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Second Towing Tank: Towing Carriage

Sub report 1 – Design Criteria

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Second Towing Tank: Towing Carriage

Sub report 1 – Design Criteria

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Abstract

On September 30, 2016, the Flemish government approved the construction of the Flanders Maritime Laboratory. The construction of the Flanders Maritime Laboratory started on February 27, 2017. Among other installations, this laboratory will have a towing tank. The purpose of this document is to outline the design criteria of the towing carriage which will be used in the new towing tank.

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1 Flanders Maritime Laboratory

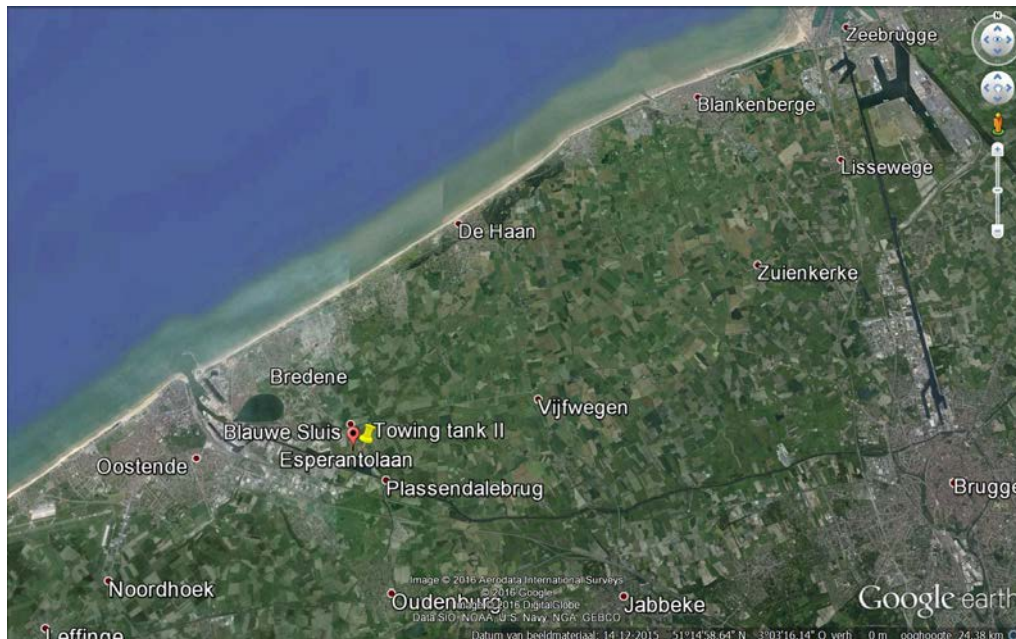
The size of the sea-going ships have been increasing since Flanders Hydraulics Research (FHR) built the first towing tank in 1992. As a result the present scale factors are increasing, which jeopardizes the accuracies that can be achieved. Moreover the shallow water challenges, such as wave reflection, critical speed,... put a severe limit on the possibilities of the current towing tank.

In 2009 a project was initiated to build a second towing tank. The dimensions of this towing tank are given in Table 1 and will be elaborated in Chapter 3.

Table 1 – Main dimensions of the second towing tank

Total length	174.0 m
Useful length	140.0 m
Width	20.0 m
Maximum water depth	1.0 m
Length of ship models	3.5 – 8.0 m

Figure 1 – Location of the second towing tank (Wetenschapspark, Ostend) 51°13'4.98"N 2°59'37.50"E



FHR has not sufficient space to build a tank of this size at its present location in Antwerp, for this reason a second site has been designated in Ostend, by the department Mobility and Public Works of the Flemish Government (Figure 1). The tank will also aim at manoeuvring and seakeeping tests in shallow water.

It should be equipped with a 4 DOF captive carriage, with possibilities to mount a 6 DOF hexapod and to operate in free running mode.

Figure 2 – Top view of the Maritime Laboratory (level +1). The contour of the new towing tank is marked in red.

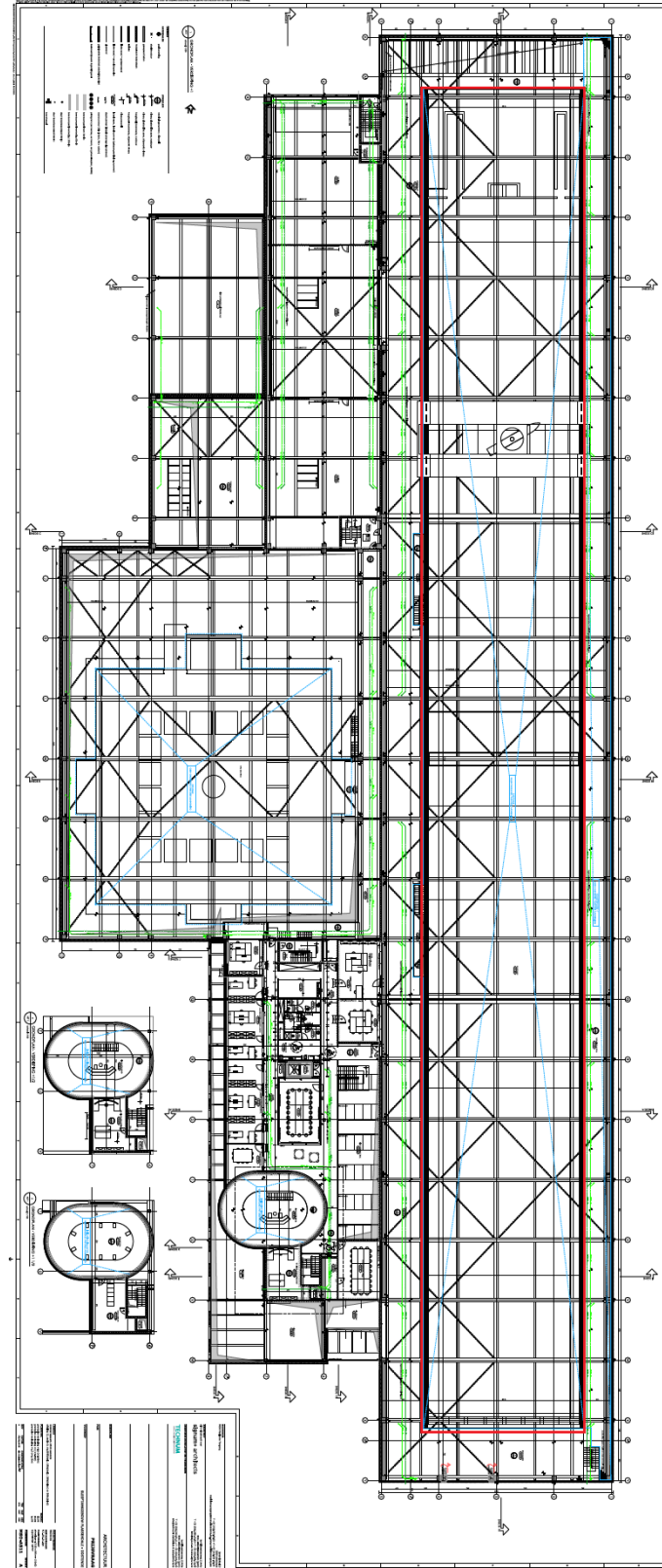
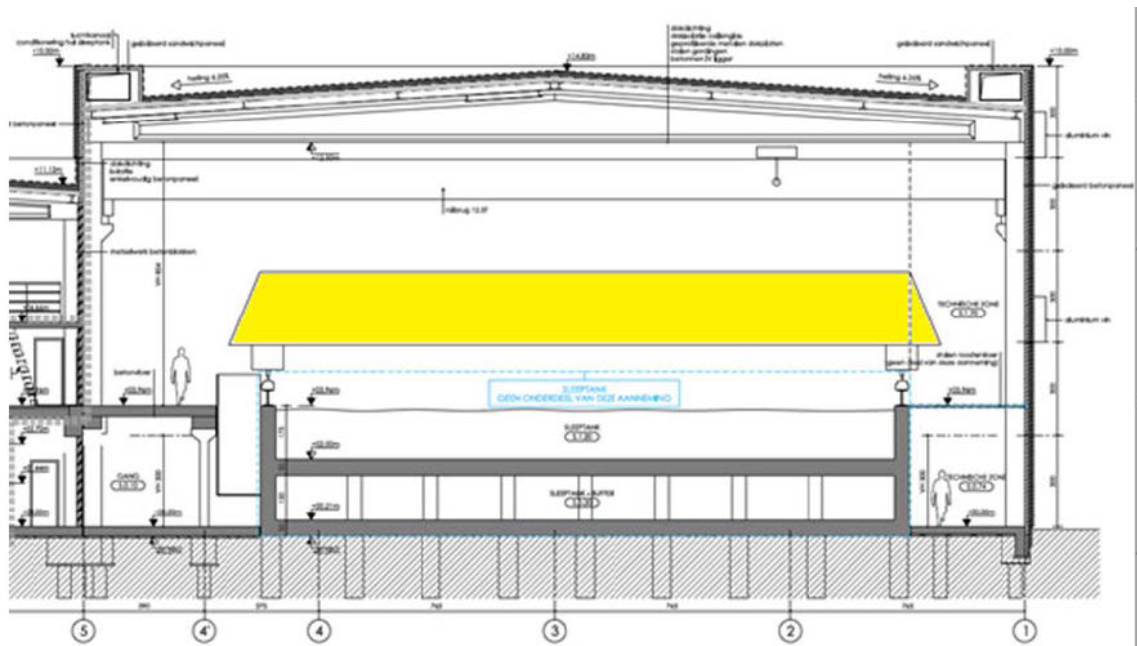


