heave/roll/pitch resonance frequencies, together with choosing wave amplitudes of moderate magnitudes, tank side wall interaction can be further restricted. A more recent study (Tello Ruiz et al., 2017) on tank side wall interaction reveals that such magnitudes are rather small and can be neglected for moderate wave amplitudes. When comparing the model test results to calculation methods it is highly recommended to include the tank side walls.

6 FREE RUNNING MODEL TESTS (FW)

In self-propelled free running model tests, the vessel uses its own propeller and rudder to sail through the towing tank, whilst the carriage mechanism follows the ship and records the position of the ship as well as propeller and rudder readings. For the present benchmark data, two free running tests are selected (see Table 5). With respect to the safety of the vessel in harsh weather conditions, it is valuable to know the speed loss when sailing in head seas. In order to determine this speed loss, the calm water velocity as a function of the propeller rate (revolutions per second) is determined. Free running tests in waves are performed at a rotational speed by which the velocities corresponding to 6 knots and 16 knots full scale are achieved. The straight course in waves is guaranteed using a PID controller, which controls the rudder based on a feedback system.

6.1 MEASURED TIME SERIES.

All logged time series for the test corresponding to 16 knots at full scale (test FW2, see Table 5) are given in ASCII format. For the test corresponding to 6 knots at full scale (FW1), only the wave gauge readings, wave maker position and the position and velocity of the vessel, are given. The variables which are given in the time series, with their respective units, are presented in Appendix 2. The time series averaged over 0.25 s, are given in Appendix 3. During the free running test, the ship is decoupled from the towing carriage (see Figure 1 b). The latter follows the ship model throughout the test, with a precision of ± 1.4 mm.

As the tests are self-propelled, propeller (rpm, thrust and torque) and rudder (deflection, X-force rudder, Y-force rudder and torque) are recorded (at 40 Hz) during the entire test.

As for the captive tests in waves, the time series can be split in various zones, using six vertical line indicators, which correspond again with a time and towing tank position (see Figure 5). Line 1 indicates the start of the acceleration of the ship model, which is done in captive mode ($x_{0acc,start}$, $t_{acc,start}$). The captive acceleration ends and the ship is released at line 2, the position $x_{0acc,end}$ and time $t_{acc,end}$. The target regime velocity of the free running test FW2 corresponds to 16 knots full scale, or 0.872 m/s model scale. The velocity after captive acceleration is 0.800 m/s. Line 3 indicates the meeting between ship and waves (x_{0wave}, t_{wave}). In between line 3 and 4, there is a transition zone for motions and forces. At line 4 ($x_{0reg,start}$, $t_{reg,start}$), the speed slightly increases to end up with a steady velocity of about 0.872 m/s. The wave maker and the beach both cause reflective waves which travel back to the ship. Line 5 indicates the position and time when the wave pattern is no longer free of reflections ($x_{0reg,end}$, $t_{reg,end}$). The end of the free running phase is indicated by the sixth vertical line (x_{0dec}, t_{dec}).

6.2 CALM WATER SELF-PROPULSION TESTS.

The speed loss in waves can only be estimated, if the corresponding calm water velocity of the vessel at the given propeller rate is known. In order to obtain this reference, six self-propelled calm water tests have been performed. The tests are listed in Table 9. In this table, the attained forward speed in steady condition is given together with the measured propeller rate. The ratio of the vessel's forward speed and the angular velocity of the propeller is constant for all self-propelled tests. Calculating velocities at intermediate rotational speeds can thus be performed using linear interpolation.

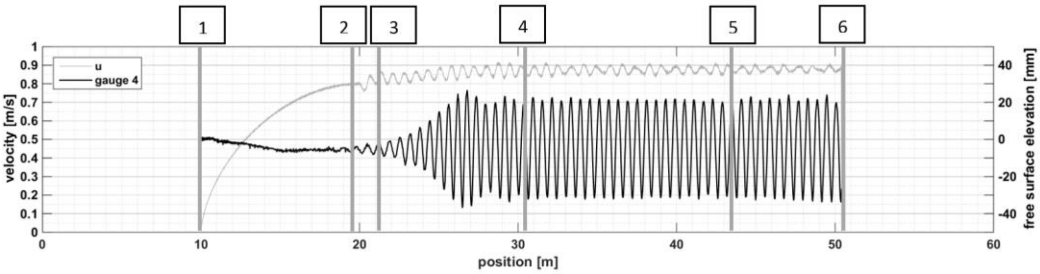

Figure 5. Longitudinal component velocity and WG4 readings as a function of longitudinal position in the towing tank [test FW2, see Table 5]

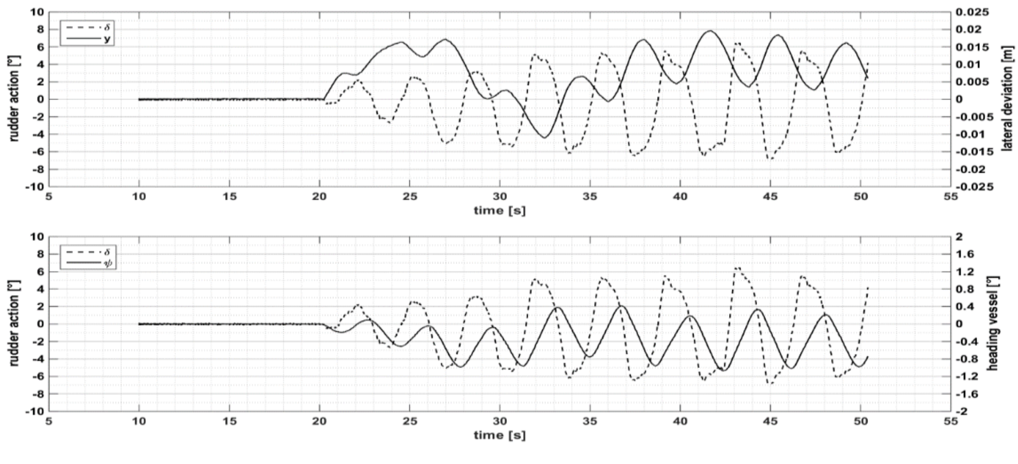

Figure 6. Performance autopilot for self-propelled test in waves [test FW2, see Table 5].

Table 9. Self-propelled calm water tests performed with the DTC at 100% UKC.

n_{theo}/n_{max} [%]	n [rps]	u [m/s]	u/n [m/(s.rps)]
30	4.93	0.315	1.07E-03
40	6.56	0.439	1.12E-03
50	8.19	0.562	1.14E-03
65	10.63	0.741	1.16E-03
75	12.27	0.849	1.15E-03
85	13.90	0.973	1.17E-03

6.3 PERFORMANCE OF THE PID CONTROLLER

A PID controller is used to steer the rudder to follow an intended course. The PID system is tested to its limits in high and/or long waves, as there are drift forces (direct wave action / reflections form side wall) which cause the vessel to deviate from its desired path. An extensive testing phase was needed to tune the PID coefficients to react appropriately to the feedback information provided by the towing carriage. The main objectives were ensuring that the deviation (lateral position of the CoG and yaw motion) is limited and the rudder deflection (δ_R) and its time derivative ($\dot{\delta}_R$) are within the limits of normal operations on full scale vessels. An example of the PID-controlled course as a function of the vessel's longitudinal tank position is given in Figure 6.

7 CONCLUSIONS

The Knowledge Centre Manoeuvring in Shallow and Confined Water has selected model test data which were obtained during the execution of seakeeping tests with the DTC container carrier in the framework of the European SHOPERA project, to open a joint research effort on the validation and verification of different research methods. The paper discusses eight captive (bare hull) and two free running benchmark tests, carried out in the Towing Tank for Manoeuvres in Shallow Water (cooperation Flanders Hydraulics Research – Ghent University), at two under keel clearances: 100% and 20% of the ship's draft.

As seven of the ten tests were performed in waves, the propagation of the waves through the tank is discussed. The influence of position and time on the measured wave pattern is presented based on Fourier analysis and an uncertainty analysis of the wave height and period. The tests at 20% UKC are performed with limited wave heights to avoid bottom touch.

The measured time series for captive and free running model tests are given in Appendix 1 and 2, respectively. For the tests performed at 0.327 m/s (6 knots full scale - CW2, CW5 and FW1), only the wave gauge readings, the wave maker position and the vessel's position and velocity components are disclosed. For the other tests, the entire time series are made available upon request, including acceleration and deceleration phase of the vessel. For both captive and free running tests, the typical time series is discussed, indicating six key moments in the series.

Captive tests are further elaborated on by investigating the uncertainty in the load cell and potentiometer readings and summarising the available knowledge concerning the selection of the steady state time window in waves.

The free running tests are performed to map the speed loss when sailing in waves. In order to do this, six self-propelled tests in calm water were performed with increasing propeller rate, to obtain the calm water velocity as a function of the propeller angular velocity. A PID controller is used to correct deviations from the desired (straight) course. The followed course and rudder angles are given for test FW2.

