BEHAVIOUR OF SHIPS APPROACHING AND LEAVING LOCKS: OPEN MODEL TEST DATA FOR VALIDATION PURPOSES

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1. INTRODUCTION

After successful conferences on bank effects [1] (Antwerp, May 2009) and on ship – ship interaction [2] (Trondheim, May 2011), the Third Conference on Manoeuvring in Shallow and Confined Water will have a non-exclusive focus on Ship Behaviour in Locks. This conference will be organised in Ghent, Belgium, from 3 to 5 June 2013, by Flanders Hydraulics Research, Ghent University (Maritime Technology Division) and the Royal Institution of Naval Architects. The initiative to organise these conferences is taken in the frame of the activities 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.

Ship behaviour in locks is a topical subject: a significant number of locks for large sea-going vessels are being designed or under construction all over the world. The new Panama Canal locks are the most famous example for sea-going vessels. With regards to inland shipping, the adaptation of existing canals requires on-going renovation of existing lock complexes.

From ship hydrodynamics point of view, lock manoeuvres involve more than just shallow water and bank effects. A series of additional effects such as density currents and the permeability of approach structures also have to be considered. Ultimately, complex ship hydrodynamics are involved, which are not yet fully understood. Several specific topics can be distinguished such as the behaviour of ships approaching and entering lock chambers, the design of approach lanes to the locks in order to reduce wave reflection and lateral forces and the development of more realistic ship – lock simulation models.

With respect to simulation models and numerical calculation methods to determine forces and moments due to ship behaviour in locks, the organisers would particularly welcome papers which focus on comparisons between the output of numerical models and benchmark model test data obtained at Flanders Hydraulics Research. A selection of the model test results has been made available by the project management and will be described in detail in this document.

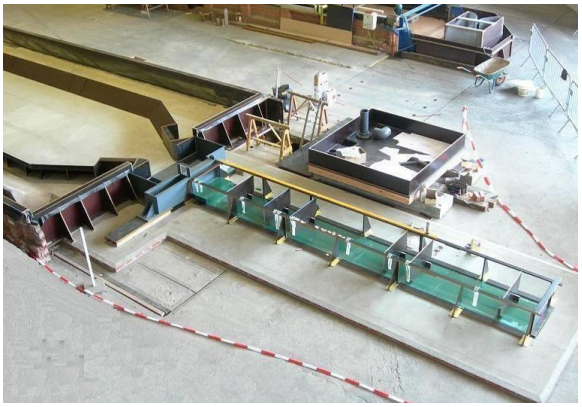
2. TESTS WITH SELF-PROPELLED MODELS

2.1 Background

In 2007-2008, model tests were executed to investigate the behaviour of vessels transiting the future Panama Canal Third Set of Locks, presently under construction. Each of the six lock chambers will have a maximum length of 488 m between the lock gates. The width of each chamber will be 55.0 m. The design ship is a so-called Post-Panamax 12000 TEU container carrier (Table 1). The main purpose was to determine design and operational criteria, such as the need and the configuration of lock approach walls, and required tug assistance. The task was assigned to the Consorcio Pos Panamax (CPP), which contracted Flanders Hydraulics Research, Antwerp, Belgium (FHR) to perform the model testing. Scientific support was provided by the Maritime Technology Division of Ghent University, Belgium. For a description of the test program and the main results, reference is made to [3] and [4].

2.2 Experimental setup

A 1/80 scale model of a lock and an approach channel has been built at Flanders Hydraulics Research (see Figure 1), according to the preliminary design of the Panama Canal Third Set of Locks. Scale models of different ship types were allowed to move on a straight line parallel to the locks' centreline, while the lateral motions are restrained by a guiding rail to which the ship model is connected at the bow and at the stern by means of guiding wheels. The frame with these wheels can be positioned eccentrically regarding the ship's longitudinal axis, which allows the model to sail along the beam with a variable eccentricity with respect to the lock axis.



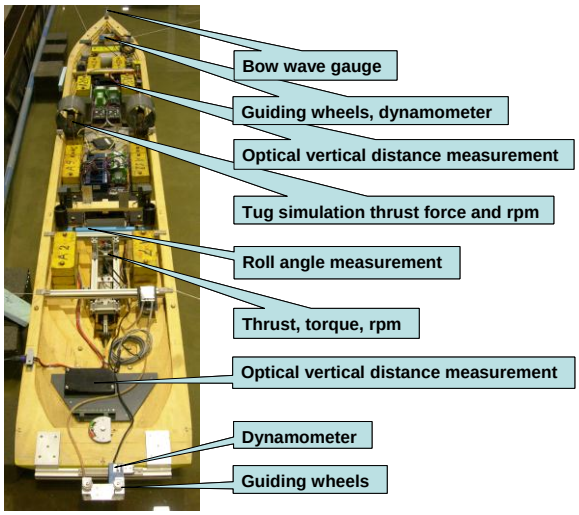


Figure 1. General view of the experimental setup.

The lateral forces in each connection point are measured by dynamometers, while the ship is free to move in vertical direction (heave, pitch and roll). The ship's velocity is controlled by changing the ship's propeller rate (rpm), or by tug assistance. This tug assistance is simulated by small model scale airplane propellers mounted on the ship model. These (air) propellers only exert forces in the longitudinal direction. A rudder is mounted on the ship model, but kept at a constant rudder angle of zero degrees.

2.3 Test scenarios

A test scenario is determined by a number of parameters:

- the ship model;
- the configuration of the approach wall;
- the overall water depth in the approach channel;
- the depth of the lock chamber with respect to the approach channel;
- the lateral position of the ship model with respect to the lock axis (eccentricity);
- density effects (fresh water – salt water);
- ship controls.

Table 1 - Ship characteristics

	12000 TEU ship	Scale model 1/80
L_{OA} (m)	365	4.563
L_{PP} (m)	348	4.350
B (m)	49	0.613
T (m)	15.2	0.190
C_B (-)	0.65	0.65
#blades	6	6
D_P (m)	9.40	0.118
P/D (-)	1.07	1.07
AEP (-)	1.03	1.03
Rudder area (m^2)	92	0.0144

Ship model: Tests have been carried out with three ship models: a 12000 TEU and a 8000 TEU container carrier and a bulk carrier. The first ship model represents the design vessel for the locks; all benchmark tests have been performed with this ship model (see Table 1 and Figure 2).

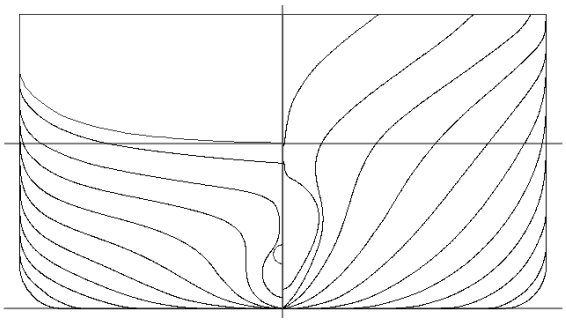


Figure 2. Design vessel for new Panama locks (12000 TEU container carrier): body plan