Figure 2 shows a top view of the new laboratory at level 1. The second towing tank will have its dedicated hall, with following inner dimensions:

- 192 m long;
- 30.6 m wide;
- 9.0 m high.

Figure 3 – Cross section of the hall of the second towing tank.



2 Operations in towing tank 1

2.1 Introduction

To set the ideas, the operations in the present towing tank will be introduced first. It is important to point out that the software for the pre and post processing of the experiments carried out in the second towing tank (TT2) must be compatible with the operations in the present towing tank (TT1).

In this chapter an overview of the most important parameters and files is given. A more global overview of towing tank 1 is given by (Delefortrie *et al.*, 2016).

2.2 Size of the present towing tank 1

The size of the tank is written in a file called *tank.sysxml*. Dimensions are given referred to the origin of a tank bound coordinate system. The origin is determined as follows:

- The longitudinal position allows the design ship model to move laterally (along y_0 -axis) without restrictions and must consequently be in the useful tank section. The positive direction is towards the wave maker and the positive coordinate is maximised. The design L_{OA} of the ship model in towing tank 1 equals 4.5 m. Taking account of the wave damping installation on the back wall of the towing tank, the available space should be at least $0.5L_{OA}$ when the midship's position is at the origin:
 - o Position of the back wall: -4.5 m;
 - o End position of the wave damping installation = X_{TMIN} = -2.80 m;
 - o Maximal position = X_{TMAX} = +71.00 m, determined by the position of the wave maker (+73 m);
 - o Position of the back wall: +76.0 m (+77.0 m for the end of the side walls supporting the rails).

Considering the size of the design ship, the useful x_0 -coordinate is further restricted to (carriage limits):

- o X_{MIN} = -0.20 m;
- o X_{MAX} = +68.00 m.

Behind the back wall (other wall than at the wave maker), a harbour¹ is present, with connection to the useful tank section, where the ship models are prepared prior to testing. The end coordinate of this harbour is -9.50 m, the end wall is -11.0 m due to the presence of the wave damping system. Consequently the total tank length is 77 + 11 = 88 m, which is also the length of the guiding rails.

- The rotation around the longitudinal axis is limited between the following values (carriage limits):
 - o PH_{IMIN} = -15.0°;
 - o PH_{IMAX} = +15.0°.

The roll angle is zero when the draft is equal on starboard and port. The roll angle is positive in clockwise direction when the bow is pointing towards the wave maker.

¹ Also known as trim tank.

- The lateral position is located on the longitudinal symmetry axis (x_0 -axis) of the useful tank section. The positive direction is towards starboard when the ship's bow is directed towards the wave maker. As the width of the useful tank section equals 7 m, the lateral coordinate is between:
 - o $Y_{\text{MIN}} = -3.50$ m;
 - o $Y_{\text{MAX}} = +3.50$ m.

The useful width is however limited by the reach of the lateral carriage:

- o $Y_{\text{MIN}} = -2.55$ m;
- o $Y_{\text{MAX}} = +2.55$ m.

The longitudinal symmetry axis of the harbour is located at -0.982 m and the width of the harbour equals 1 m.

- The maximal water depth Z_{MAX} equals 0.50 m.
- The vertical position is on the bottom of the tank. A North-East-Down (NED) coordinate system is used, but in practice water depths are given in absolute values.
- The rotation around the vertical axis is limited between the following values (carriage limits - zero degrees means ship bow pointing towards the wave maker, a clockwise rotation is positive):
 - o $\text{PSIMIN} = -130^\circ$;
 - o $\text{PSIMAX} = +220^\circ$.

Observe that the range is only 350° .

2.3 Kinematics of towing carriage 1 and auxiliary equipment

The kinematics of the carriage and auxiliary equipment are written in a file called *wagenpar*. Besides the physical boundaries for the carriage depicted in the previous section, the speed and acceleration ranges and the steering frequencies are also limited, not only for each component of the towing carriage, but also for auxiliary equipment, such as the wave maker and the carriage for ship to ship interaction tests.

The speed range is as follows (in absolute values):

- Longitudinal carriage: $u_0 = 2.00$ m/s
- Lateral carriage: $v_0 = 1.30$ m/s
- Roll mechanism: $p_0 = 16$ °/s
- Yaw mechanism: $r_0 = 16$ °/s

The acceleration range is as follows:

- Longitudinal carriage: $\dot{u}_0 = 0.40$ m/s² (in 5.0 s to maximum speed)
- Lateral carriage: $\dot{v}_0 = 0.70$ m/s² (in 1.9 s to maximum speed)
- Roll mechanism: $\dot{p}_0 = 8$ °/s² (in 2 s to maximum speed)
- Yaw mechanism: $\dot{r}_0 = 8$ °/s² (in 2 s to maximum speed)

In practice the maximal accelerations are limited by the maximal forces that may act on the ship model.