The benchmark data are digitally available upon request at info@shallowwater.be.

8 ACKNOWLEDGEMENTS

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Guillaume Delefortrie, PhD, naval architect, is expert nautical researcher at Flanders Hydraulics Research. He is in charge of the research in the Towing Tank for Manoeuvres in Confined Water and the development of mathematical models based on model tests. He has been secretary of the 27th and 28th ITTC Manoeuvring Committee and is chairman of the 29th ITTC Manoeuvring Committee.

Evert Lataire, PhD, naval architect, is currently post doctoral assistant at the division of Maritime Technology at Ghent University. He has written a PhD on the topic of bank effects mainly based upon model tests carried out in the shallow water towing tank of FHR. His fifteen year experience includes research on ship manoeuvring in shallow and confined water such as ship-ship interaction, ship-bottom interaction and ship-bank interaction.

APPENDIX 1 : CAPTIVE MODEL TESTS.

Table 10. Time series given in ASCII output files captive model tests in waves.

variable	unit	Description
time	s	
x_0	m	Long. position ship model
y_0	m	Trans. position ship model
psi	°	Course angle vessel
u	m/s	Long. velocity component
heave	mm	Mean sinkage of the ship
trim	mm/m	Trim motion
roll*	°	Roll motion
	Nm	Roll moment
z_{VF}	mm	Sinkage fore pp, centreline
z_{VA}	mm	Sinkage aft pp, centreline
X	N	Surge force
Y	N	Sway force
N	Nm	Yaw moment
WG1	mm	Free surface elevation WG1
WG2	mm	Free surface elevation WG2
WG3	mm	Free surface elevation WG3
WG4	mm	Free surface elevation WG4
Δx_{0WM}	mm	Position wave maker

* During calm water captive tests, the roll moment is measured, in Nm. During the wave tests, the roll motion is obtained.

Table 11. Longitudinal position and time indication captive model tests in waves with 100% UKC.

	Test CW1		Test CW2		Test CW3	
Zone	**x_0 [m]**	**t [s]**	**x_0 [m]**	**t [s]**	**x_0 [m]**	**t [s]**
acc,start	/	/	4.0	10.1	19.0	44.1
acc,end	/	/	6.5	25.1	25.5	59.1
wave	36.0	36.8	28.6	92.8	19.1	47.0
reg,start	36.0	51.0	33.2	106.9	29.4	63.5
reg,end	36.0	72.6	40.6	129.6	43.1	79.2
dec	/	/	43.6	138.6	53.7	91.4

Table 12. Longitudinal position and time indication captive model tests in waves with 20% UKC.

	Test CW4		Test CW5	
Zone	**x_0 [m]**	**t [s]**	**x_0 [m]**	**t [s]**
acc,start	/	/	4.0	10.1
acc,end	/	/	6.5	25.1
wave	35.0	40.8	26.8	87.3
reg,start	35.0	58.4	31.8	102.5
reg,end	35.0	86.9	38.5	123.0
dec	/	/	44.6	141.6

APPENDIX 2 : FREE RUNNING MODEL TESTS.

Table 13. Time series given in ASCII output files free running model tests in waves.

variable	unit	Description
time	s	
x_0	m	Long. position ship model
y_0	m	Trans. position ship model
psi	°	Course angle vessel
u	m/s	Long. velocity component
v	m/s	Trans. velocity component
heave	mm	Mean sinkage of the ship
trim	mm/m	Trim motion
roll	°	Roll motion
z_{VF}	mm	Sinkage fore pp, centreline
z_{VA}	mm	Sinkage aft pp, centreline
n	rps	Propeller rate
T_p	N	Propeller thrust
Q_p	Nmm	Propeller shaft torque
d_{rud}	°	Rudder angle
X_{rud}	N	X-comp. rudder force
Y_{rud}	N	Y-comp. rudder force
Q_{rud}	Nmm	Rudder torque
WG1	mm	Free surface elevation WG1
WG2	mm	Free surface elevation WG2
WG3	mm	Free surface elevation WG3
WG4	mm	Free surface elevation WG4
Δx_{0WM}	mm	Position wave maker

Table 14. Longitudinal position and time indications free running model tests at 100% UKC.

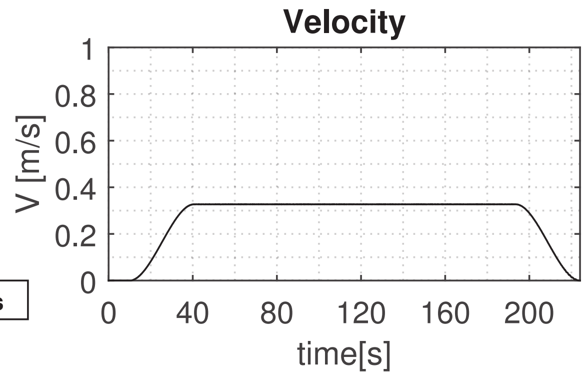
	Test FW1		Test FW2	
Zone	**x_0 [m]**	**t [s]**	**x_0 [m]**	**t [s]**
acc,start	15.0	10.1	10.0	25.1
acc,end	22.6	60.1	20.0	50.1
wave	23.8	64.3	20.9	51.1
reg,start	29.8	81.8	30.4	62.3
reg,end	40.5	114.6	48.9	83.5
dec	42.4	120.5	50.4	85.2

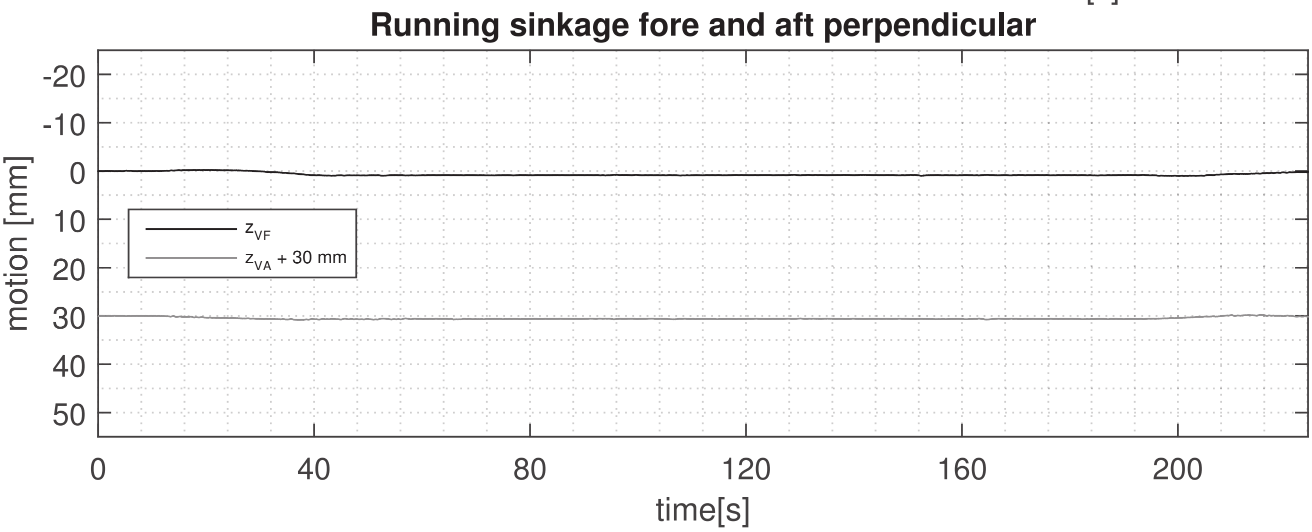
APPENDIX 3 : MODEL TEST RESULTS.