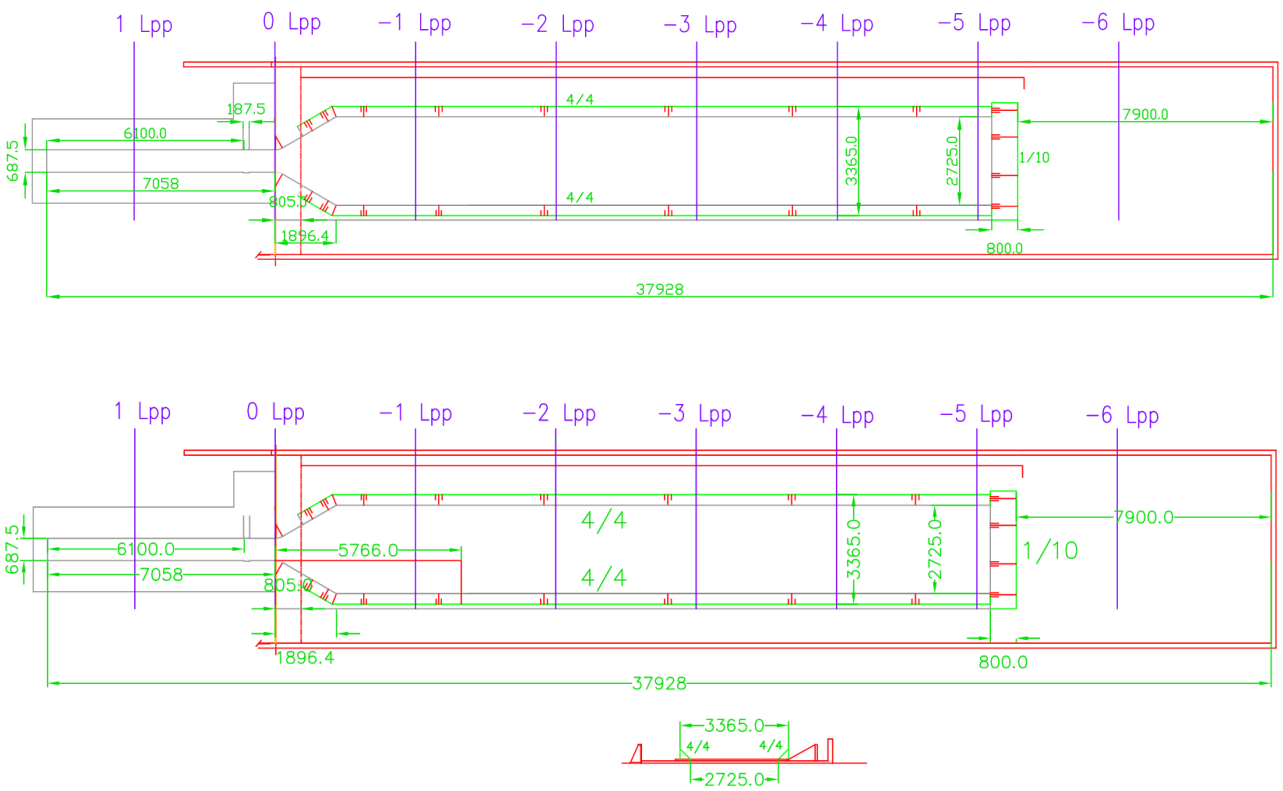


Figure 3. Different approach wall configurations on the Pacific entrance: No approach wall (top) – Closed approach wall (bottom).

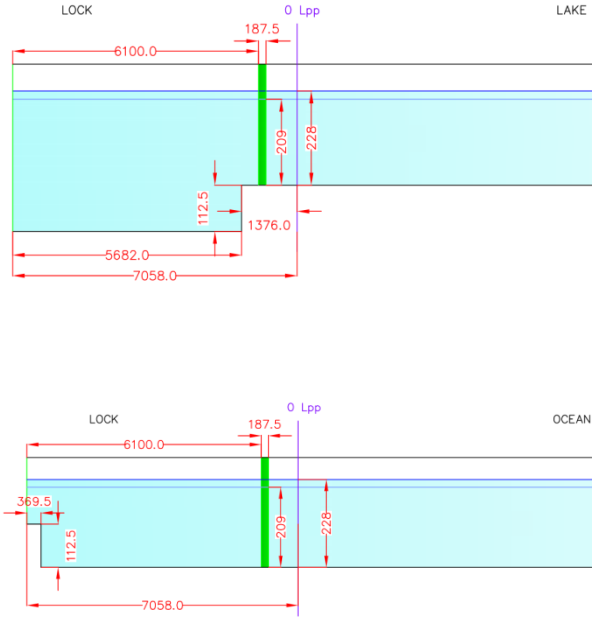


Figure 4. Transverse view of the ocean side (top) of and lake side (bottom) of the lock complex.

Approach wall configuration: At the entrance to the lock chamber four different approach wall configurations have been tested: a closed vertical wall, a permeable wall, a series of piles and no wall. The benchmark data only concern tests executed without approach wall and with a closed wall, see Figure 3.

Overall water depth in the approach channel: Most tests with the 12000 TEU container carrier model were carried out with an under keel clearance of 20% of the ship's draft. A selection of tests was also carried out with lower (10%) and higher (30%) UKC values.

Lockage sequence: As each new lock complex consists of three locks connecting the (Pacific or Atlantic) Ocean to the Gatún Lake, six different scenarios have to be considered:

- ocean ➔ lock (up)
- lock ➔ lock (up)
- lock ➔ lake (up)
- lake ➔ lock (down)
- lock ➔ lock (down)
- lock ➔ ocean (down).

The bottom level of the approach channel at the ocean side of the lock complex is equal to the bottom level of the lower lock chamber. The bottom level of the upper lock chamber, on the other hand, is lower than the bottom level of the approach channel at the lake side; in the case of the new Panama locks, this difference is about 9 m (or one third of the total height difference of 27 m) or 112.5 mm on model scale (see Figure 4). For this reason, the bottom level of the lock chamber was adjustable in the model test setup.

Eccentricity: When positioned in the centre of the lock chamber, the design vessel has a horizontal clearance of 3.0 m at each side with respect to the lock walls. Tests were also carried out with two eccentricities: 1.5 m and 0.6 m off wall (19 mm and 7.5 mm model scale, respectively).

Density effects: Due to the difference in density between the water in the lock chamber and in the approach channel, density exchange currents are generated during spilling operations and during the opening of the lock gate. In order to investigate both effects, the model scale lock was equipped with a gate that could be opened according to a realistic opening law, and spilling outlets were constructed in front of the lock gate (see Figures 5 and 6). Two culverts were provided on each side. The outlet area of the culverts on each side was 0.545m long and 0.082m high. While brackish water was used in the approach channel (density: 1012 kg/m³) during the entire experimental program, the lock was filled with fresh water during density exchange current tests. The fresh water was dyed red so that its flow is visible during recording. During these tests the ship could be waiting along the approach wall (static test) or already be approaching the lock (dynamic test). During the static tests the ship was connected to the guiding rail with a dynamometer which disabled the longitudinal acceleration of the vessel, while measuring the longitudinal force acting on the vessel. During dynamic tests the time between the initiation of the opening of the gates and the entrance bow in the lock was a significant parameter. Reflecting floats were present on the water allowing to determine the magnitude and direction of the surface flow velocity.

Ship controls: The use of the ship's propeller during each test is prescribed as a function of the ship's longitudinal position. The tug simulating air fans are used to keep the ship's speed as close as possible to a desired value, which is also given as a function of the longitudinal position.

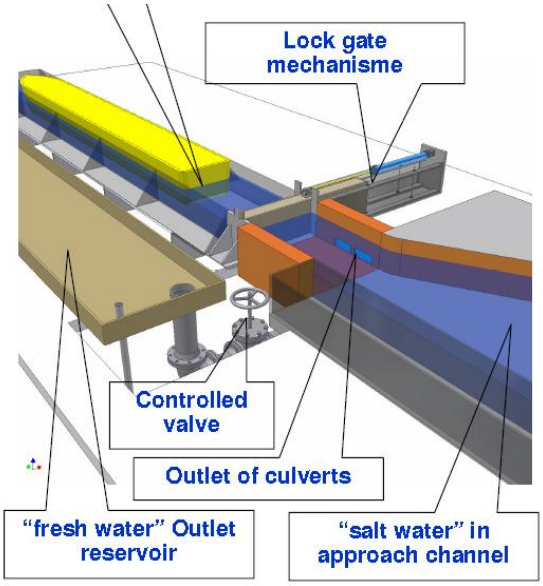


Figure 5. Setup for density effects.

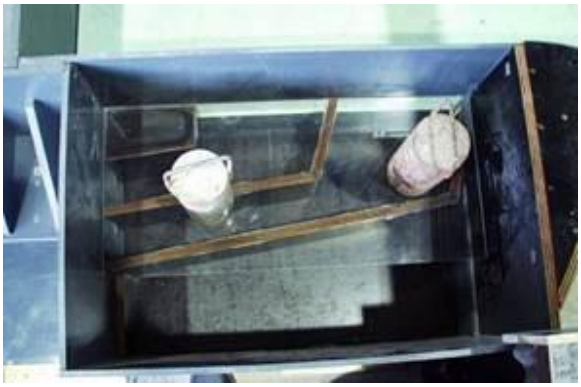


Figure 6. Detailed top view of the two culverts that were used to simulate the lock spill.