The speed controlled carriage for ship to ship interaction tests has a towing speed of at least 0.1 m/s.

The wave maker piston has a stroke length of 300 mm. Its maximal velocity is 600 mm/s and the maximal acceleration is 4400 mm/s².

2.4 Positioning of the carriage

The carriage is controlled based on position, which is important to perform tests in confined water. As the carriage is fully automated, an XML file lists the positions that each component of the carriage must follow during tests.

Manual positioning is also possible, based on the parameters written in the file *positie.sysxml*. Two possible modes exist:

- Normal mode:
 - o Speed longitudinal carriage $VX2 = 0.35 \text{ m/s}$
 - o Speed lateral carriage $VY = 0.03 \text{ m/s}$
 - o Speed yaw mechanism $VPSI = 1.5 \text{ }^\circ/\text{s}$
- Slow mode (e.g. to leave or enter the harbour):
 - o Speed longitudinal carriage $VX1 = 0.05 \text{ m/s}$
 - o Speed lateral carriage $VY1 = 0.01 \text{ m/s}$
 - o Speed yaw mechanism $VPSI = 1.5 \text{ }^\circ/\text{s}$

The roll mechanism can also be positioned, but based on a MOTOR signal (see the following section).

The accelerations in manual positioning are:

- $DX = 0.06 \text{ m/s}^2$ (longitudinal)
- $DY = 0.01 \text{ m/s}^2$ (lateral)
- $DPSI = 0.1^\circ/\text{s}^2$ (yaw table)

The manual positioning can be interrupted by pressing ESC. The decelerations of the carriage in this case are given by (ESCX, ESCY, ESCPSI).

The standard values of the allowable slip of the carriage mechanisms, i.e. the deviation between measured and steered position, are:

- $SLPX = 0.010 \text{ m}$ (longitudinal)
- $SLPY = 0.005 \text{ m}$ (lateral)
- $SLPPSI = 0.100^\circ$ (yaw table)

The carriage has several home positions, among which the origin of the tank bound axis system, where the measured positions can be reset.

2.5 Measurement registration and steering of the control equipment

The file *IO.sysxml* contains the relationship between the measured electric tension (e.g. on a strain gauge) and a physical unit (e.g. the longitudinal force acting on the ship model).

PIOCS® (Programmable Input Output Control) control the data acquisition. Each PIOC can measure up to 24 analogue and 20 digital signals. A PIOC can also steer up to 4 analogue and 20 digital signals. Alternatively, one or more motor steering components can be added to a PIOC.

The communication between the PIOC and the steering PC occurs over a LAN connection. A directional wireless bridge connects the carriage with the shore. Timing and synchronisation is assured by an implementation of the IEEE 1588 (PTP) timing protocol.

In general the *IO.sysxml* determines for each signal:

- which channel (*label*)
- with a certain name (*Naam*)
- is enabled (*enabled*)
- on which PIOC (*ModuleNumber*)
- and which channel of that PIOC (*ModuleIoNumber*)

The detailed information depend on the type of signal (measurement/steering/motor):

- Digital measurement (DIGIN):
 - Text message when active (*ActiveTEXT*)
 - Text message when non active (*NonActiveTEXT*)
 - If an alarm should be triggered when active (*ActiveAlarm: 1/0*)
 - If an alarm should be triggered when non active (*NonActiveAlarm: 0/1*)
- Analogue measurement (ANIN):
 - An analogue signal (measured tension x) is translated to a physical unit y using the relationship $y = A \cdot x + B$; A, B
 - It is possible to set both an upper limit (*UpperLimit*) and a lower limit (*LowerLimit*) for the unit y ;
 - Unit: the dimension of y (e.g. N)
- Digital steering (DIGUIT):
 - Text message when active (*ActiveTEXT*)
 - Text message when non active (*NonActiveTEXT*)
- Analogue steering (ANUIT):
 - An analogue signal (steering tension x) is translated to a physical unit y using the relationship $y = A \cdot x + B$; A, B
 - It is possible to set both an upper limit (*UpperLimit*) and a lower limit (*LowerLimit*) for the unit y ;
 - Unit: the dimension of y (e.g. rpm)
 - RampTimeStep determines the time interval during which y can change with RampStepSize
 - RampStepSize: the maximal step size of y
- Motor steering (MOTOR):
 - Unit: the dimension of the motor mechanism (e.g. deg)
 - The minimal (*MinPos*) and maximal positions (*MaxPos*) of the motor
 - The relationship between the motor pulses and the physical unit (*Transmission*)
 - The relationship between the direction of the motor and the physical unit (*Sign*)
 - The velocity when the motor is positioned manually (*DefaultVel*)
 - The acceleration when the motor is positioned manually (*DefaultAcc*)
 - The time to go from zero acceleration to default acceleration when the motor is positioned manually (*DefaultOnset*)
 - Information regarding the reset position of the motor:
 - The digital measurement triggering the home position (*HomeInputName*)
 - The value of the physical unit at the home position (*HomeRef*)
 - A high (*HomeVelHigh*) and low (*HomeVelLow*) velocity to look for the home position
 - The acceleration (*HomeAcc*) to look for the home position
 - The initial direction to look for the reset position (*HomeSign*)

2.6 Energy supply

The entire carriage uses a 380V-63A guiding rail to deliver the needed power. The installed power capacity is:

- 4 engines of 7.2 kW on the longitudinal carriage, of which only 2 are being used;
- 1 engine of 4.3 kW on the lateral carriage
- 1 engine of 1.0 kW on the yaw table

The power of the other components is less than 10% of the power of all these motors.

3 Towing tank 2

3.1 Size

On February 27, 2017 the construction of the Flanders Maritime Laboratory has started. The gross length of the towing tank is 174 m. The overall length of the design ship model is 8.0 m. Following an analogous methodology as for the first towing tank, the origin of the tank coordinate system can be determined:

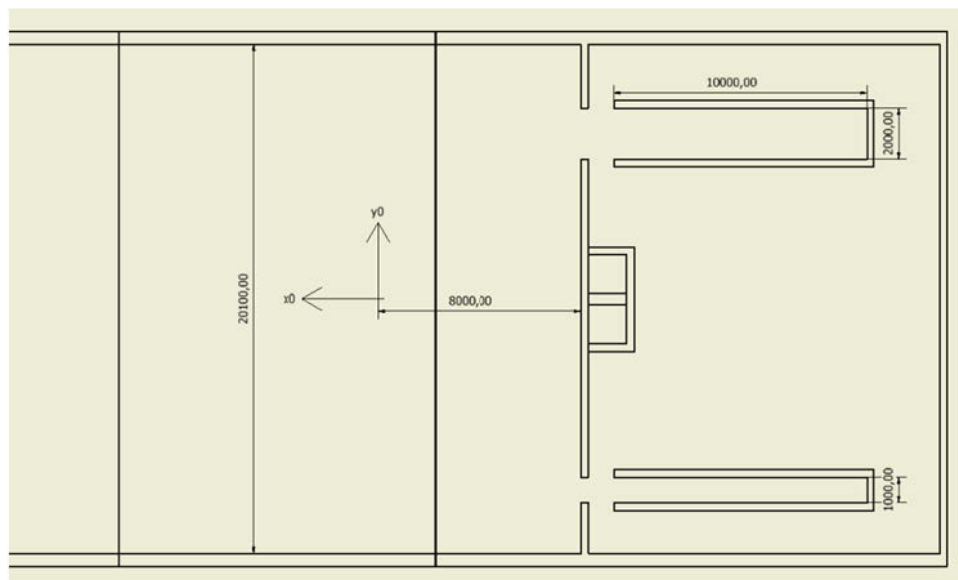
- On the longitudinal axis symmetry;
- On the bottom of the towing tank;
- The positive tank x_0 -coordinate is pointing towards the wave maker and is maximised.