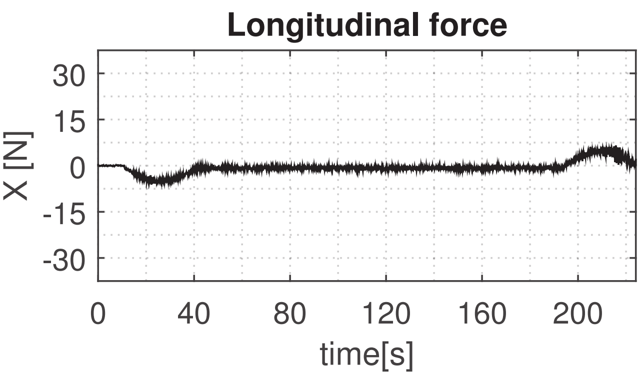
General test parameters

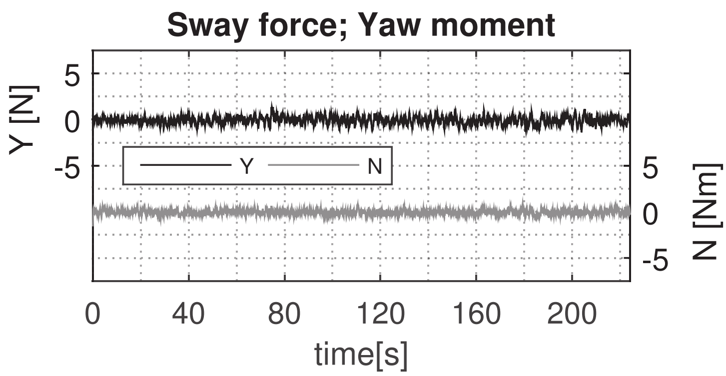
Test ID :	C1
Test mode :	Captive
Model scale velocity :	0.327 m/s
Full scale velocity :	6 knots
Under keel clearance :	100%
λ_{theo} / L_{pp} :	/
Wave height WG2 :	/
Wave period WG2 :	/

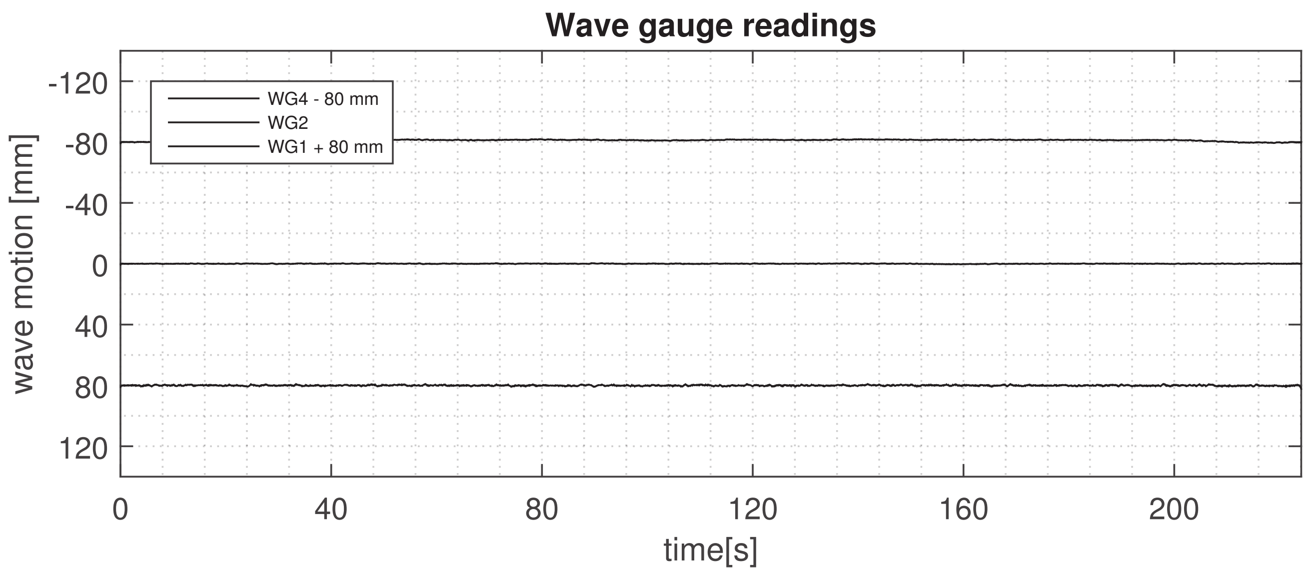
REMARK : All visualised points are averaged over :0.25 s