2.4 Conventions

All test results are provided in model scale dimensions. The graphs are plotted as a function of time; for lock entry or exit tests, the origin of the

time scale corresponds with alignment of the ship's fore perpendicular with the knuckle, i.e. the beginning or end of the narrow section. The longitudinal position of the ship in the lock is also referred with respect to this point.

A ship-fixed coordinate system is used for determining ship kinematics and dynamics. The origin is located on the waterline, at half distance between the fore and the aft perpendiculars. The longitudinal Ox-axis is pointing ahead, the lateral Oy-axis is directed towards starboard, and the vertical Oz-axis is positive in downward direction. As a result, longitudinal forces are positive if directed ahead, lateral forces to starboard are positive, as are moments with the bow to starboard (see Fig. 2). Eccentricity with respect to the lock centreline are positive if the ship is positioned to the starboard side of the centreline. Concerning vertical motions, a sinkage of the ship is considered to be positive.

2.5 Benchmark tests

Table 2 gives an overview of the main characteristics of the benchmark tests. All measured test results are displayed in Figures 7 through 12. The data is available in a digital file format on request.

Table 2. Overview of benchmark tests with self-propelled models.

	Ship type	Water depth (m)	Approach wall	Test type	Eccentricity (m)	Density effect
A	12000 TEU	0.228	Closed	Ocean➔Lock	0.000	No
B		0.209	Closed	Ocean➔ Lock	0.000	No
C		0.228	None	Lock ➔Ocean	0.019	No
D		0.228	Closed	Lock ➔Ocean	0.019	No
E		0.228	Closed	Lock ➔ Lake	0.019	No
F		0.228	Closed	Ocean ➔ Lock	0.000	Static

Two lock entry tests with a 12000 TEU container carrier model in the closed approach wall configuration have been selected as benchmark tests (A, B).

The first test (A) was carried out with an under keel clearance of 20% of the ship's draft. The ship model was accelerated by means of its own propeller until a speed of 4 knots (full scale) was reached. At that time the propeller rpm was set to zero. One ship length before the ship's bow reached the approach wall (if any), the propeller rate was set to dead slow while the ship's speed was maintained by the "tugs" to a value of 2 knots full scale (0.115 m/s model scale) until the ship was completely within the narrow section. Finally the model was stopped with all the power of the ship control available (ship propeller and fans). The following graphs are shown as a function of time:

- Position (in ship lengths), set speed and actual speed;
- Longitudinal forces: propeller thrust and tug force, as well as propeller rate;
- Lateral force and yawing moment;
- Absolute running sinkage of the ship's bow and stern; height of bow wave (i.e. water level at the bow relative to the ship model) and water level elevation at the closed lock door.

Test B follows a similar scenario, but is carried out at an under keel clearance of only 10%. Moreover, the propeller is only used during the acceleration phase, while during the passage of the approach wall and the entrance of the lock the ship's speed was controlled by tugs only.
Tests C, D and E are lock exit tests: the ship model starts at rest in the lock chamber and is accelerated by its own propeller (dead slow) and the tugs (maximum available power) to a speed of 2 knots full scale. During these three tests the position of the ship was eccentric with respect to the centreline of the lock chamber. Test C was carried out in a configuration without approach wall, while D and E were executed within the closed approach wall configuration. Tests C and D concern lock-ocean transits, while during test E the ship model left the lock in the direction of the lake; therefore, the under keel clearance was constant during the two first tests, while the water depth in the lock chamber was larger than outside the lock during test E.

Test F is a static test with density exchange. Tugs and propeller are inactive. The longitudinal forces required to keep the longitudinal position fixed are displayed, as well as the time history of the discharge of fresh water and of the opening of the lock gate. The flow pattern at the surface at selected time steps is given as well, see Figure 13.

3. CAPTIVE MODEL TESTS

3.1. Background

In the 1990s a systematic captive model test series was carried out in the towing tank for manoeuvres in shallow water (co-operation Flanders Hydraulics Research – Ghent University) in Antwerp as a first step in a feasibility study for receiving bulk carriers with larger beam in the Pierre Vandamme Lock in Zeebrugge. This lock has a length of 500m, a width of 57 m and a depth of 18.5m. A scale model (1/75) of the lock configuration was constructed in the towing tank, with special attention to the asymmetric layout of the approach channel.

Eventually, the waterway authorities decided not to

have the problem fully investigated. Nevertheless, the model test series provide a lot of information on the behaviour of ships approaching and entering a lock. Flanders Hydraulics Research, who is the owner of the test results, decided to make the measurements of a limited number of tests public as benchmark data.

3.2. Experimental setup

The towing tank at Flanders Hydraulics Research has an overall length of 88m and a width of 7.0 m, allowing a maximum water depth of 0.5 m. It is equipped with a planar motion carriage for captive manoeuvring tests. A fully automated operation allows unmanned testing 24 hours a day, 7 days a week. A full description is given in [5].

A scale model of the approach channel to the lock was constructed in the towing tank by means of vertical walls, as shown in Figure 14 in an earth-fixed co-ordinate system (x_0,y_0).

The ship model was a 1/75 scale model of a bulk carrier, with main dimensions listed in Table 3; the body plan is given in Figure 15.

Table 3 - Ship characteristics: bulk carrier

	Full scale	Scale model 1/75
L_{OA} (m)	265.0	3.533
L_{PP} (m)	259.2	3.456
B (m)	43.0	0.573
T (m)	17.342	0.231
C_B (-)	0.854	0.854
#blades	4	4
D_P (m)	6.95	0.093
P/D (-)	0.663	0.663
AEP (-)	0.630	0.630
Rudder area (m^2)	65.7	0.0117

All tests started with the model's midship section at zero x_0-position. After an acceleration phase over a distance of 2 m, the model was towed with constant velocity until the model's midship section reached a position x_0 = 27.5m and was then decelerated over a distance of 0.5m. Following parameters were varied: under keel clearance, eccentricity, drift, speed, propeller rate. Not all combinations can be considered as realistic.

3.3. Benchmark tests.

Three model tests have been selected for benchmark data. During these three tests, the propeller was turned off. The variation of the other parameters is summarized in Table 4.

Table 4. Overview of benchmark tests with captive models

	Water depth to draft ratio h/T (-)	Speed (m/s)	Drift angle (deg)	Eccentricity y_0-$y_{0,CL}$ (m)
G	1.2	0.15	0.0	0.000
H	1.2	0.10	-2.0	0.000
I	1.1	0.15	0.0	0.050

The test results are displayed in Figures 16 to 18. For each test, plots are given of the longitudinal and lateral force components and the yawing moment exerted by the carriage on the ship model. The vertical displacement of the fore and aft perpendicular are given as well. All measurements are plotted as a function of the longitudinal position x_0 of the model's midship section. For conventions concerning ship kinematics and dynamics, reference is made to section 2.4.

4. CONCLUDING REMARKS

By publishing these benchmark tests, the *Knowledge Centre for Manoeuvring in Shallow and Confined Water* has the intention to stimulate research on ship behaviour in locks by providing research institutes experimental data that can be used for evaluating numerical methods and mathematical models.

The test results can be used in publications and reports on condition that reference is made to this paper and that the model tests have been executed at Flanders Hydraulics Research, Antwerp. For the tests described in Chapter 2, mention must be made of the Panama Canal Authorities who commissioned the tests.

5. REFERENCES

[1] ELOOT, K.; VANTORRE, M. (editors), *International Conference on Ship Manoeuvring in Shallow and Confined Water: Bank Effects (Antwerp, May 2009)*, The Royal Institution of Naval Architects, London, 2009.

[2] PETTERSEN, B.; BERG, T.E.; ELOOT, K.; VANTORRE, M. (editors), *2nd International Conference on Ship Manoeuvring in Shallow and Confined Water: Ship to Ship Interaction (May 18-20, 2011, Trondheim, Norway)*, The Royal Institution of Naval Architects, London, 2011.

[3] DELEFORTRIE, G., WILLEMS, M., VANTORRE, M. & LAFORCE, E., Behavior of post panama vessels in the Third Set of Panama locks, *International Conference on Marine Simulation and Ship Maneuverability (MARSIM*

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[4] DELEFORTRIE, G., WILLEMS, M., LAFORCE, E., VANTORRE, M., DE MULDER, T., DE REGGE, J. & WONG, J., Tank test of vessel entry and exit for third set of Panama locks, *Proceedings of the International Navigation Seminar following PIANC AGA 2008*, pp. 517-523, Beijing, China. Communications Press, 2008.