For the case of towing tank 2, this means:

- The rails start at -22.5 m;
- The end of the harbours is at -19.3 m;
- The harbours' entrance is at -8 m;
- A wave maker can be installed at +142 m.

Mind that two harbours will be implemented: one for ship models up till 4.5 m long (harbour 1) and one for ship models up till 8.0 m long (harbour 2), see Figure 2.

Figure 4 – Detail of the tank at the origin of the tank coordinate system. The connections between tank and harbours still needs to be designed hence the opening in between.



On both end walls of the tank a wave damping mechanism has to be implemented (not necessarily the same as for towing tank 1). At the end wall near the harbours the wave damping mechanism can be maximally 4 m long. Before the wave maker the maximal length is 2 m. As such the useful tank section is delimited by:

- XTMIN = - 4.00 m;
- XTMAX = +140.00 m.

The width of the towing tank is 20 m, the limiting lateral coordinates are then:

- $Y_{TMIN} = -10.0$ m;
- $Y_{TMAX} = +10.0$ m.

The water depth variation in the tank is between $Z_{TMIN} = 100$ mm and $Z_{TMAX} = 1000$ mm. On top of this static water depth a wave amplitude up till 200 mm can occur.

The width of the harbours is as follows:

- Harbour 1 (small ship models): 1 m;
- Harbour 2 (large ship models): 2 m.

The longitudinal symmetry axis of each harbour is at y_0 -value:

- Harbour 1 (small ship models): -7.55 m;
- Harbour 2 (large ship models): $+6.55$ m.

3.2 Position in hall

The towing tank has an eccentric position with respect to the hall. Next to the negative y_0 - coordinate, the available width will be only 1.80 m. This side will serve as a technical zone for the, to be designed, power supply to the carriage. Power outlets with 240 V and 380 V are available. On the other side of the tank (positive y_0 - coordinate), sufficient space should be available (4.10 m) to allow the passage of a fork lift truck next to the tank.

The ship models are instrumented in the harbours, which requires an ergonomic working height. Given the maximal water level in the tank, the height of the tank wall and the height of the second floor, the bottom level of the harbours is the same as of the tank bottom. In other words the harbour section will be at an intermediate level. The side walls of the harbours (1.20 m height) are lower compared to the tank walls. Both harbours can be closed with a watertight door. The guiding rails of the carriage continue to the end of the harbours so that the longitudinal carriage can move the ship models to the harbours.

3.3 Tank tolerances

The flatness (combination of slope and vertical position) tolerance on both the side walls and the entire tank bottom is 1 mm. The deviation of the side walls with respect to the x_0 axis of the towing tank are not larger than ± 10 mm with a gradient of maximal 1 mm/m.

3.4 Water usage

3.4.1 Filling and emptying

Due to the frequent water level variations a performant emptying and filling system has to be available. The pump system is designed to be only used by the towing tank. The discharge design rate of $1000 \text{ m}^3 \text{ per h}^{(2)}$ is obtained by a set of pumps, e.g. four, to have a redundant system and to enable smaller discharge rates as well, e.g. for smaller water level variations.

² In this way the tank can be filled or emptied in $\frac{1}{2}$ working day.

The filling and emptying actions move the water between the tank and the underlying water reservoir with a capacity of 3,600 m³, which is 120% of the maximal water volume in the tank. The pumps are located within the water reservoir and the connection with the tank is located between $x_0 = -1$ m and $x_0 = -4$ m, as close as possible to the side walls. The wave damping mechanism should be designed to cope with filling and emptying actions.

Each harbour has to possess its own pump to enable independent filling actions. Both harbours can be closed with a watertight door so that each harbour can be levelled independently from the other harbour or from the tank.

3.4.2 Wave generation

A wave generation mechanism is foreseen at the positive end of the tank $x_0 = +142$ m. A wave damping mechanism has to be installed both behind and before the wave maker, the latter only when the wave maker is not operated. At present a piston type wave maker with segmented flaps covering the entire water depth (1.25 m) is preferred.

The limiting working conditions:

- maximal amplitude: +/- 0.5 m;
- maximal velocity: +/- 1 m/s;
- maximal acceleration: 4.4 m/s²;

allow the generation of 10 m long waves with a height of 0.2 m at water depths of minimal 0.4 m.

The different flaps should allow the generation of waves with an angle up till 45° referred to the longitudinal axis of the tank ($\leq 45^\circ$).

4 Design criteria of the new towing carriage

4.1 Setup

The carriage is composed of the following parts which together enable any continuous movement (within the kinematic limits) of a ship model in the horizontal plane:

- Longitudinal carriage;
- Lateral carriage;
- Yaw mechanism.

The yaw mechanism is considered to be a hollow tube with inner gear teeth with estimated diameter R_{ym} of 3 m, in which different sub setups can be connected:

- Free roll, heave and pitch (3 DOF carriage, in which the ship model is captive in all directions in the horizontal plane);
- Roll mechanism (4 DOF carriage: this is considered to be the basic setup, in which the ship model is free to heave and pitch or heave and pitch are fixed);
- Hexapod (3+ 6 DOF carriage);
- Free running (carriage is used as tracking system).

The suggested order of the different axes is as follows:

1. Longitudinal carriage (x -axis)
2. Lateral carriage (y -axis)
3. Yaw mechanism (around z -axis)
4. Application point (can be positioned vertically) of the ship model (z -axis)
5. (Free/Captive) heave (z -axis)
6. Captive roll (around x -axis) and (free/captive) pitch (around y -axis)

4.2 Reach

In this section the global reach is presented which will lead to the carriage size limits in section 4.3. The full kinematics of the carriage are discussed in section 0. Given the maximal sizes in longitudinal direction, tests with a 8 m long ship model should be possible between:

- $X_{MIN} = 0.00$ m
- $X_{MAX} = +136.00$ m

In other words the minimal useful test length is 136 m for the largest ship model.

The lateral carriage should have a larger reach compared to the one of the first towing tank, e.g. to test ship bank interaction at small distances:

- $Y_{MIN} = -10.0 + \delta$ m
- $Y_{MAX} = +10.0 - \delta$ m

A small distance is here understood as 0.05 m between the ship model's side and the tank wall. δ is then determined by the half width of a small ship model : or $0.20 + 0.05$ m = 0.25 m.

The range of the yawing table has to be extended compared to the range of towing carriage 1:

- PSIMIN = -130°
- PSIMAX = 600°

which corresponds to 2 full rotations and 10° overlay.

The rotation around the longitudinal axis is limited between the following values:

- PHIMIN = -20.0° ;
- PHIMAX = $+20.0^\circ$.

The longitudinal carriage should be able to travel on the gross length of the guiding rails. The connection between the guiding rails and the side walls can be realised by means of a steel profile, e.g. a reinforced I-profile.

