4th MASHCON, Hamburg - Uliczka et al. (eds) - © Bundesanstalt für Wasserbau ISBN 978-3-939230-38-0 (Online)
DOI: 10.18451/978-3-939230-38-0_29

RUNNING SINKAGE AND TRIM OF THE DTC CONTAINER CARRIER IN HARMONIC SWAY AND YAW MOTION: OPEN MODEL TEST DATA FOR VALIDATION PURPOSES

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SUMMARY

After successful conferences on bank effects, ship – ship interaction and ship behaviour in locks, the Fourth International Conference on Ship Manoeuvring in Shallow and Confined Water (MASHCON) has a non-exclusive focus on ship – bottom interaction. With increasing ship sizes in vertical and horizontal dimensions, a clear understanding of the interaction between a ship and the bottom of the waterway will help to improve the operations and increase the safety of manoeuvring ships. 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 while executing tests with the DTC container carrier in the framework of the European SHOPERA project. The benchmark data are harmonic yaw and harmonic sway tests with the bare hull of the DTC at full draft and 20% under keel clearance at rest.

NOMENCLATURE

A_M	Midship section area (m²)
B	Breadth of ship (m)
C_B	Block coefficient (-)
Fr	Froude number based on L_{PP} (-)
Fr_h	Froude number based on water depth h (-)
Fr_{crit}	Critical value of Froude number (based on water depth) accounting for blockage (non-dimensional "Schijf velocity") (-)
GM_T	Transverse metacentric height (m)
h	Water depth (m)
I_{xx}	Mass moment of inertia about Ox-axis (kg m²)
I_{yy}	Mass moment of inertia about Oy-axis (kg m²)
I_{zz}	Mass moment of inertia about Oz-axis (kg m²)
KG	Height of centre of gravity above keel (m)
L_{PP}	Length between perpendiculars (m)
n	Propeller rate (rps)
N	Yaw moment (Nm)
O_0	Origin of the earth-bound axis system
$O_0x_0y_0z_0$	Earth-bound reference system
O	Origin of the ship-bound axis system
Oxyz	Ship-bound reference system
O'	Origin of the horizontal bound towing carriage system
O'x'y'z'	Horizontal bound towing carriage system
p	Roll velocity (rad/s)
q	Pitch velocity (rad/s)
r	Yaw velocity (rad/s)
r_A	Amplitude of yaw velocity (rad/s)
S	Wetted surface (m²)
t	Time (s)
t_{harm}	Start time of harmonic motion (s)
Δt	Time interval (s)
T	Test period (s)
T_{design}	Design draft (m)
u	Longitudinal velocity component (m/s)
v	Lateral velocity component (m/s)
v_A	Amplitude of sway velocity (m/s)
V	Velocity (m/s)
w	Vertical velocity component (m/s)
x_G	Longitudinal coordinate of the centre of gravity (m)
X	Longitudinal force (N)
Y	Lateral force (N)
$y_{0,A}$	Sway amplitude (m)
β	Drift angle (deg)
δ_R	Rudder angle (deg)
φ	Roll angle (deg)
θ	Pitch angle (deg)
ψ	Course angle (deg)
ψ_A	Yaw amplitude (deg)
Ω	Canal cross section area (m²)
AP	Aft Perpendicular
CG	Centre of Gravity
DTC	Duisburg Test Case
FHR	Flanders Hydraulics Research
FP	Fore Perpendicular
LCB	Longitudinal Centre of Buoyancy
UKC	Under Keel Clearance

1 INTRODUCTION

After successful conferences on bank effects [1] (Antwerp, May 2009), ship – ship interaction [2] (Trondheim, May 2011) and ship behaviour in locks [3] (Ghent, May 2013), the Fourth Conference on Manoeuvring in Shallow and Confined Water (MASHCON) has a non-exclusive focus on ship – bottom interaction. This conference is organised in Hamburg, Germany, from 23 to 25 May 2016, by the Federal Waterways Engineering and Research Institute, Flanders Hydraulics Research and Ghent University (Maritime Technology Division). 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.