[5] VAN KERKHOVE, G.; VANTORRE, M.; DELEFORTRIE, G., Advanced model testing techniques for ship behaviour in shallow and confined water. *AMT '09 Conference Proceedings*, pp. 158-172, 2009.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to the Panama Canal Authorities for their permission to publish the results of the tests with self-propelled ship models described in Chapter 2.

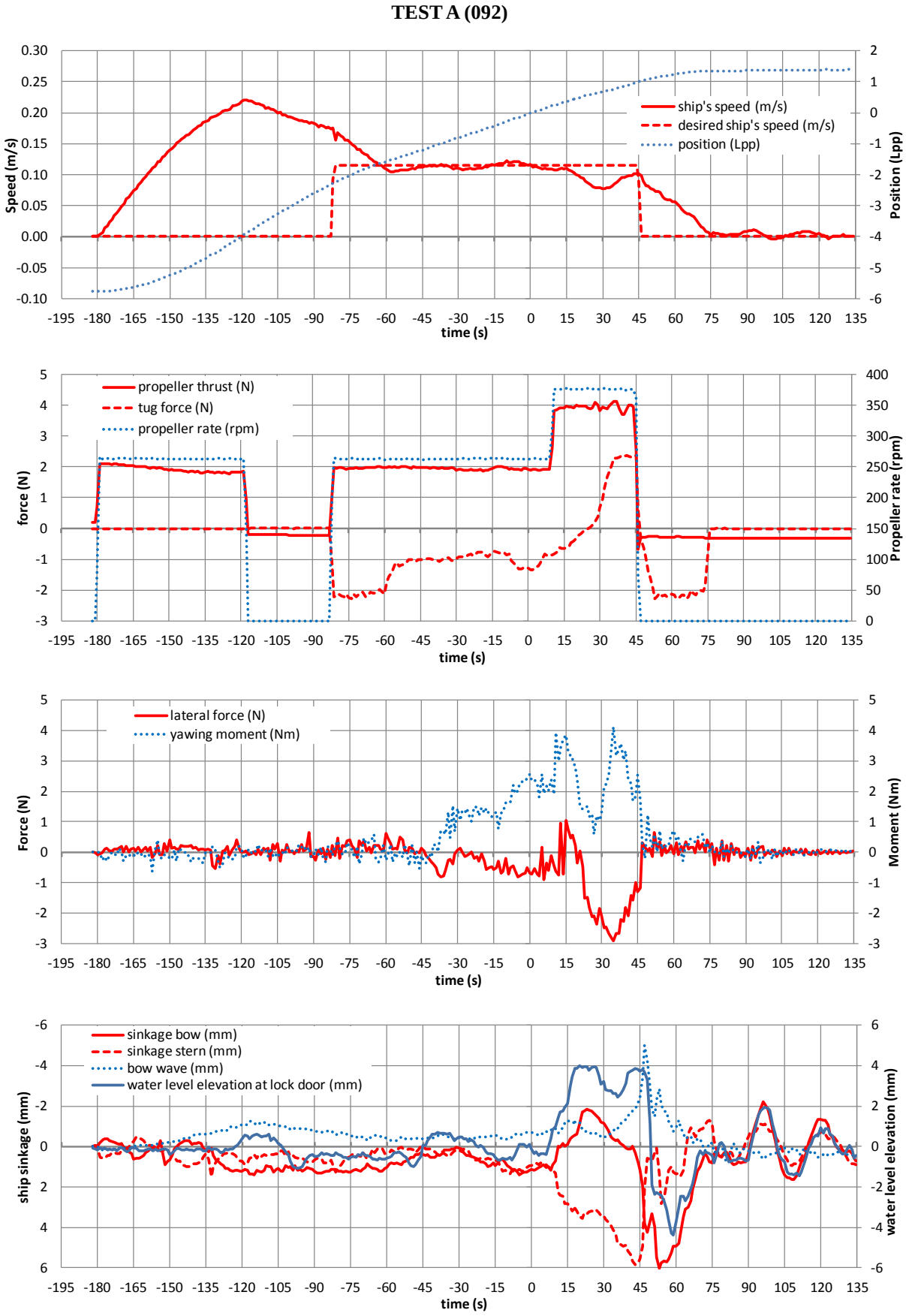

Figure 7. Benchmark test A.

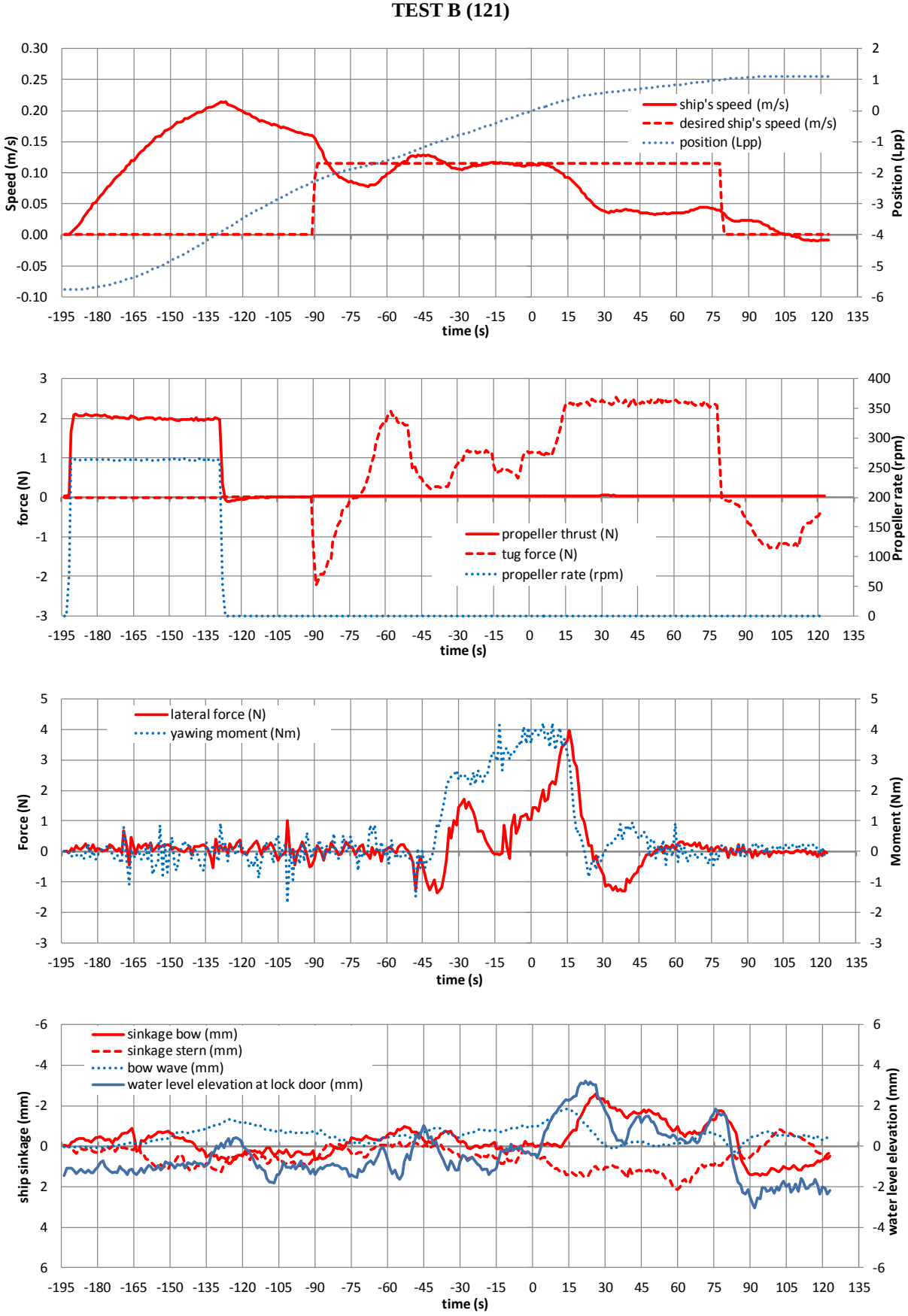

Figure 8. Benchmark test B.