4.3 Size limits

4.3.1 Longitudinal direction

The length of the longitudinal carriage (size in direction of the x_0 -axis) is not larger than 10 m. Any ship model will be connected in the middle of the longitudinal carriage (the longitudinal coordinate of the carriage is equal to the longitudinal coordinate of the ship).

The length of the longitudinal carriage must allow:

- the positioning of a ship model in one of the harbours;
- the execution of tests between XMIN and XMAX.

4.3.2 Lateral direction

Figure 5 – Cross section of the towing carriage (view from wave maker to harbours).

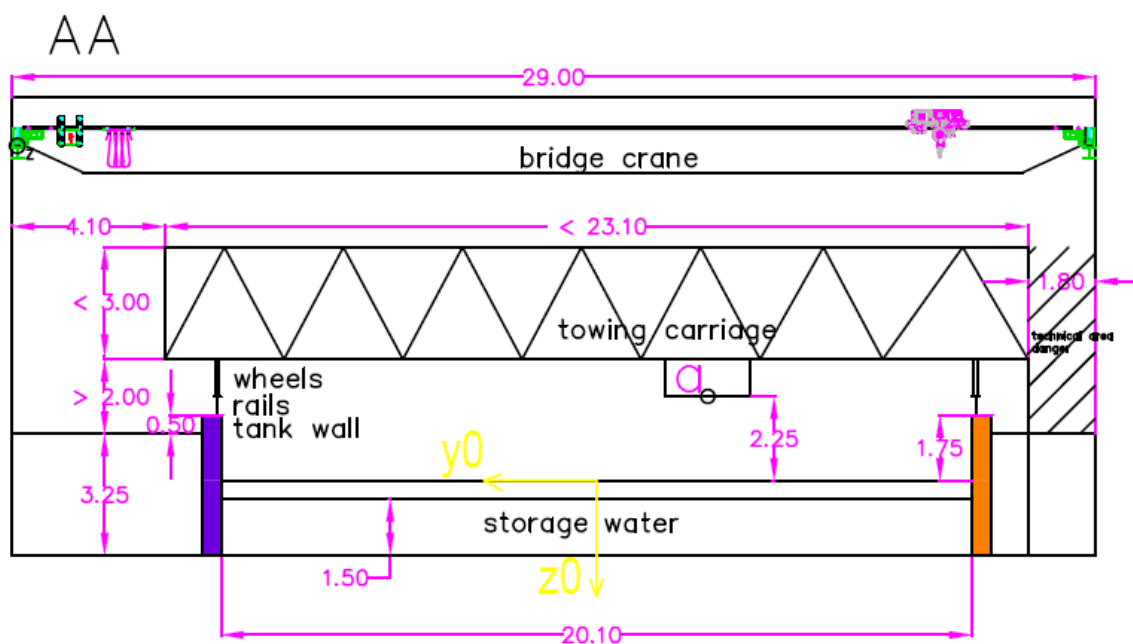


Figure 5 shows the typical lateral section of the carriage. a represents the application point of the ship model. The maximal width of the longitudinal carriage (size in direction of the y_0 -axis) is 23.10 m to allow the operations depicted in section 3.2 and to allow the lateral carriage to move close to the tank walls.

4.3.3 Vertical direction

The maximal height of the construction is 5 m, referred to the bottom of the second floor, or 6.25 m, referred to the bottom of the towing tank. In this way the overhead bridge crane can safely pass the carriage.

For safety reasons the minimal free height between the bottom of the second floor and the longitudinal carriage is 2 m.

The carriage without ship model has to be able to move to any longitudinal position, therefore both the longitudinal and the lateral carriage, including the yaw mechanism, must allow a free height of 2.25 m with respect to the bottom of the towing tank.

The accumulated height of the wheels of the longitudinal carriage, the guiding rails and the reinforced I-profile must be around 1.50 m.

4.3.4 Weight

To design the side walls of the tank the weight of the carriage was estimated based on the towing carriage used in the tank of HSVA (Hamburg, Germany)³. This carriage has a span of 18 m and weights 73 ton. The estimated weight for a span of 20 m is therefore 100 ton (factor $20^3/18^3$), which is the maximal weight of the carriage.

1/3 of the weight of the HSVA carriage is to be ascribed to the lateral carriage. In other words when the lateral carriage reaches its extreme position 2/3 of the weight is applied on a single rail. For a carriage with a pair of wheels on each rail, 66 ton was taken as load limit for a single wheel. Other driving mechanisms could lead to a better load distribution on the rails.

4.3.5 Size with respect to ship models

The connection between the carriage and the ship model (during captive tests) should be as compact as possible. For instance, the width of the connection mechanism has to allow a maximal roll angle of $\pm 20^\circ$.

If necessary, a different connection system may be used for larger ship models (8 m) or smaller ship models (4 m).

The added weight of the connection mechanism to the ship model should always be as small as possible.

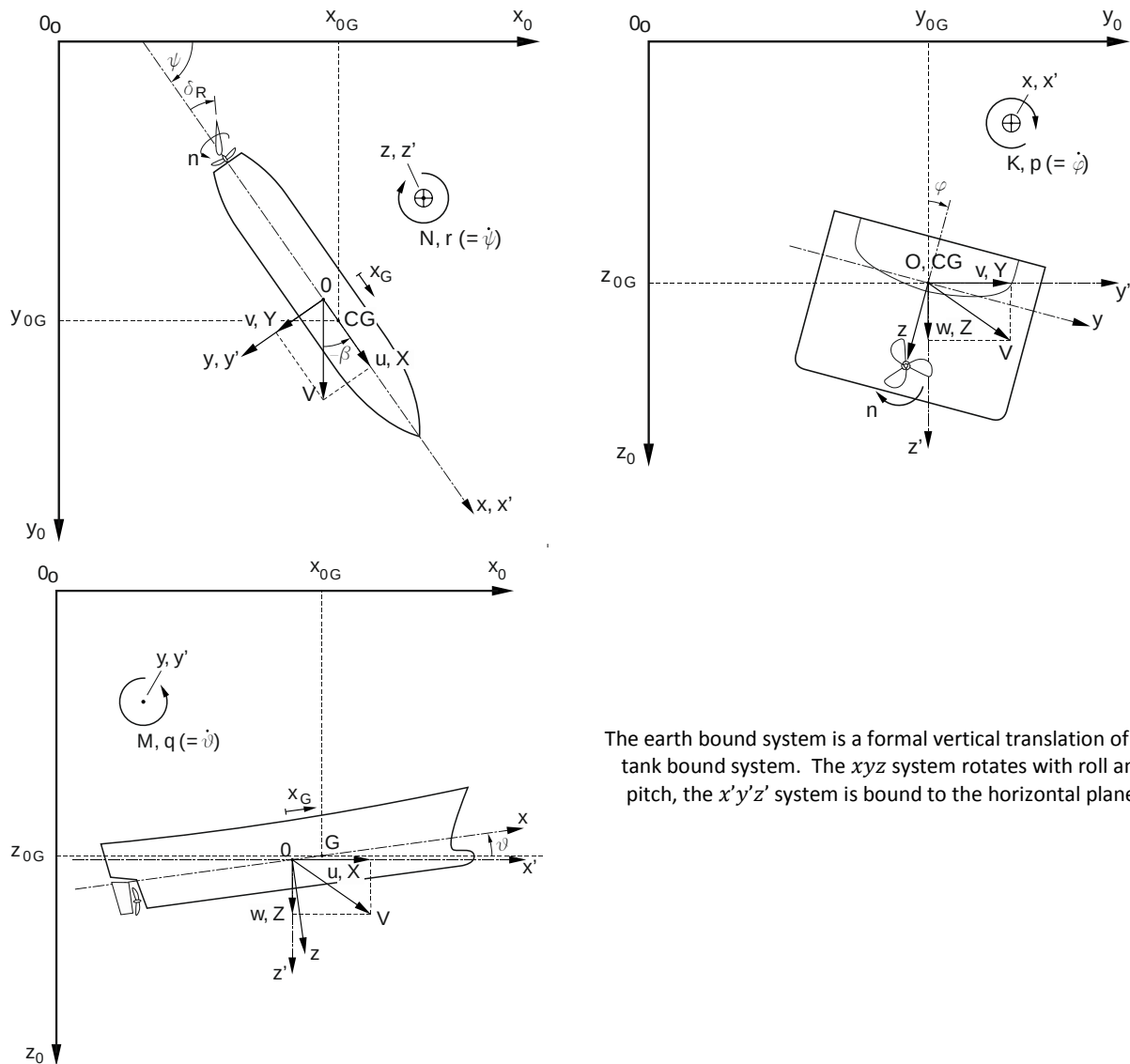
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4.4 Kinematics