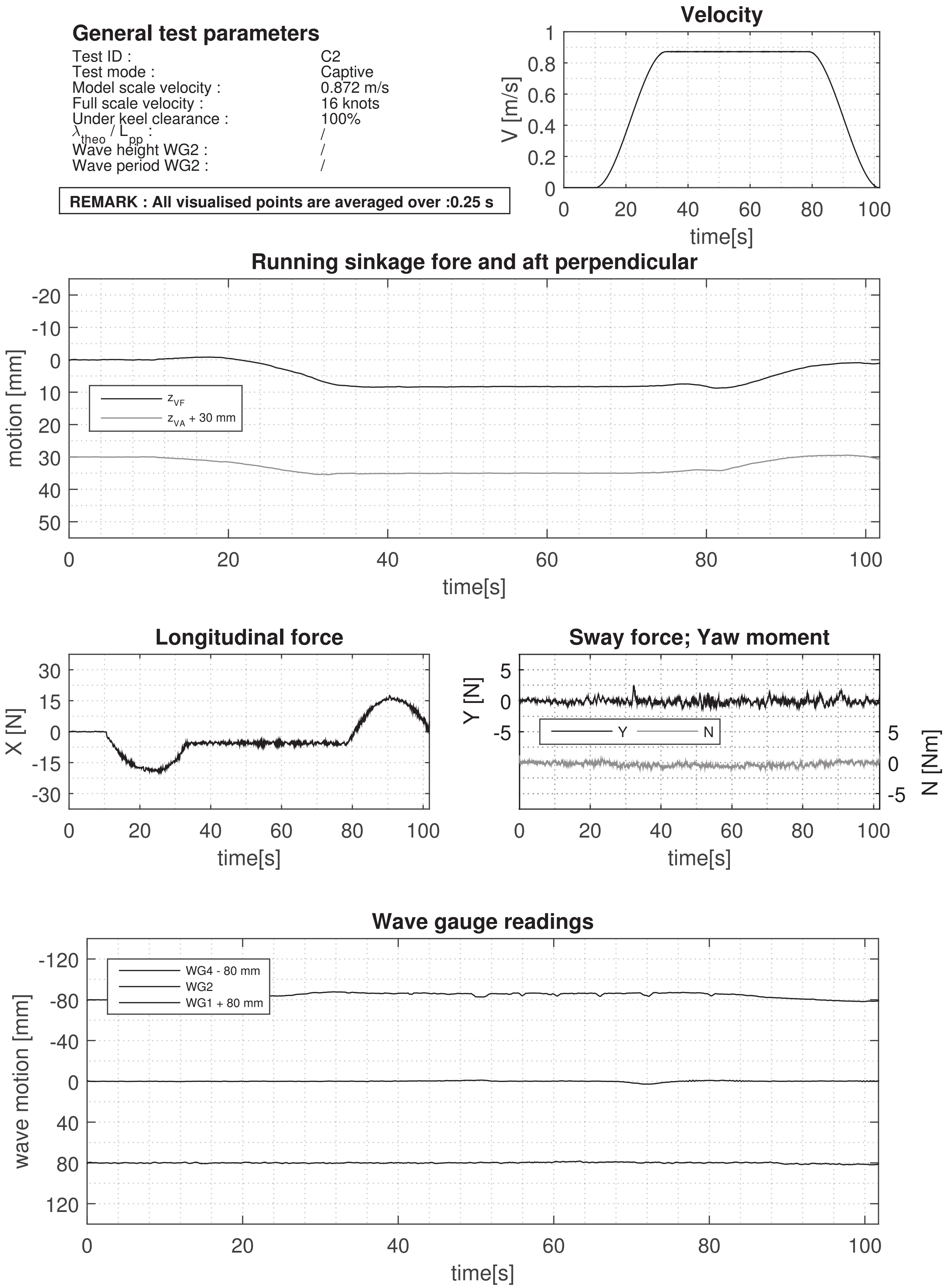








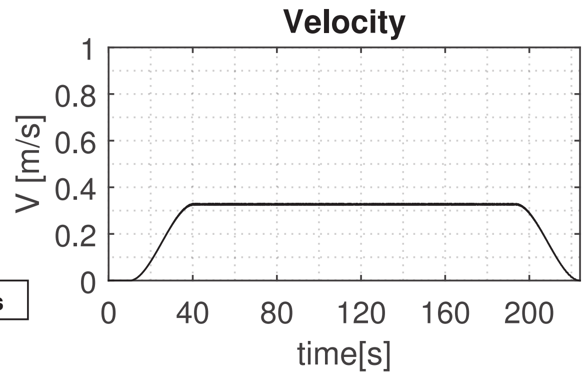


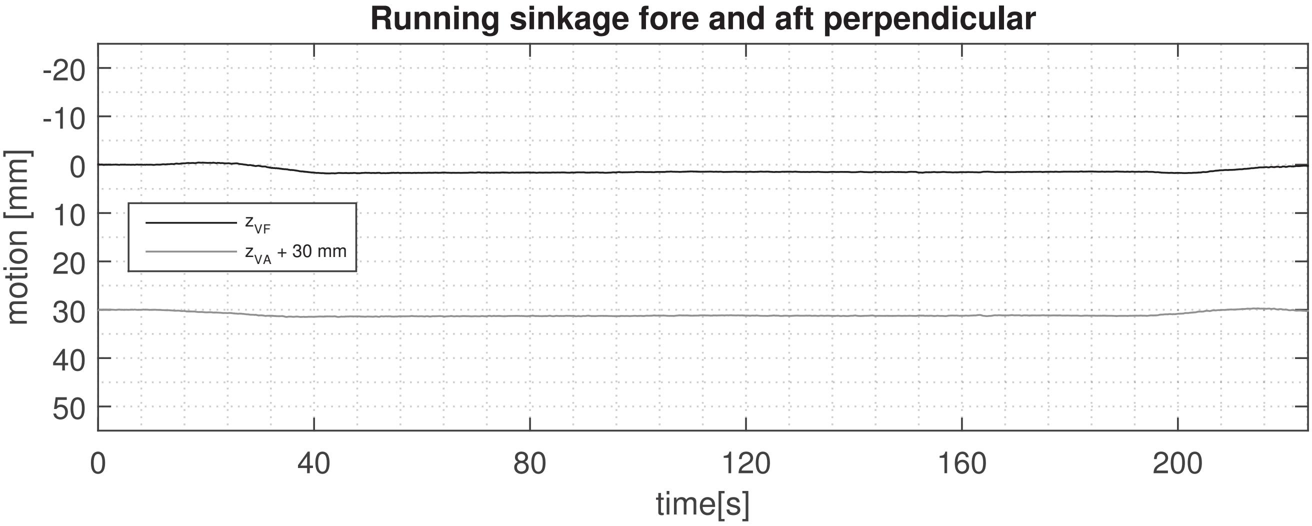

General test parameters
Test ID : C2
Test mode : Captive
Model scale velocity : 0.872 m/s
Full scale velocity : 16 knots
Under keel clearance : 100%
λ_{theo} / L_{pp} : /
Wave height WG2 : /
Wave period WG2 : /
REMARK : All visualised points are averaged over :0.25 s
Velocity
V [m/s]
time[s]
Running sinkage fore and aft perpendicular
motion [mm]
z_{VF}
z_{VA} + 30 mm
time[s]
Longitudinal force
X [N]
time[s]
Sway force; Yaw moment
Y [N]
N [Nm]
Y
N
time[s]
Wave gauge readings
wave motion [mm]
WG4 - 80 mm
WG2
WG1 + 80 mm
time[s]

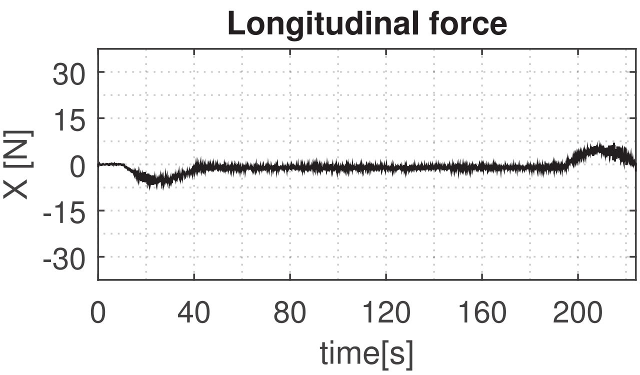
General test parameters

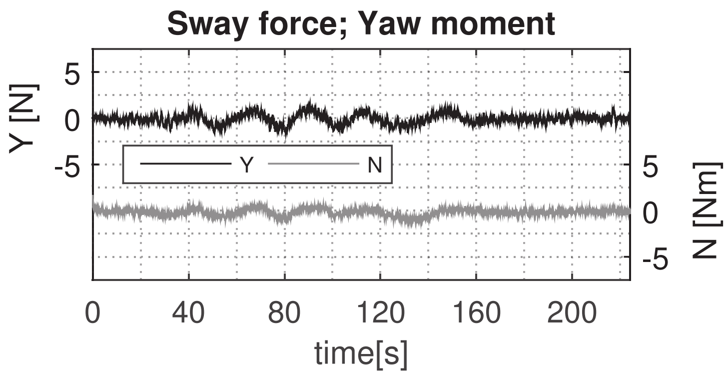
Test ID :	C3
Test mode :	Captive
Model scale velocity :	0.327 m/s
Full scale velocity :	6 knots
Under keel clearance :	20%
λ_{theo} / L_{pp} :	/
Wave height WG2 :	/
Wave period WG2 :	/

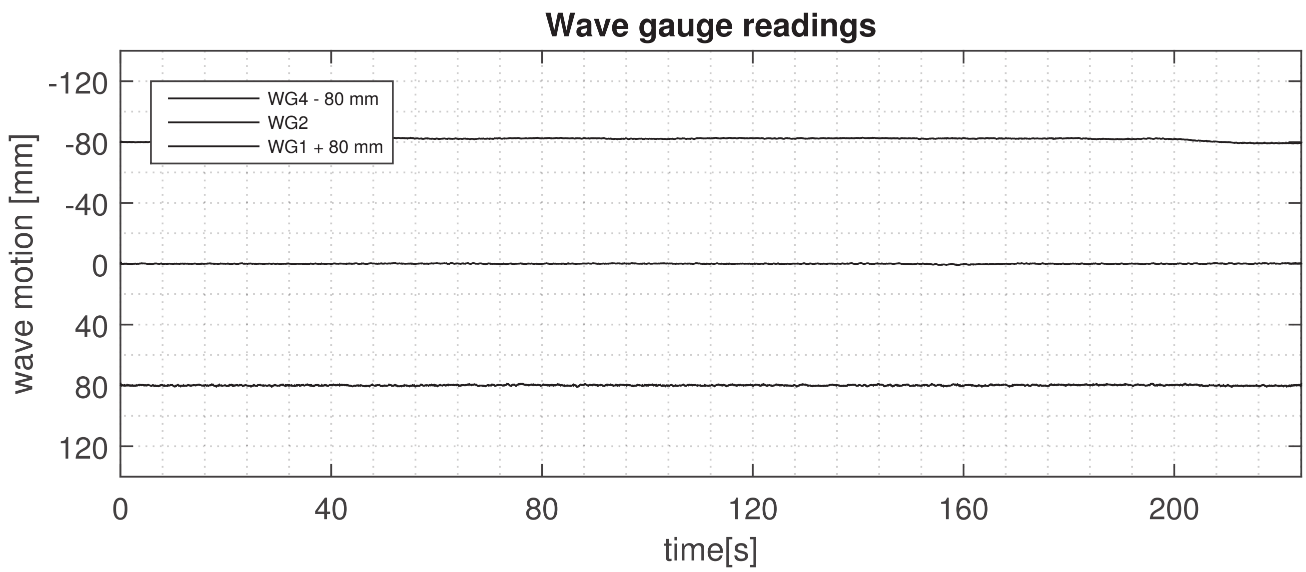
REMARK : All visualised points are averaged over :0.25 s