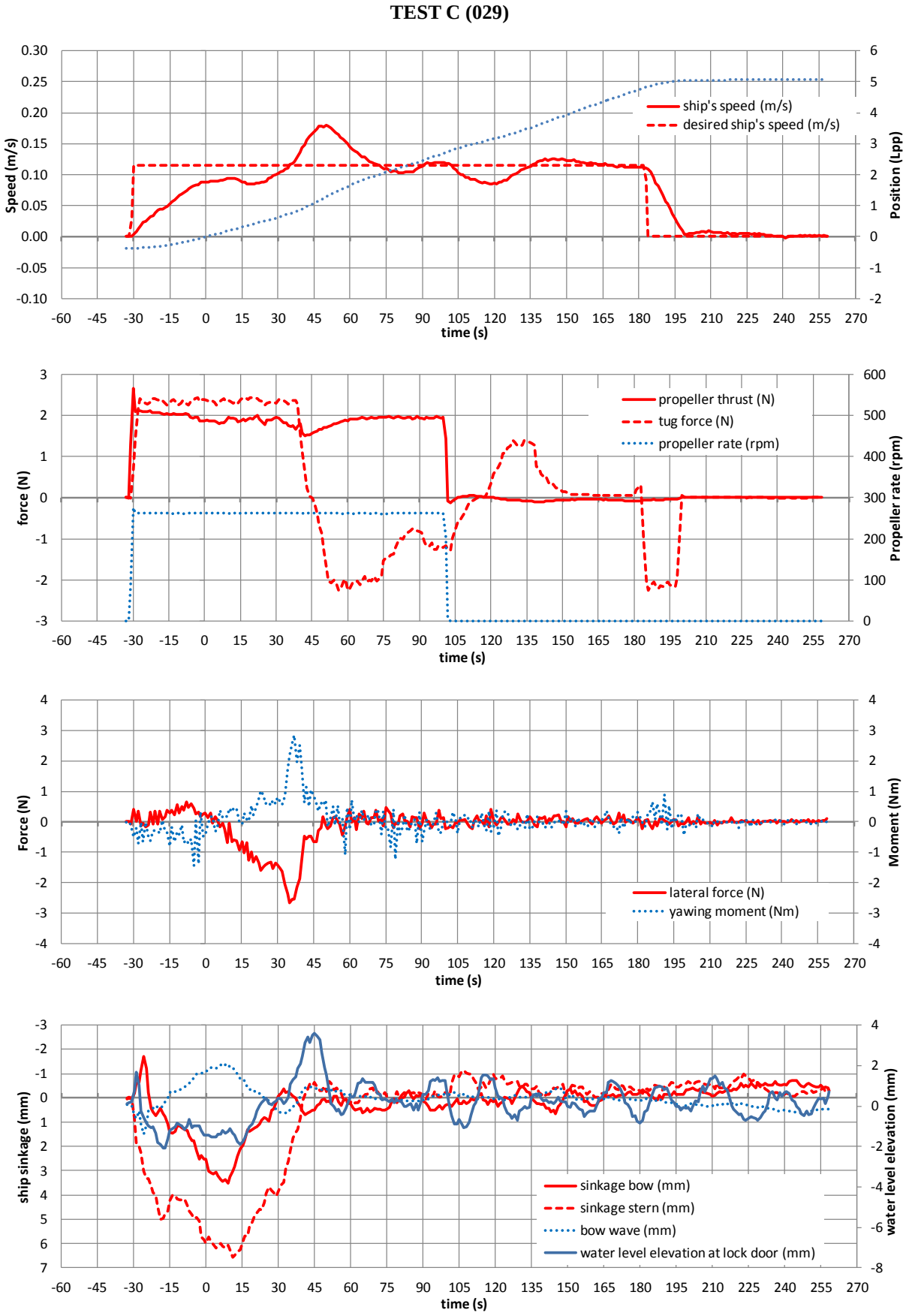

Figure 9. Benchmark test C.

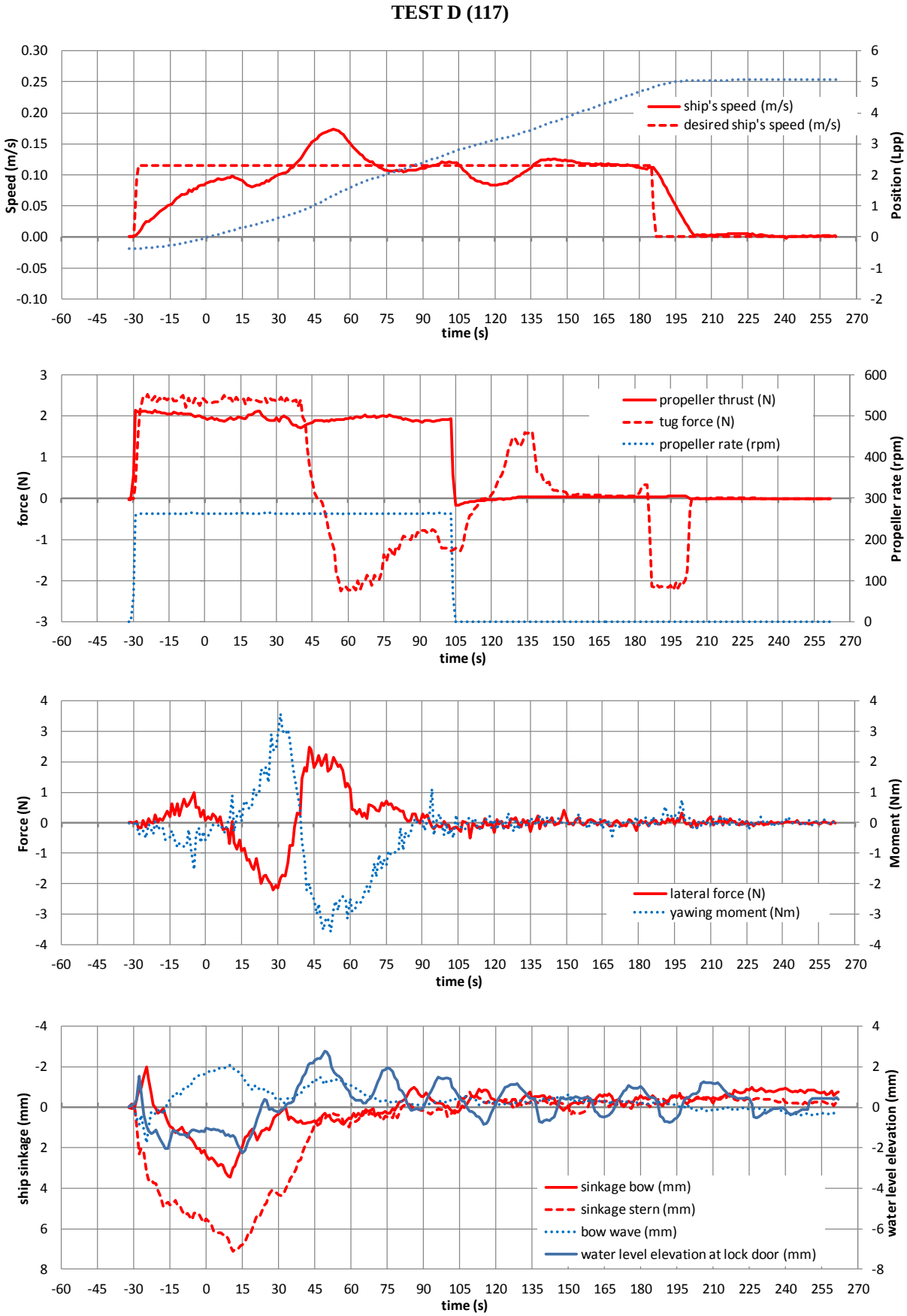

Figure 10. Benchmark test D.