4.4.1 Coordinate system

Figure 6 shows the applicable coordinate system.

Figure 6 – Ship- and earth bound coordinate system: projections in different planes.



The earth bound system is a formal vertical translation of the tank bound system. The xyz system rotates with roll and pitch, the $x'y'z'$ system is bound to the horizontal plane.

4.4.2 Positions, velocities and accelerations

The design criteria with respect to positions, velocities and accelerations during the tests are listed in:

- Table 2 during test execution;
- Table 3 during manual positioning.

Values are always referred to the origin of the ship bound axis system.

Table 2 – Design kinematic conditions of the carriage during test execution.

DOF	Position in tank	Velocities (if steered)	Accelerations (if steered)
Surge	Between $(XTMIN + 2 R_{ym})$ and $(XTMAX - 2 R_{ym})$	± 3.000 m/s	± 0.400 m/s ²
Sway	± 9.75 m	$\pm 1.300^{(4)}$ m/s	± 0.700 m/s ²
Heave	± 0.20 m	± 0.700 m/s	± 0.700 m/s ²
Roll	$\pm 20^\circ$	$\pm 15^\circ/\text{s}$	$\pm 8^\circ/\text{s}^2$
Pitch	$\pm 6^\circ$	$\pm 15^\circ/\text{s}$	$\pm 8^\circ/\text{s}^2$
Yaw	Between -130° and $+600^\circ$	$\pm 15^\circ/\text{s}$	$\pm 8^\circ/\text{s}^2$

Table 3 – Design kinematic conditions of the carriage during manual positioning.

DOF	Position in tank	Velocities (if steered)	Accelerations (if steered)
Surge	Between -17 m and $(XTMAX - 2 R_{ym})$	± 1.000 m/s	± 0.400 m/s ²
Sway	± 9.75 m (except harbour limitations)	± 1.000 m/s	± 0.400 m/s ²
Heave	Between 0.25 m and 2.25 m above tank bottom	± 0.100 m/s	± 0.050 m/s
Roll	$\pm 20^\circ$	$\pm 5^\circ/\text{s}$	$\pm 1^\circ/\text{s}^2$
Pitch	$\pm 6^\circ$	$\pm 5^\circ/\text{s}$	$\pm 1^\circ/\text{s}^2$
Yaw	Between -130° and $+600^\circ$ (except harbour limitations)	$\pm 5^\circ/\text{s}$	$\pm 1^\circ/\text{s}^2$

4.5 Accuracy

4.5.1 Carriage components

- The straightness of the longitudinal carriage (as a whole, measured with respect to the connection point of the ship) should have a minimal accuracy of 0.04 mm per 1000 mm;
- The straightness of the lateral carriage (as a whole, measured with respect to the connection point of the ship) should have a minimal accuracy of:
 - 0.01 mm per 1000 mm in the horizontal plane, i.e. 0.2 mm over the tank width;
 - 0.01 mm per 1000 mm in the vertical plane.
- The reset positions of the longitudinal and lateral carriages need a position accuracy of ± 2 mm. This can be achieved by a position switch, which resets the positions when triggered. The longitudinal position switch should be moveable.
- The reset positions of the yaw and roll mechanisms need a position accuracy of $\pm 0.01^\circ$. This is achieved by resetting an encoder after positioning the yaw or roll mechanism at the assumed zero point.
- The accuracies of the hexapod should be of the same magnitude. The vertical accuracy should be 0.15 mm and the pitch accuracy 0.01° (1 mm per 4 m).

⁴ The value of the towing carriage 1 is sufficient because of tank resonance.

4.5.2 Ship model alignment

The ship model has to be connected precisely to the carriage in such way that alignment errors can be detected and corrected. In general the connection between ship model and carriage should be as simple as possible.

Table 4 – Kinematic accuracy during tests.

DOF	Resolution	Position accuracy	Velocity accuracy (if steered)	Acceleration accuracy (if steered)
Surge	0.1 mm	1.5 mm	The maximum of 0.5 mm/s and 0.50%	0.5 N error: ⁽⁵⁾ 0.025 mm/s ²
Sway	0.1 mm	1.3 mm Position accuracy when performing a harmonic sway motion: 0.70% of the motion amplitude, but never larger than 10 mm.	The maximum of 0.5 mm/s and 0.50%	0.5 N error: 0.025 mm/s ²
<i>Heave</i> ⁶	0.05 mm	0.15 mm	The maximum of 0.5 mm/s and 0.50%	2.5 N error: 0.050 mm/s ²
Roll	0.01°	0.03° Position accuracy when performing a harmonic roll motion: 0.70% of the motion amplitude	The maximum of 0.08 °/s and 3.00%	0.1 Nm error: 0.08°/s ²
<i>Pitch</i>	0.01°	0.03° Position accuracy when performing a harmonic pitch motion: 0.70% of the motion amplitude	The maximum of 0.08 °/s and 3.00%	0.5 Nm error: 0.03°/s ²
Yaw	0.01°	0.03° Position accuracy when performing a harmonic yaw motion: 0.70% of the motion amplitude	The maximum of 0.08 °/s and 3.00%	0.5 Nm error: 0.03°/s ²

⁵ Acceptable errors on a ship model with a displacement of 1 ton.

⁶ *Italic values are valid for the hexapod*

4.5.3 Slip errors

The slip errors should be below:

- $SLPX = 0.01$ m for the longitudinal carriage;
- $SLPY = 0.005$ m for the lateral carriage;
- $SLPPSI = 0.100^\circ$ for the yaw mechanism;

Slip errors in the other degrees of freedom (if steered) should have similar, realizable limits.