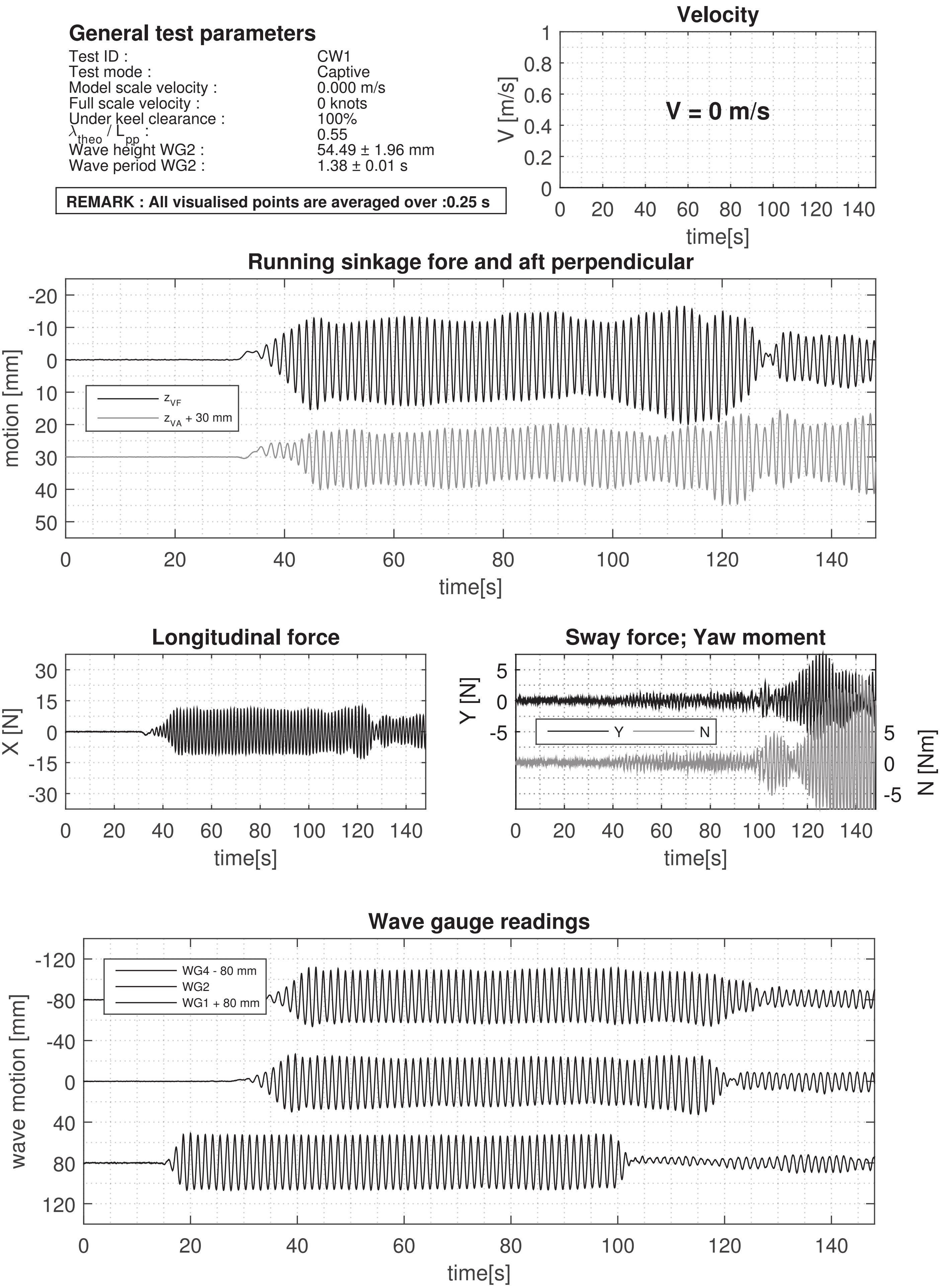








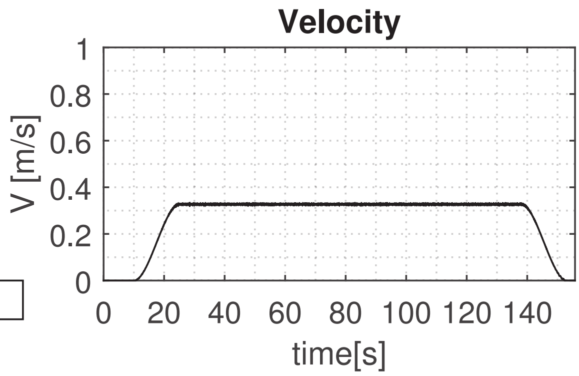


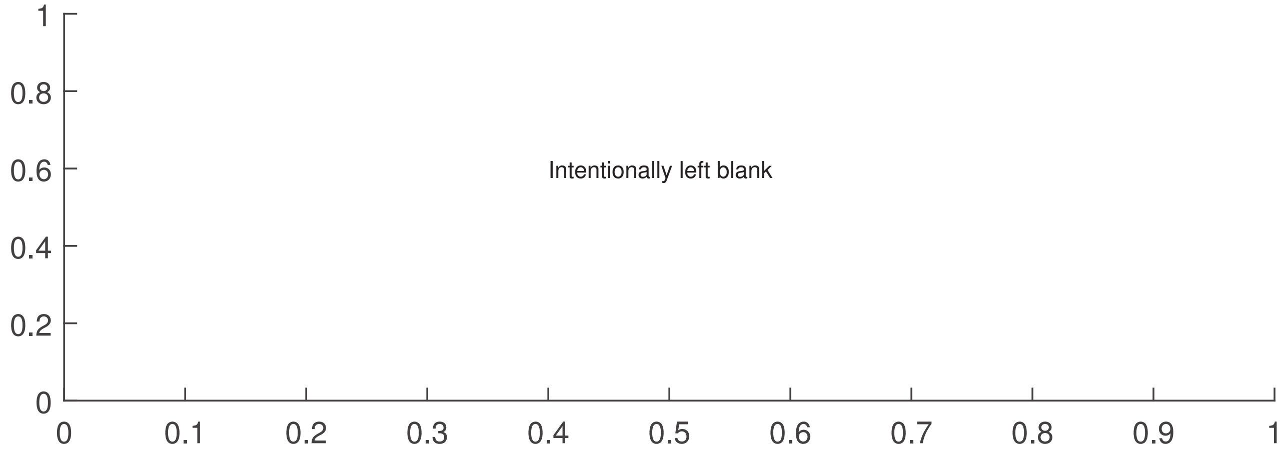

General test parameters
Test ID : CW1
Test mode : Captive
Model scale velocity : 0.000 m/s
Full scale velocity : 0 knots
Under keel clearance : 100%
λtheo / Lpp : 0.55
Wave height WG2 : 54.49 ± 1.96 mm
Wave period WG2 : 1.38 ± 0.01 s
REMARK : All visualised points are averaged over :0.25 s
Velocity
V = 0 m/s
V [m/s]
time[s]
Running sinkage fore and aft perpendicular
motion [mm]
zVF
zVA + 30 mm
time[s]
Longitudinal force
X [N]
time[s]
Sway force; Yaw moment
Y [N]
N [Nm]
Y
N
time[s]
Wave gauge readings
wave motion [mm]
WG4 - 80 mm
WG2
WG1 + 80 mm
time[s]

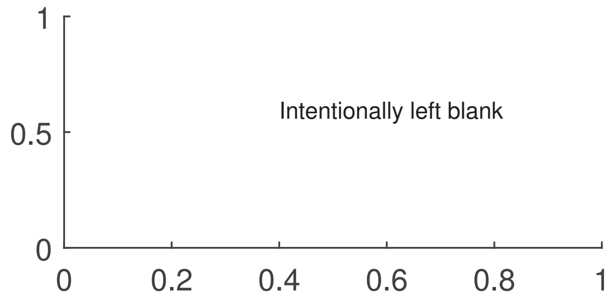
General test parameters

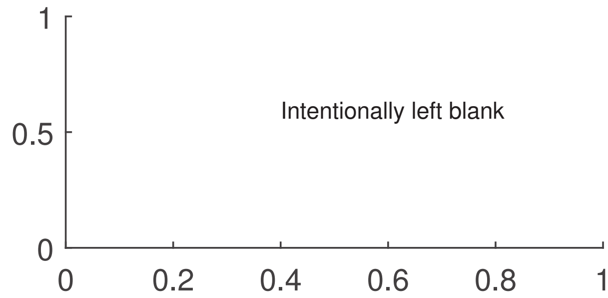
Test ID :	CW2
Test mode :	Captive
Model scale velocity :	0.327 m/s
Full scale velocity :	6 knots
Under keel clearance :	100%
λ_{theo} / L_{pp} :	0.55
Wave height WG2 :	62.31 ± 0.95 mm
Wave period WG2 :	1.38 ± 0.01 s

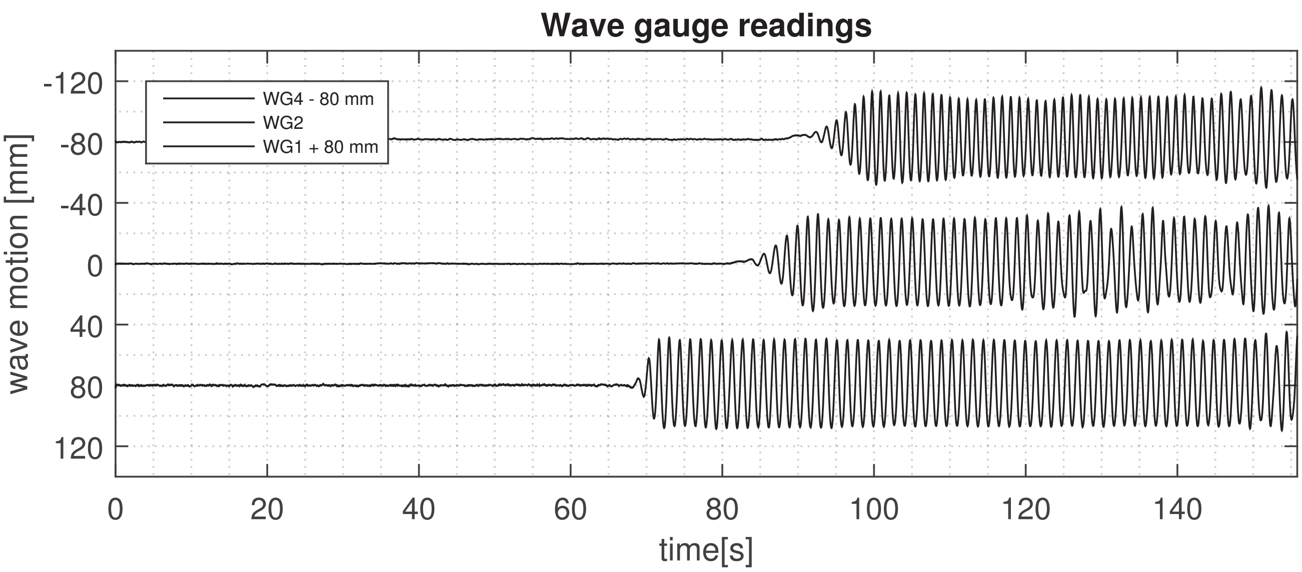
REMARK : All visualised points are averaged over :0.25 s