With increasing ship sizes in all dimensions and optimisations in the design and maintenance of waterways, a clear understanding of the interaction between a ship and the bottom of the waterway helps to improve the operations and to increase the safety of manoeuvring ships. The extension of knowledge on ship-bottom interaction focusses on:

- Squat
- Shallow water effects on ship behaviour
- Effect of bottom topography on ship behaviour
- Effect of fluid mud layers on ship behaviour
- Probability and hydrodynamic aspects of bottom contact
- Required manoeuvring margin
- Regulations and design guidelines
- Nautical bottom – equivalent bottom: definition and determination

These topics are covered from different points of view:

- Practical aspects
- Simulation models
- Field observations
- Experimental results
- Numerical calculations, including CFD

To open a joined research effort on the validation and verification of the different research methods, the Knowledge Centre has selected model test data which were obtained while executing tests with a container carrier in the framework of the European SHOPERA project (Energy Efficient Safe SHip OPERAtion [4]).

2 MODEL TEST SET-UP

Tests have been executed with a scale model of the Duisburg Test Case (DTC) container ship in the Towing Tank for Manoeuvres in Shallow Water (cooperation Flanders Hydraulics Research – Ghent University, Antwerp Belgium).

The following sections describe the ship model, the towing tank, the chosen reference axis systems and the environmental conditions.

2.1 SHIP MODEL

The Duisburg Test Case (DTC) is a hull design of a typical 14,000 TEU container ship, developed at the Institute of Ship Technology, Ocean Engineering and Transport Systems for benchmarking and validation of numerical methods [5].

The DTC is a single-screw vessel with a bulbous bow, large bow flare, large stern overhang and a transom stern. The ship is tested as bare hull and as appended hull equipped with a fixed-pitch five-bladed propeller with right rotation and a twisted rudder with a Costa bulb.

The ship particulars are presented in
Table 1. The ship model is made at a scale of 1:89.11.

Table 1. Ship particulars

Particulars		Ship	Model
Scale	-	1	1:89.11
L_{PP}	m	355	3.984
B	m	51	0.572
T_{design}	m	14.5	0.163
Displacement	m³	173,925	0.2458
C_B	-	0.661	0.661
S	m²	22,051	2.777
LCB from AP	m	174.032	1.953
KG	m	19.78	0.222
GM_T	m	5.17	0.058
I_{xx}	kgm²	7.6976E+10	13.7
I_{yy}	kgm²	1.1889E+12	211.6
I_{zz}	kgm²	1.2316E+12	219.2

2.2 TOWING TANK

The characteristics of the towing tank also determine the model test set-up. The dimensions of the towing tank (Table 2) allow the use of ship models with a length of typically 4 m. The particulars and possibilities of the towing tank have been extensively described in [6]. In captive mode the ship model can be positioned in the three horizontal degrees of freedom (surge, sway and yaw) with roll fixed or free and heave and pitch always free. Roll was fixed during the tests.

Table 2. Main dimensions of the towing tank at FHR

Total length	87.5 m
Effective length	68.0 m
Width	7.0 m
Maximum water depth	0.5 m
Length of ship models	3.5 to 4.5 m

2.3 REFERENCE AXIS SYSTEMS

In Figure 1, Figure 2 and Figure 3 three rectangular and right-handed coordinate systems are presented. $O_0x_0y_0z_0$ is the earth-bound reference system of the towing tank. The vertical O_0z_0-axis points downwards, while the horizontal O_0x_0- and O_0y_0-axes are located at the free water surface at rest. $O_0x_0z_0$ is the longitudinal vertical symmetry plane of the towing tank.

Oxyz is a ship-bound coordinate system: the origin O is located at the intersection of the midship's section (at ½ L_{PP} fore of AP and ½ L_{PP} aft of FP) Oyz, the ship's vertical longitudinal plane of symmetry Oxz and the waterline Oxy at rest. The orientations of the positive coordinate axes are directed from stern to bow for the longitudinal axis Ox, towards starboard for the transversal axis Oy and from the waterline towards the keel for the Oz-axis. For a right-handed axis system looking in the positive direction of each axis, the rotation angles are positive clockwise in common science definition.