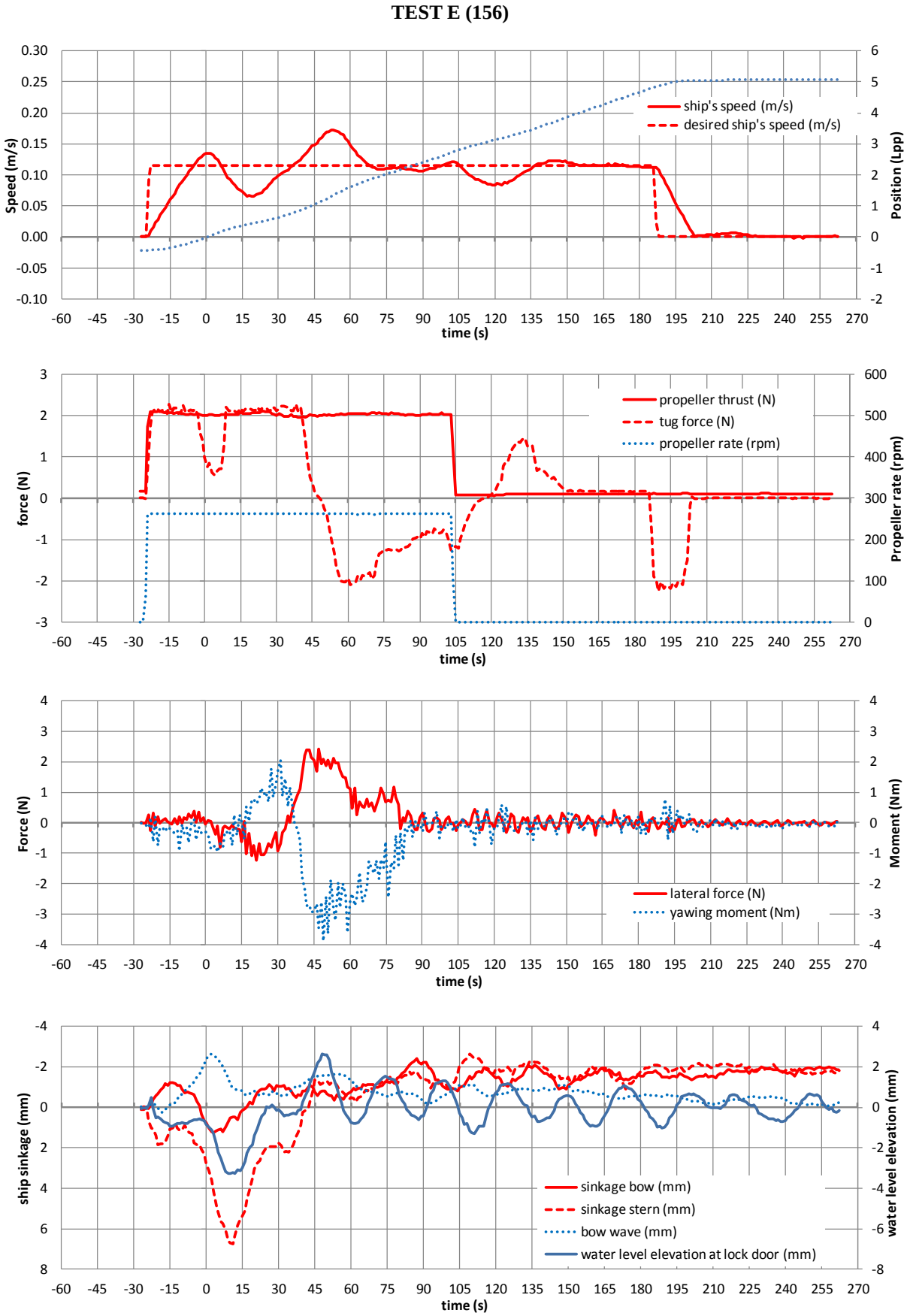

Figure 11. Benchmark test E.

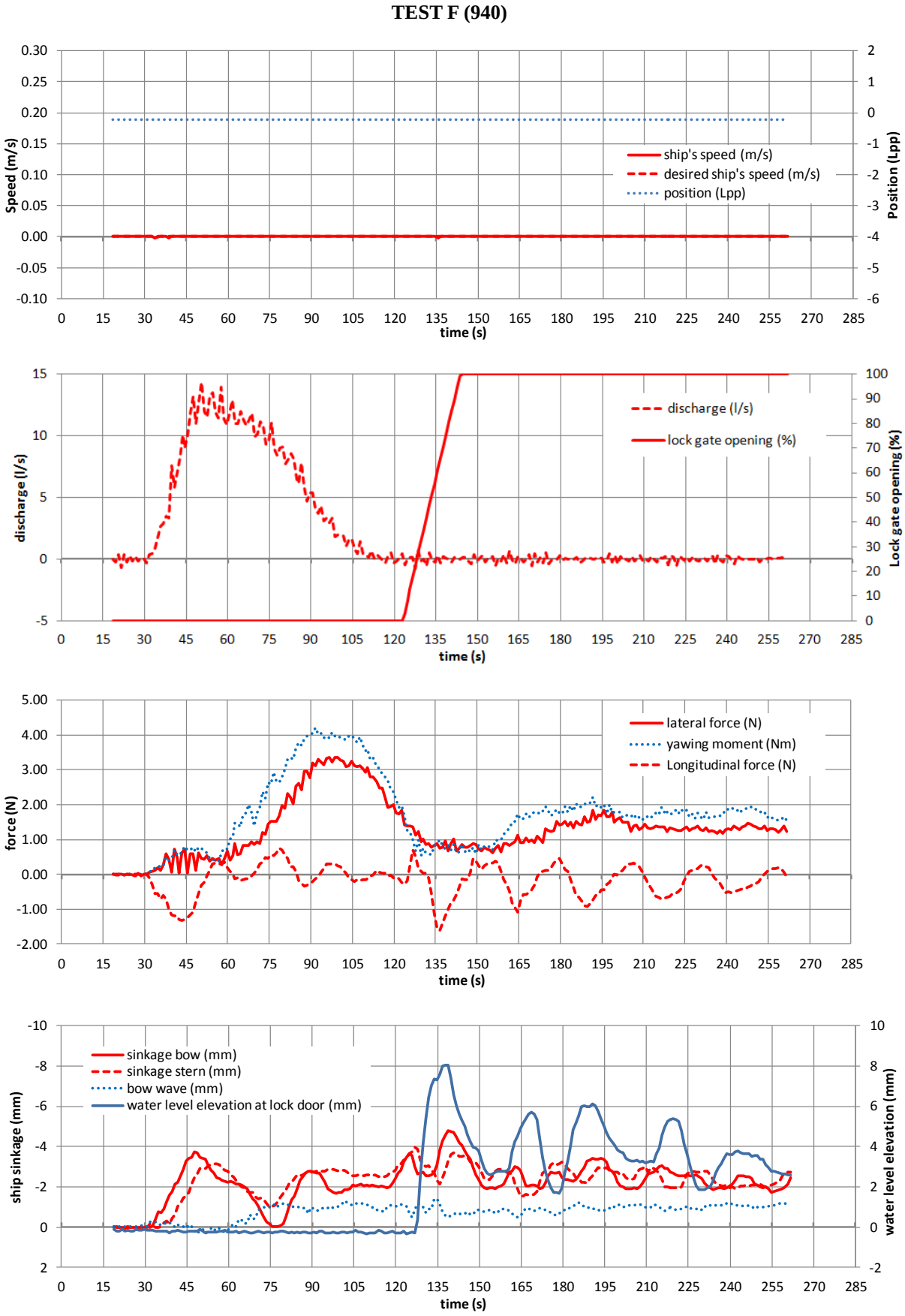

Figure 12. Benchmark test F.