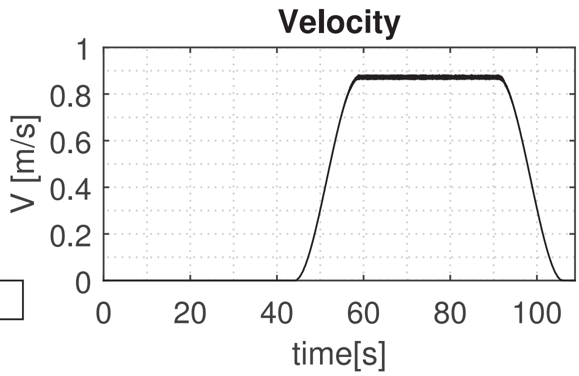


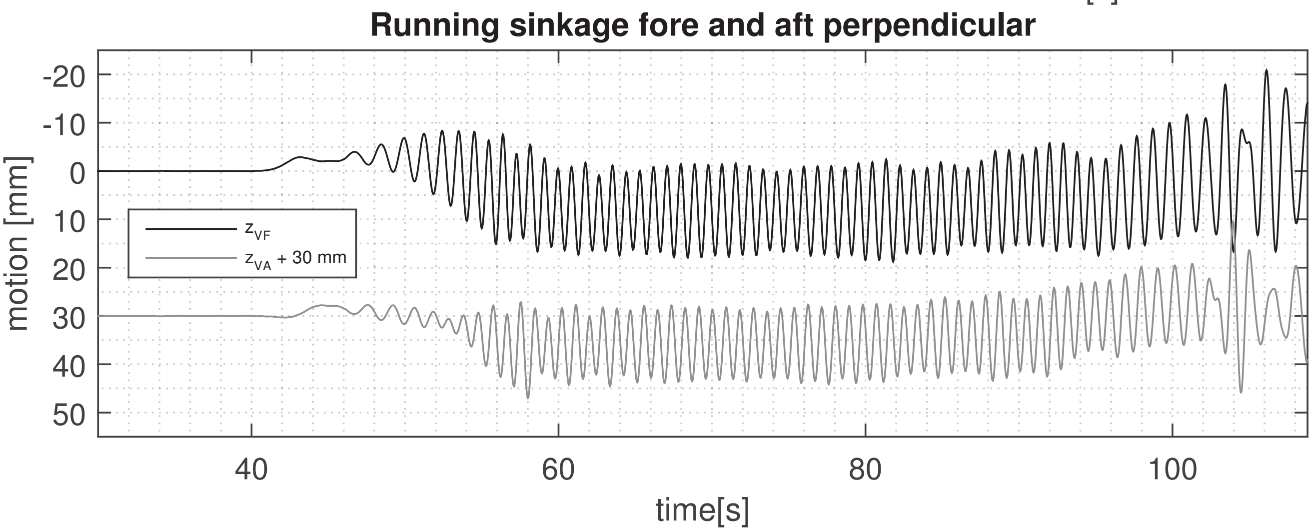


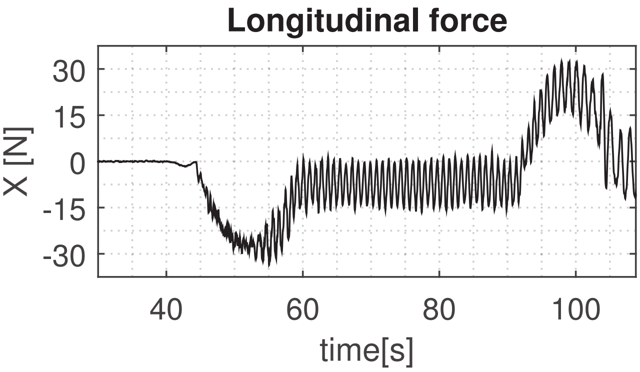
General test parameters

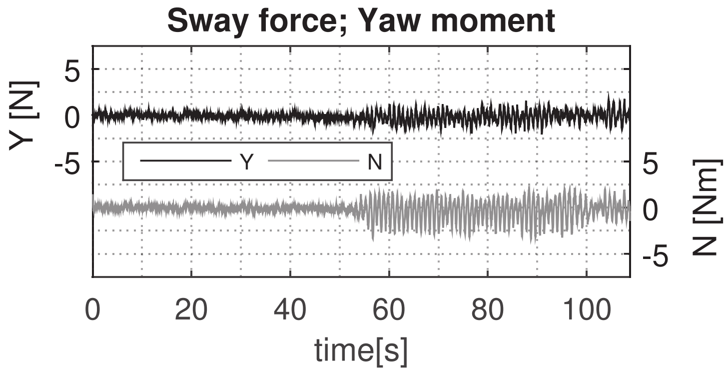
Test ID :	CW3
Test mode :	Captive
Model scale velocity :	0.872 m/s
Full scale velocity :	16 knots
Under keel clearance :	100%
λ_{theo} / L_{pp} :	0.55
Wave height WG2 :	62.35 ± 0.64 mm
Wave period WG2 :	1.38 ± 0.01 s

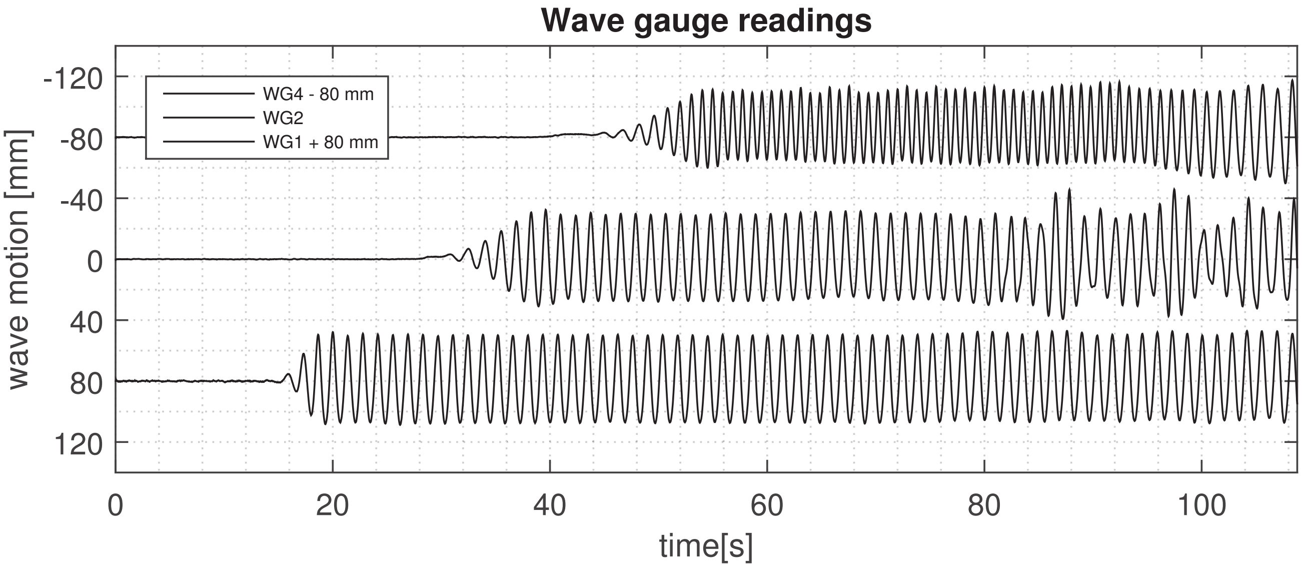
REMARK : All visualised points are averaged over :0.25 s