4.5.4 Kinematic resolution

Table 4 show the accuracy limits during tests. These accuracy limits have to be met, taking into account

- the cumulative deviations due to temperature variations F_t ;
- the cumulative deviations due to the uncertainty induced by the position gauges F_v ;
- the cumulative deviations due to the geometric accuracy of each sub mechanism F_g .

The cumulative deviation has to be computed by the square root of the sum of squares of each possible deviation. The computed value is then multiplied with a safety factor of $4/3$. The outcome of this computation has to be smaller or equal to the values mentioned in Table 4. Each possible deviation is determined by the carriage constructor, based on a detailed design, and is reported to the client.

4.6 Dynamics

4.6.1 Friction

For the degrees of freedom that can be free the static friction force of the connection between the ship and the carriage may not be larger than:

- 2 N for the heave motion;
- 1 Nm for the pitch motion;
- $1/8$ Nm for the roll motion.

4.6.2 Stiffness

The carriage should be built according to common construction rules, but ideally taking account of all design criteria mentioned in this report. Special attention is drawn to the stiffness of the construction. The different parts have to be designed in such way that the effect of the dynamic loads, mentioned in Table 5, minimizes the elastic deformations, so that the geometric accuracies can be met. The most appropriate steel should be selected to build the carriage. The main colour of the carriage is RAL 1021.

The static vertical deflection of the longitudinal carriage due to the lateral carriage should be less than 0.8 mm.

The horizontal stiffness of the longitudinal carriage has to limit the displacement in longitudinal direction on one side to 0.6 mm if a load of 6,000 N is applied on the other side.

The mechanism has to be sufficiently stiff. The displacement of any point on the ship model due to elastic deformation of the mechanism may not be larger than 1.2 mm when the maximal load on the ship model is applied (Table 5) on top of the own weight of the towing carriage.

The loads mentioned in Table 5 were scaled from the design loads of the carriage in towing tank 1. Any exceedance of loads activates a safety mechanism (e.g. abort a test). The loads with ship model apply on the ship model. The application point of these loads is thus 2 to 3 m below the base of the longitudinal carriage.

Table 5 – Design loads.

DOF	Maximal load on ship model (Range of dynamometers)		Maximal load on carriage	
	Captive mode	Free running mode	Captive mode	Free running mode
Surge	1.0 kN	p.m.	6.4 kN	p.m.
Sway	1.0 kN		8.0 kN	
<i>Heave</i> ⁷	<i>10.0 kN</i>		$\geq 10.0 \text{ kN}^{(8)}$	
Roll	1.0 kNm		$\geq 1.0 \text{ kNm}$	
<i>Pitch</i> ⁷	<i>8.0 kNm</i>		$\geq 8.0 \text{ kNm}$	
Yaw	8.0 kNm		16.0 kNm	

4.6.3 Fatigue

The mechanism for the longitudinal carriage should be designed for an utilisation of 15,000 h. The mechanism of the other modes should be designed for 7,500 h. One may assume that during operations the mechanisms move with a constant speed equal to 2/3 of the maximal speed.

4.6.4 Vibrations

The eigenfrequency of the carriage may not be smaller than 30 Hz (resonance). The eigenfrequency has to be computed for the following modes:

- Lateral construction (bending and torsion)
- Longitudinal construction (bending and torsion)

⁷ Italic values are valid for a hexapod

⁸ A safety factor has to be agreed for $\leq$. The maximal weight of a ship model is for instance 65 kN. This load will apply when the towing tank is emptied involuntary. In such case a safety mechanism must be implemented, in this example the ship model could be lowered.

4.7 Guiding rails

Train rails of which the upper surface is milled and finished are used to guide the carriage. By means of lateral guiding wheels on one of the rails excessive lateral deviations of the carriage can be avoided. The lateral surface of this rail will also need a specific coating. It is important to limit the (vertical) movements of the rails. The position of the rails, both in vertical and in horizontal direction, has to be adaptable. The accuracies for the rails is as follows:

- Vertical deviation < 1 mm (full length), < 0.2 mm level difference between both sides of the tank;
- Lateral deviation in the horizontal plane: < 0.4 mm (full length for the lateral guiding rail), < 0.8 mm (full length for the other rail).
- Maximal steepness in the vertical plane < 0.1 mm per 1 m;
- Maximal steepness in the horizontal plane: < 0.2 mm per 1 m (lateral guiding rail), < 0.4 mm per 1 m (other rail);
- Maximal deviation of the width of the running surface: < 0.1 mm.

The rail's adjustment is performed with bolts, located every +/- 0.5 m. The bolts are supported by flanges in the profile supporting the rails, see Figure 7 for an example in towing tank 1. Better solutions are also possible. The width of the rails has to be determined during design.

Figure 7 – Detail of the rails in towing tank 1



a. Monitoring the rail's position



b. Rail and profile

4.8 Environmental conditions

- In production phase: draft- and dust-proof;
- High humidity (min 60% - max 80%);
- Reference temperature water + air: 15°C (allowed range between 12° and 20°C).

The towing carriage must operate in an environment with a large humidity. The used materials have to be stainless and corrosion resistant.

4.9 Operating the carriage

4.9.1 Automatic mode

The normal production operation mode is a fully automated mode in which tests can be conducted 24/7. This implies a significant operational reliability.

The software and data acquisition for towing tank 2 should be as similar as possible to towing tank 1 and have at least the same functionalities. A useful extension is the automation of the water levelling, which includes the adaptation of the height of the connection mechanism and that the safety against bottom touch is guaranteed.

During test execution the carriage mechanisms are steered in real-time on position. Depending of the degrees of freedom the coordinates of each position are given in a test file. Based on the position, the system applies adequate control parameters to steer the velocity and acceleration of the mechanisms.

4.9.2 Manual mode

In any case a manned operation of the carriage has to be possible. This requires the construction of a bridge, which for visibility reasons has to be either on both sides of the carriage (2 steering facilities) or an open bridge in the middle of the carriage if the construction allows it (1 steering facility). Due to height limitations the upper part may only be used for passage to and from the bridge. However it should be possible to have a fluid access to the bridge(s) when the carriage is at the following positions:

- $x_0 = -15.0 \text{ m}$, $y_0 = Y_{\text{HARBOUR1}}$ of Y_{HARBOUR2}
- $x_0 = X_{\text{MIN}}$, $y_0 = 0$
- $x_0 = X_{\text{MAX}}$, $y_0 = 0$

It would be nice if several persons (clients) can join the bridge to witness a towing test.

In general the access and the accommodation of the bridge(s) has to comply with the applicable ergonomic regulations. All accesses to the bridge(s) and the bridge(s) should be designed for a load capacity of 15 kN/m².

4.9.3 Connection of sub setups

The following connection setups should be “easily” swappable (it should cost less than 5 man days):

- 4 DOF for 8 m and 4 m ship models (the default setup, see 4.9.4);
- If necessary: a separate setup for 4 DOF 4 m;
- If necessary: a separate setup for 3 DOF (i.e. roll is free);
- Free running ;
- 6 DOF Hexapod (optional) .

Therefore, all of the above setups should share the same connection interface. The following connections have to be provided between the steering unit and the ship model:

- cables for the analogue measurement signals (from ship model to PC for data acquisition);
- cables for the digital steering signals (from PC to ship model for steering);
- cables for the analogue steering signals (from PC to ship model for steering);
- video cables;
- cables for PLC steering;
- feeder cables, e.g. to charge batteries in the ship model.