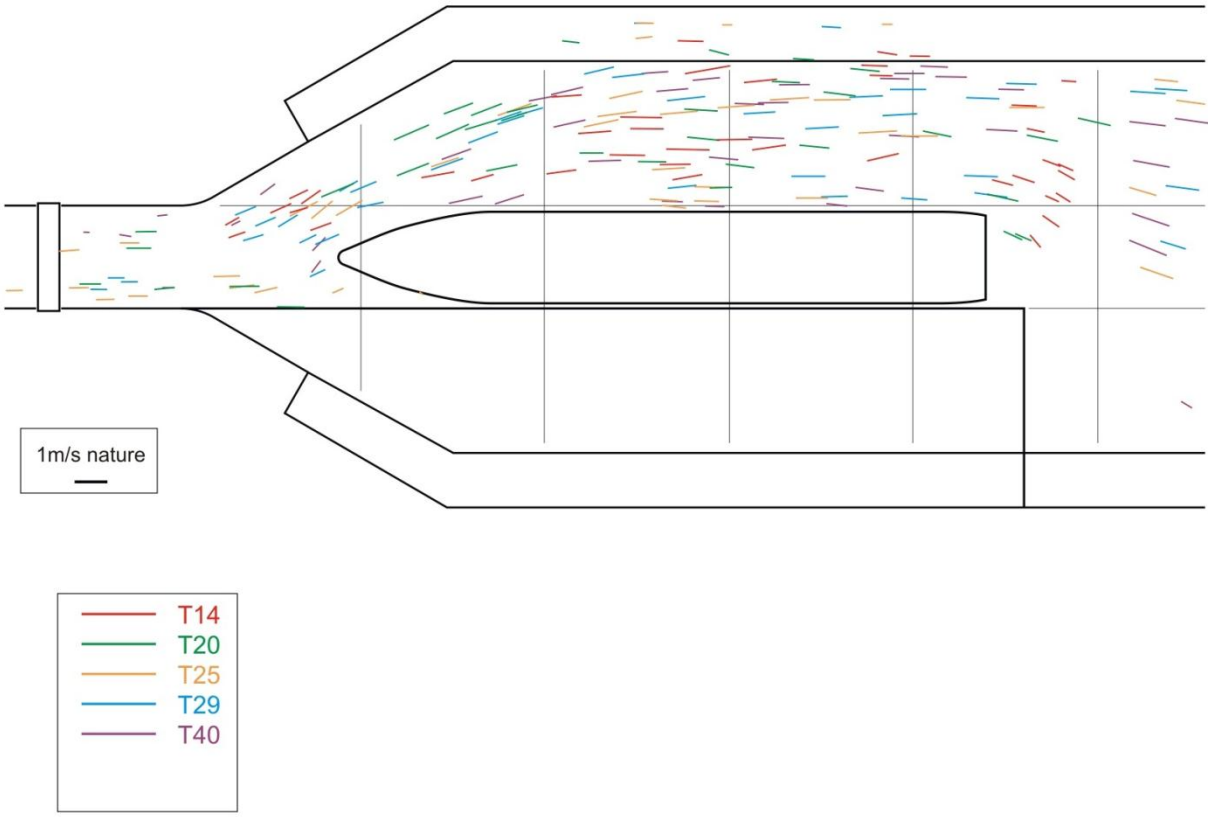

Figure 13. Benchmark test F: surface flow at discrete time steps (Tm denotes the situation m minutes full scale after the start of the test; m has to be multiplied by 6.7 to obtain the model time in seconds).

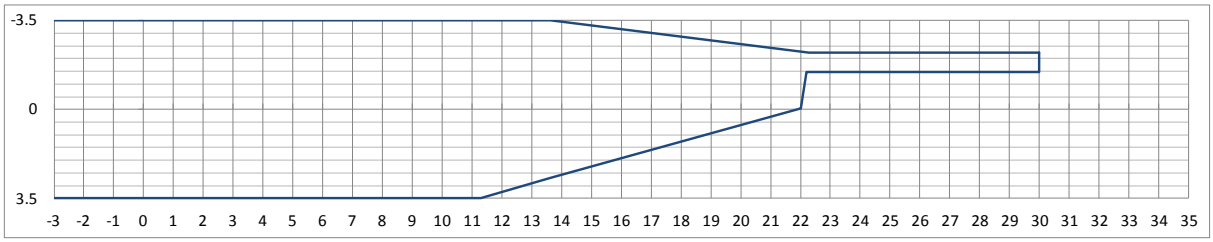

Figure 14. Lock configuration in towing tank for captive model tests (benchmark tests G, H and I). The tank walls are determined by y0 = ±3.50 m, the lock centerline by y0 = -1.846 m. Contour points are given by the table below.

x_0 (m)	y_0 (m)	x_0 (m)	y_0 (m)
11.305	3.500	13.621	-3.500
22.000	-0.028	22.291	-2.224
22.195	-1.468	30.000	-2.224
30.000	-1.468		

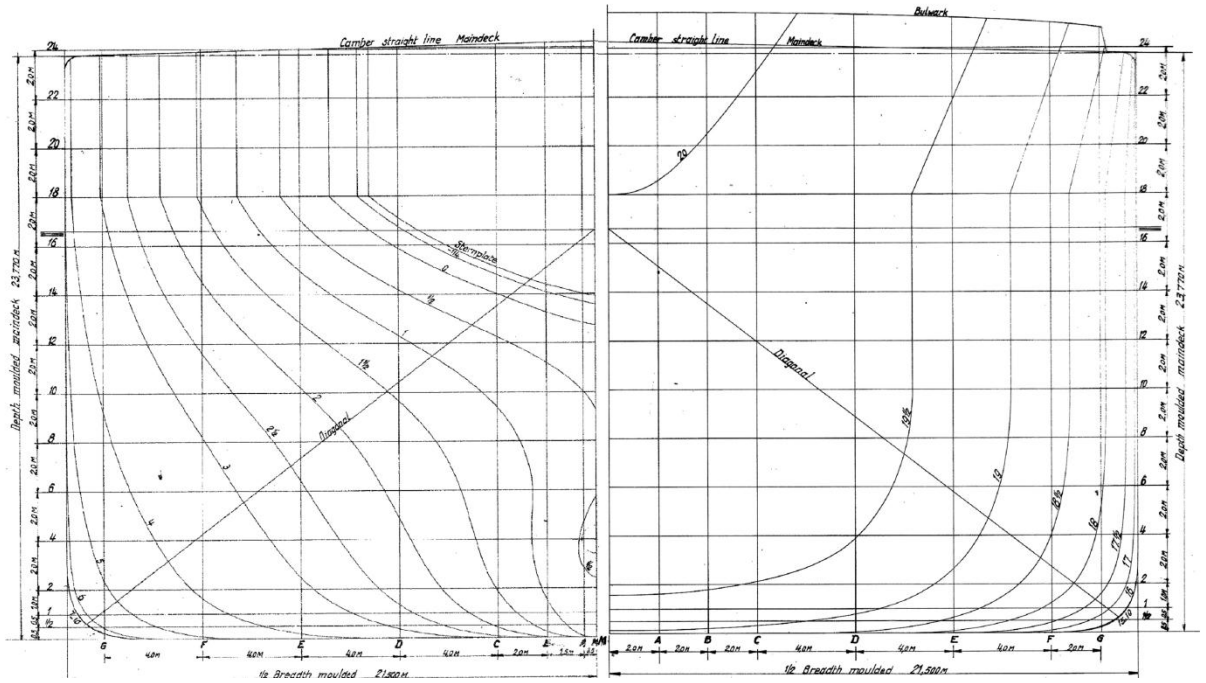

Figure 15. 1/75 scale model of bulk carrier used during captive benchmark tests: body plan