O'x'y'z' is a horizontal-bound towing carriage coordinate system with origin O' that does not change with heave, pitch nor roll motions of the ship; as a result, O'x'y' always remains horizontal. At rest, Oxyz and O'x'y'z' coincide. O'x'y'z' is used during testing and thus also during modelling the ship hydrodynamics based upon model tests.

For clarification the body Oz-axis in Figure 2 is rotated with θ (Oxz-plane) and in Figure 3 with φ (Oyz-plane) with respect to the axis O_0z_0 or the towing carriage axis O'z'. As mentioned above, during the benchmark tests the roll angle φ was kept fixed at 0 deg.

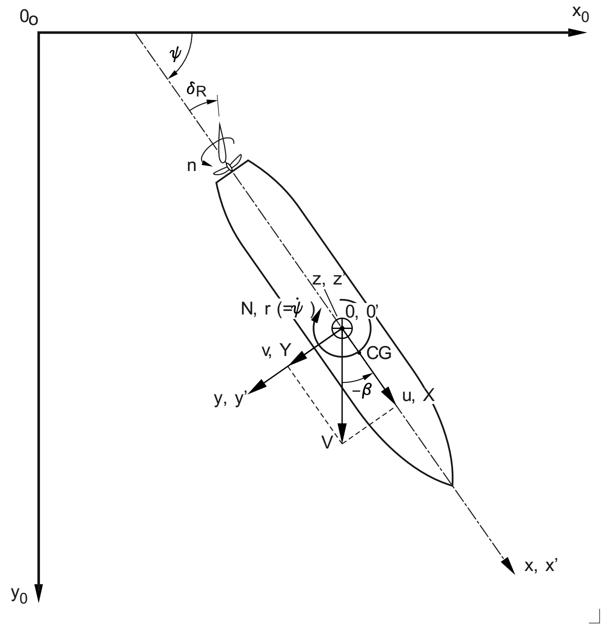

Figure 1. Ship- and earth-bound (towing tank) coordinate system: projection on the $O_0x_0y_0$ plane

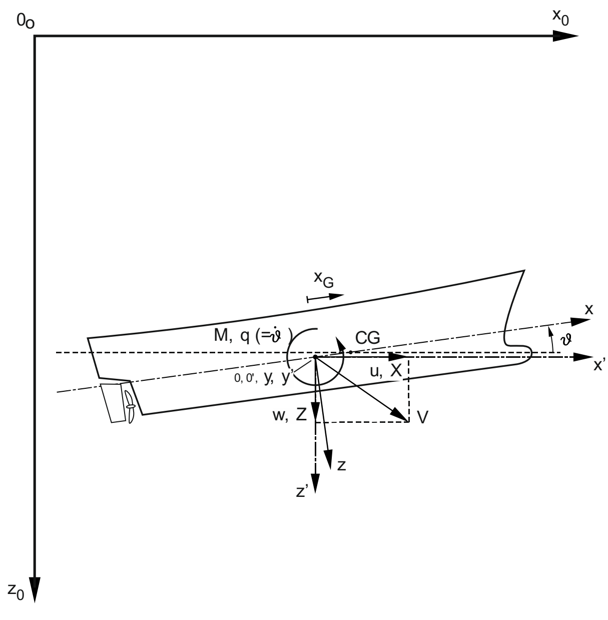

Figure 2. Ship- and earth-bound (towing tank) coordinate system: projection on the $O_0x_0z_0$ plane

2.4 ENVIRONMENTAL CONDITION

Although the DTC has been tested at the maximal possible water depth for free-running tests in the towing tank of FHR (which is 200% of the draft) and in a shallow water depth corresponding to 120% of the draft, only test results with the shallow water condition, 20% UKC, will be reported and used for the benchmark data. At this UKC, the water depth is 17.4 m at full scale and 0.195 m at model scale. The tests were conducted in still water.