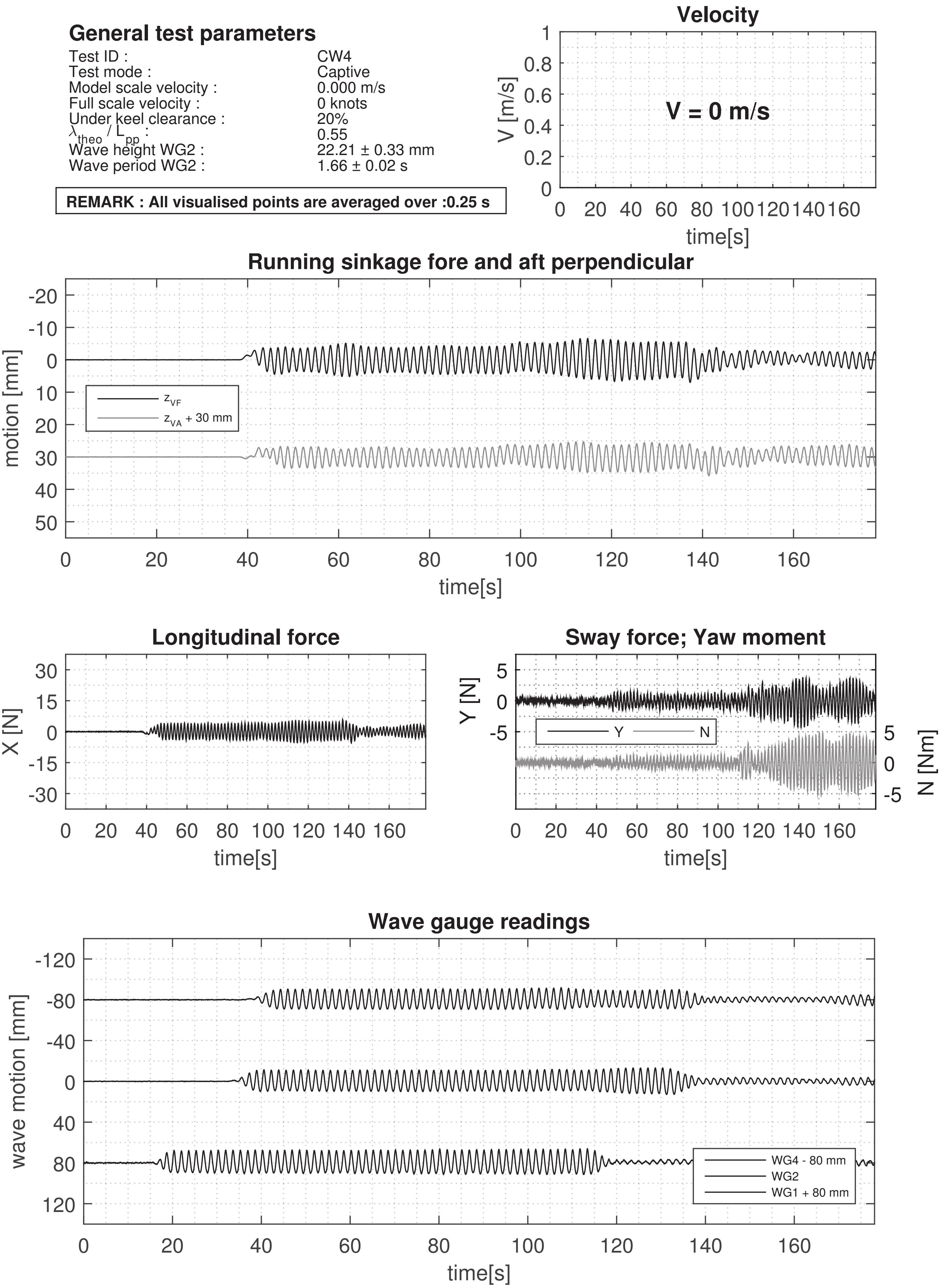








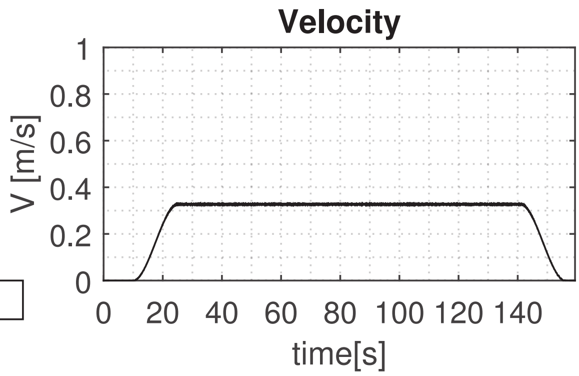


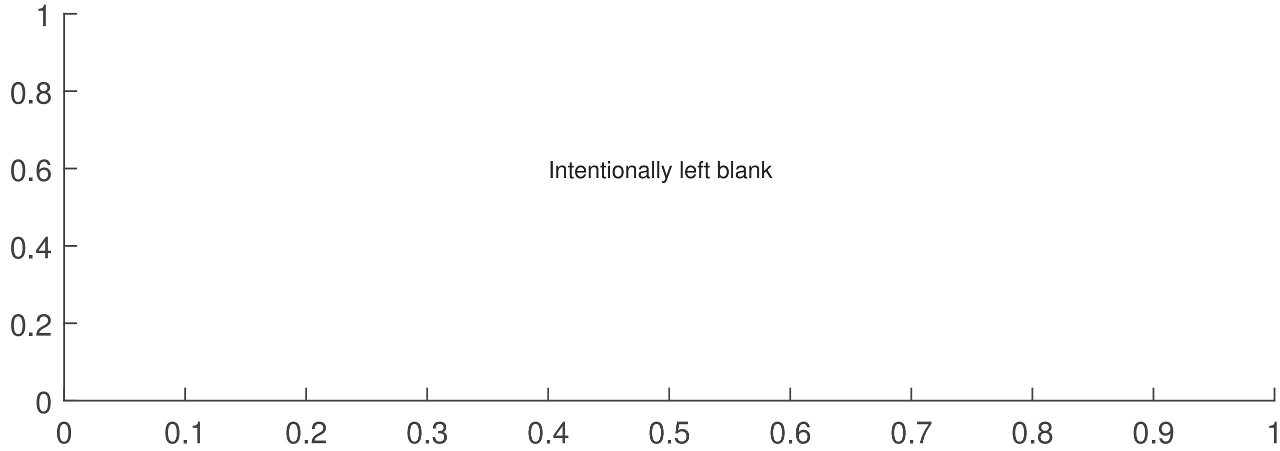

General test parameters
Test ID : CW4
Test mode : Captive
Model scale velocity : 0.000 m/s
Full scale velocity : 0 knots
Under keel clearance : 20%
λ_{theo} / L_{pp} : 0.55
Wave height WG2 : 22.21 ± 0.33 mm
Wave period WG2 : 1.66 ± 0.02 s
REMARK : All visualised points are averaged over :0.25 s
Velocity
V = 0 m/s
V [m/s]
time[s]
Running sinkage fore and aft perpendicular
motion [mm]
z_{VF}
z_{VA} + 30 mm
time[s]
Longitudinal force
X [N]
time[s]
Sway force; Yaw moment
Y [N]
N [Nm]
Y
N
time[s]
Wave gauge readings
wave motion [mm]
WG4 - 80 mm
WG2
WG1 + 80 mm
time[s]

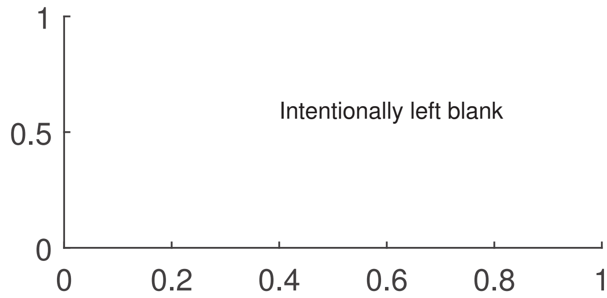
General test parameters

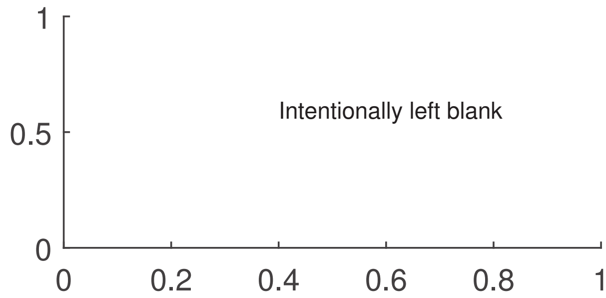
Test ID :	CW5
Test mode :	Captive
Model scale velocity :	0.327 m/s
Full scale velocity :	6 knots
Under keel clearance :	20%
λ_{theo} / L_{pp} :	0.55
Wave height WG2 :	21.36 ± 0.31 mm
Wave period WG2 :	1.66 ± 0.03 s