TEST G

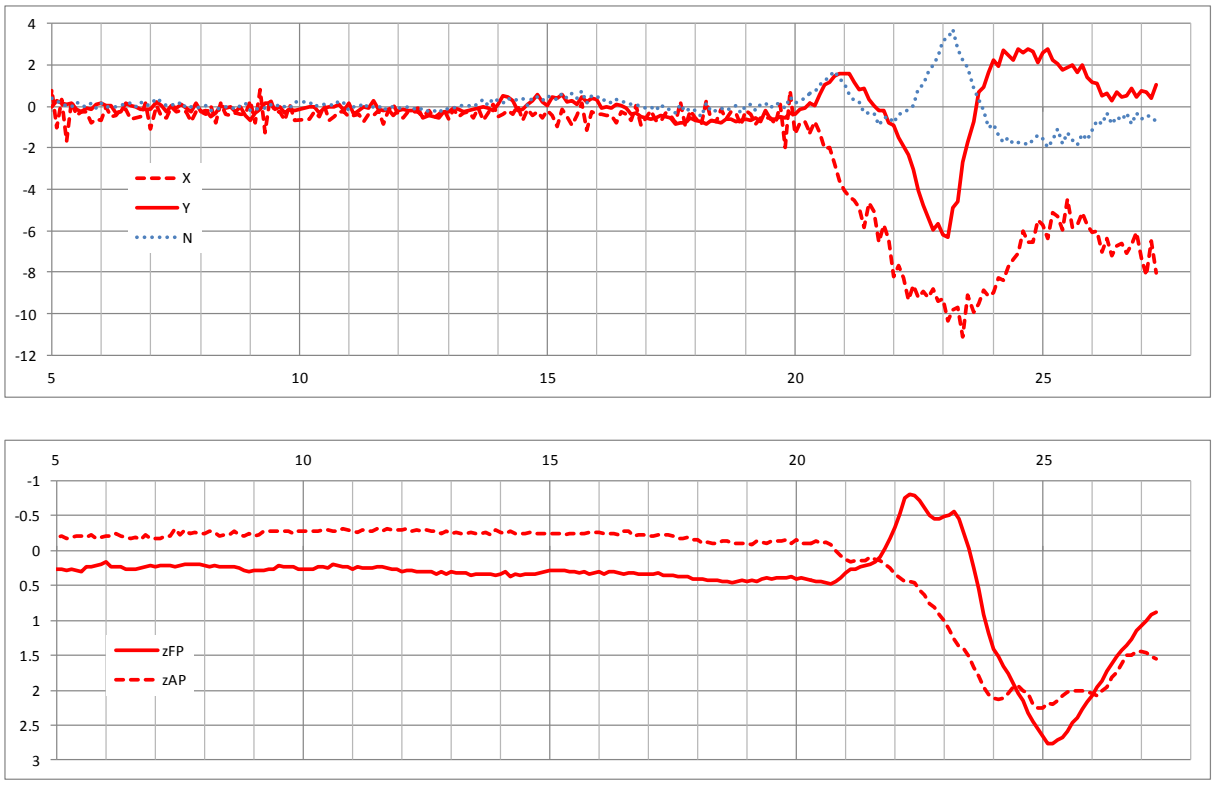

Figure 16. Benchmark test G.

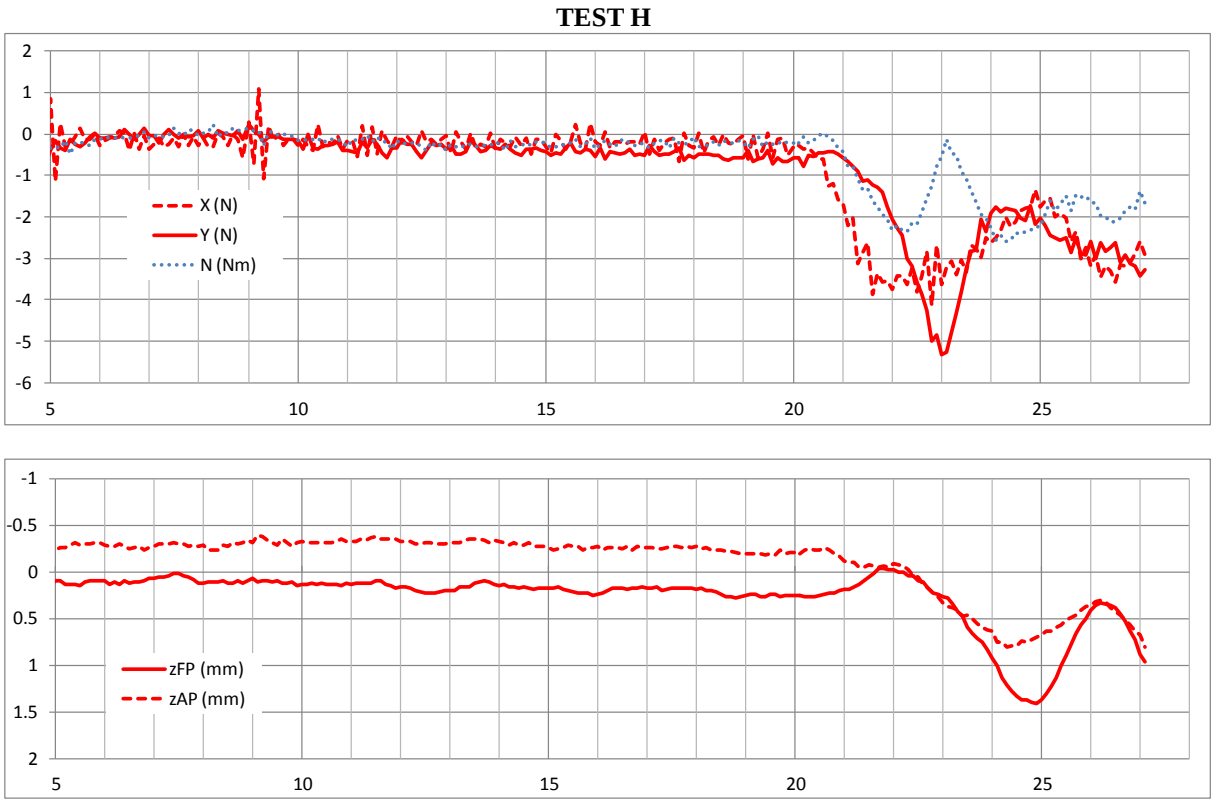

Figure 17. Benchmark test H.

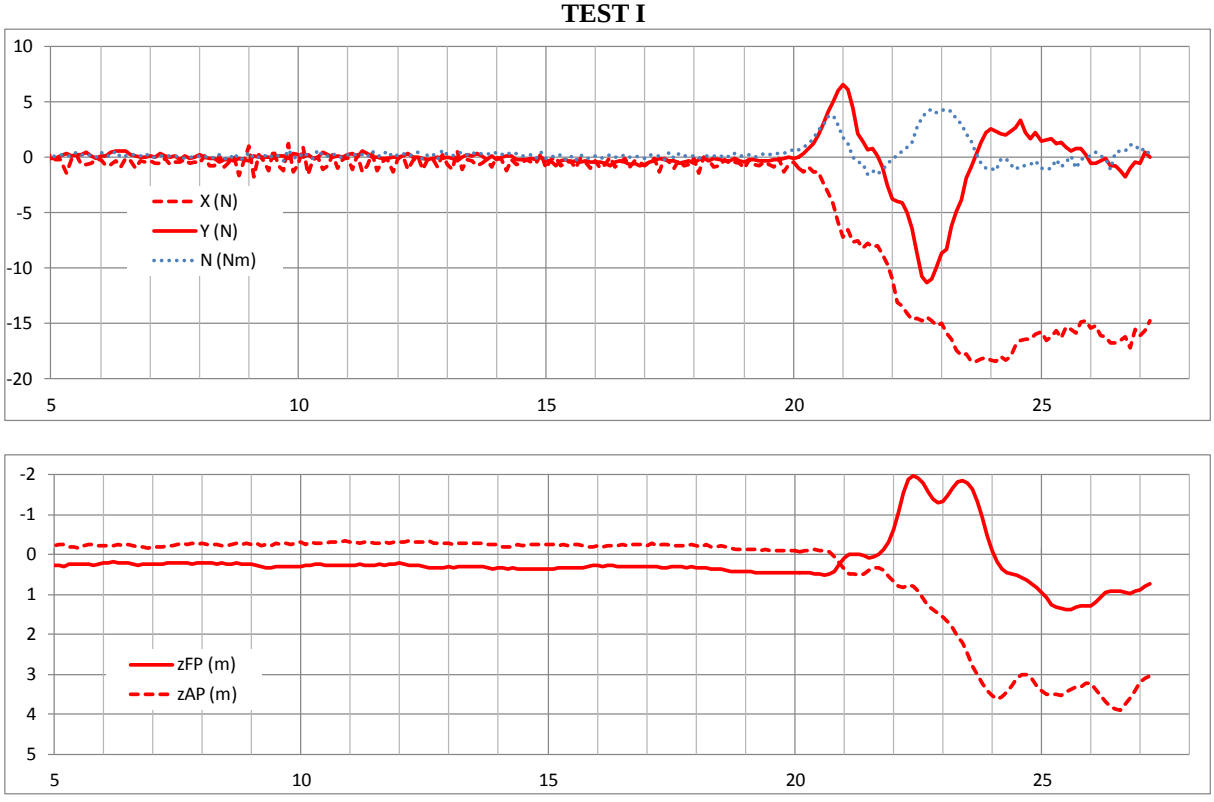

Figure 18. Benchmark test I.