These cables are preferably joined in an energy chain on the longitudinal carriage. The length of the structure should be sufficiently flexible to allow all possible motions of the mechanisms.

In the captive modes the forces are measured by means of dynamometers which allow for micro strain displacements. Each steered mode has to be equipped with a displacement sensor with encoder feedback. In case of power interruption any movement should be directly and automatically interrupted by enabling the brakes.

4.9.4 Additional requirements for 4 DOF (and 3 DOF)

In this case the following degrees of freedom are steered:

- Surge
- Sway
- Yaw
- Roll (only for 4 DOF)

It means that the ship is captive in the above degrees of freedom. In the other degrees of freedom the ship can either be fixed or free. The default condition is that the ship is free to heave and pitch, while restrained in the other degrees of freedom. The connection mechanism between the carriage and the ship model must allow these free motions (see also 4.6.1 for the friction considerations). These free motions are also monitored during the tests.

4.9.5 Additional requirements for 6 DOF hexapod

This is an optional submechanism. Steering and force measurements are needed in all 6 DOF. In practice the horizontal degrees of freedom will be covered by the longitudinal carriage, lateral carriage and yawing mechanism to overcome the limited amplitudes of a hexapod. Steering must be possible from the ship model's point of view and internally translated to correct piston settings.

4.9.6 Additional requirements for free running

See tender WL_07_08 (In Dutch). The information from this tender can be used.

It is important to point out that free running tests can be operated 24/7. This means that at a certain point the carriage positions and releases the ship model. The ship model can independently, by means of a control routine, carry out a trajectory, while it is followed as close as possible by the towing carriage. Once the trajectory is finished, the ship model is grabbed again by the carriage. Especially the connection between ship and carriage in captive mode could be improved compared to the situation in towing tank 1.

4.10 Safety

The carriage should comply with the relevant legislation on safety. The safety should be as good as (or even better than) on the present carriage. Attention is drawn to:

- the dispatch of alarm signals, both in manual and automatic modes;
- the emergency stop procedure;
- ergonomics.

Undesired motion of the captive degrees of freedom should be limited, for instance by end run switches (IP 67). An activation of such switch is equivalent to the emergency stop procedure. For instance, in the present towing tank, the entrance to the harbour is protected by an end run switch. To enter the harbour the switch has to be short cut with a key. The location of the end run switches should be mobile.

A risk assessment of the carriage operations is required.

4.11 Power supply

The choice of the entire electric gear (motors, cables, sockets, inductors, thyristors, relays, fuses, transformers, etc. ...) has to be justified with computations. The power supply has to be determined during the design stage. A preliminary estimated is given in Table 6. Based on the mass m and the maximal acceleration a the maximum power can be determined as:

$$P = mav_{max}$$

The values of the yaw mechanism was scaled from towing carriage 1. Values for the hexapod and the filling/emptying are based on examples provided in the literature.

Table 6 – Estimation of needed power

Component	Mass	Acceleration	Maximum power
Longitudinal carriage	100 ton	0.4 m/s ²	120 kW
Lateral carriage	30 ton	0.7 m/s ²	28 kW
Yaw mechanism	p.m.	8 °/s ²	28 kW
Hexapod	p.m.	p.m.	28 kW
Filling/emptying	p.m.	p.m.	16 kW
Wave maker	p.m.	p.m.	65 kW
Total	p.m.	p.m.	285 kW

Based on an efficiency of 1/1.73, the theoretical maximum power is 500 kW. For a tension of 380 V this means a rated current of 1,300 A. However, a maximum power of 500 kW is unlikely because not all components will be operated simultaneously. The maximum power is therefore expected to be 350 kW.

4.12 Design questions

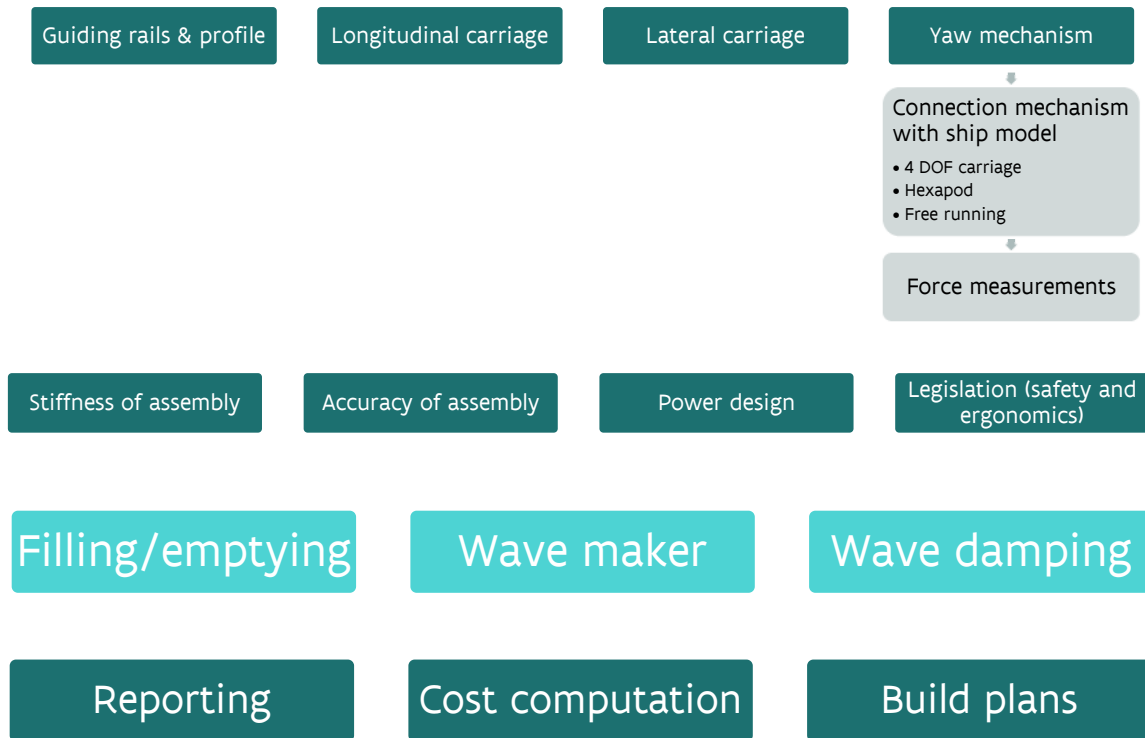
Besides the design criteria listed until now, other questions have to be tackled during the design phase, for instance:

- How will the forces be measured?
- Is single point towing still feasible?
- How to cope with different sizes of ship models?
- How to connect the different sub mechanisms to the hollow tube of the yaw mechanism? All sub mechanisms need to be positionable and moveable between the minimal (0.10 m) and maximal water level (1.00 m).

5 Design and build

In January 2018 a design and build tender will be published. Figure 8 shows the different components of the design phase.

Figure 8 – Steps in the design phase



6 References

Delefortrie, G.; Geerts, S.; Vantorre, M. (2016). The Towing tank for Manoeuvres in Shallow Water. *MASHCON 2016*: Hamburg, Germany. ISBN 9783939230380. pp. 226–235. doi:10.18451/978-3-939230-38-0

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