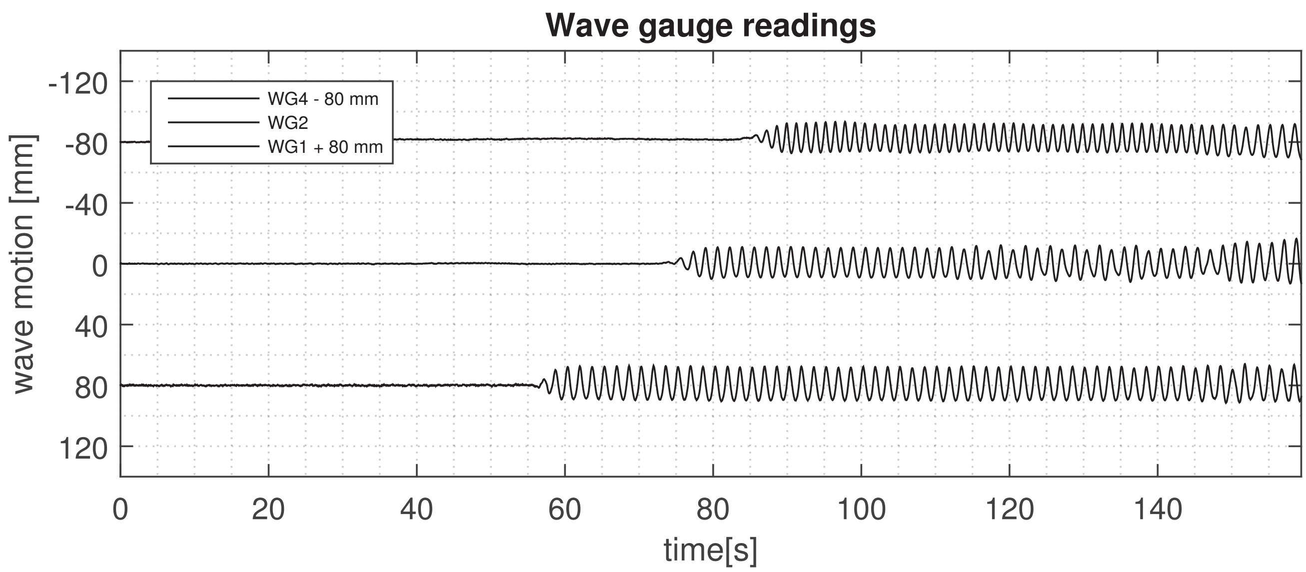
REMARK : All visualised points are averaged over :0.25 s







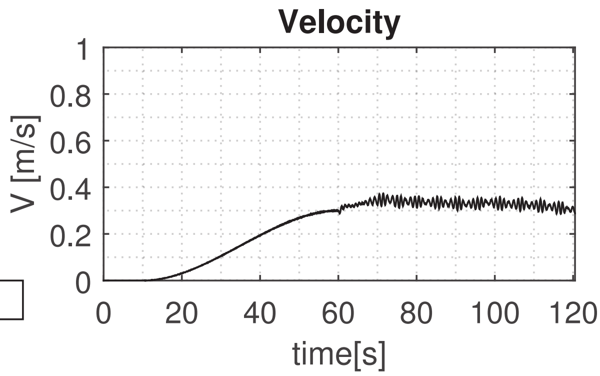


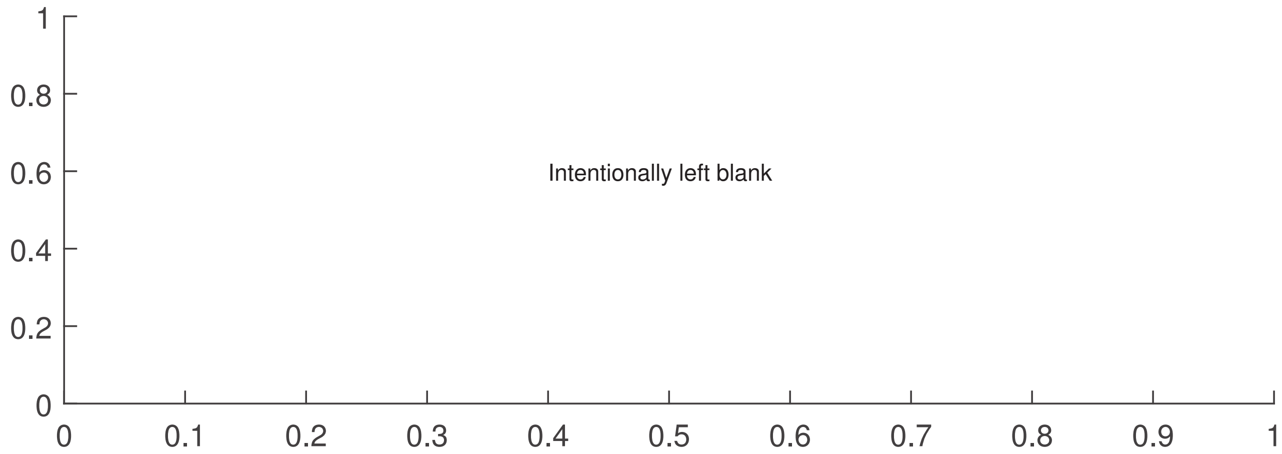


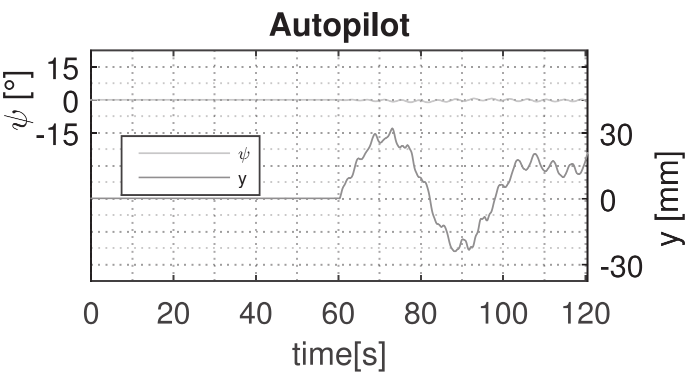
General test parameters

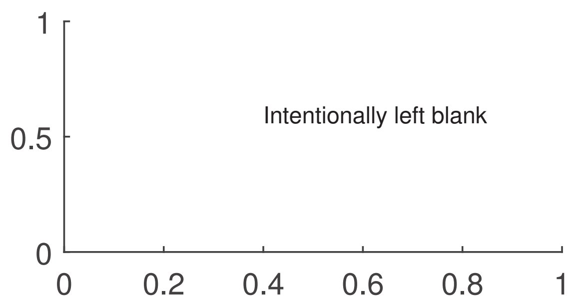
Test ID :	FW1
Test mode :	Free running
Target model scale velocity :	0.327 m/s
Target full scale velocity :	6 knots
Under keel clearance :	100%
λ_{theo} / L_{pp} :	0.55
Wave height WG2 :	56.92 ± 0.51 mm
Wave period WG2 :	1.39 ± 0.01 s

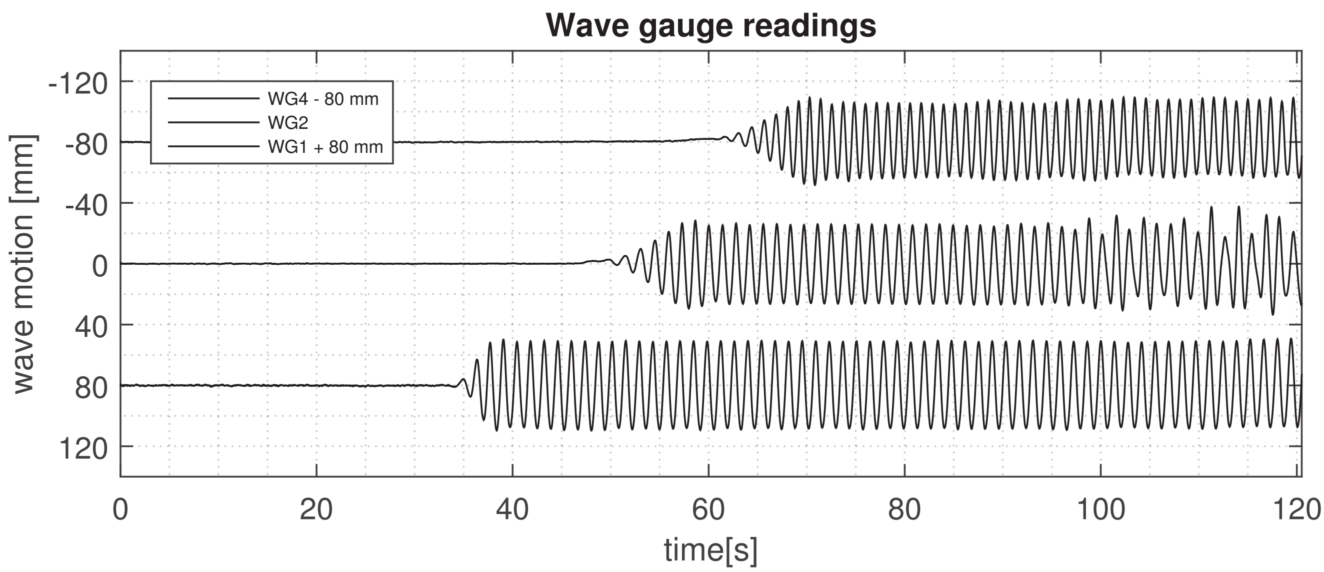
REMARK : All visualised points are averaged over :0.25 s











General test parameters

Test ID :	FW2
Test mode :	Free running
Target model scale velocity :	0.872 m/s
Target full scale velocity :	16 knots
Under keel clearance :	100%
λ_{theo} / L_{pp} :	0.40
Wave height WG2 :	60.72 ± 1.12 mm
Wave period WG2 :	1.09 ± 0.01 s

REMARK : All visualised points are averaged over :0.25 s