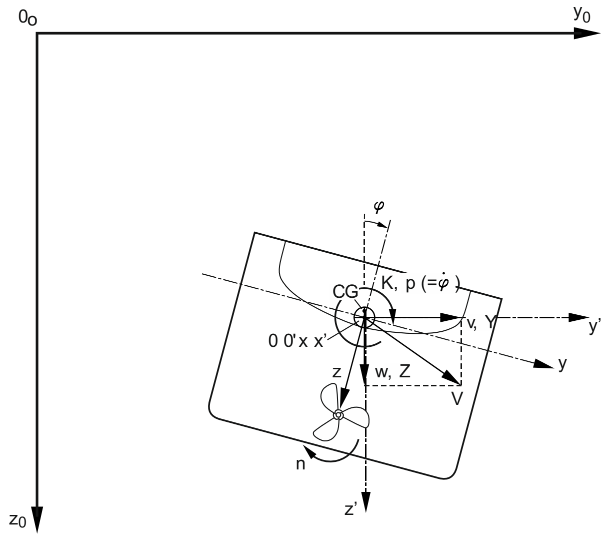

Figure 3. Ship- and earth-bound (towing tank) coordinate system: projection on the $O_0y_0z_0$ plane

2.5 MODEL TEST PROGRAM

The benchmark data are harmonic yaw and harmonic sway tests with the bare hull of the DTC. The ship model executes a pure sway motion with a prescribed sway amplitude and test period during the harmonic sway test. During the harmonic yaw test the ship model executes a pure yaw motion with a chosen yaw amplitude and test period. The ship model has a zero drift angle during the harmonic yaw tests. During both types of tests, the longitudinal component *u* is kept at a constant value.

Tests have also been executed with the appended hull at zero propeller rate and at the model self-propulsion point. Other test types, such as stationary tests at constant speed with or without drift and without yaw, are added as a reference to illustrate the dependence of the test type and kinematical test parameters. These tests are only reported to frame the benchmark data in a broader test matrix.

Table 3. Tested forward speeds

Full scale speed (knots)	Model speed (m/s)	Fr = $\frac{V}{\sqrt{gLpp}}$	Fr_h = $\frac{V}{\sqrt{gh}}$	Fr_h/Fr_{crit}
11	0.599	0.096	0.433	0.63
16	0.872	0.139	0.630	0.91

The selected tests are executed according to full scale ship speeds of 11 and 16 knots which correspond to Froude numbers Fr (based upon the ship length L_{PP}) of 0.096 and 0.139 (Table 3). While these speeds can be considered as moderate for a container carrier at full sea, they are in the higher range for the 20% UKC environmental condition, taking account of the corresponding Froude depth numbers Fr_h of 0.43 and 0.63, as displayed in Table 3. Apparently, the highest test speed comes close to the critical speed ("Schijf speed", see [8]), which takes a value of 0.95 m/s at model scale (17.4 knots at full scale):

$$\boldsymbol{Fr_{crit}} = \left(\mathbf{2}\,\mathbf{sin}\left(\frac{\boldsymbol{Arcsin}\left(\mathbf{1}-\frac{\boldsymbol{A_M}}{\boldsymbol{\Omega}}\right)}{\mathbf{3}}\right)\right)^{\frac{3}{2}} \quad \mathbf{(1)}$$

The ratio of the highest test speed and this critical speed is 91%, which is larger than the 84% cut-off value for subcritical speeds as determined in [9].

2.6 MEASUREMENTS

The results of the sinkages are presented as a mean running sinkage z_{VM} and trim. The trim is positive bow up and the sinkage is positive downwards. Sinkage is presented as the vertical displacement at the midship position. The trim is presented as the difference in vertical position at the fore and aft perpendicular, made non-dimensional with the length between perpendiculars. The sinkages at the fore and aft perpendicular are not shown to reduce the number of derived values in this paper but can nevertheless be calculated from the mean sinkage and trim.

The forces and moments measured in the horizontal-bound towing carriage coordinate system have contributions of the velocity and acceleration dependent parts. The longitudinal force X is pure resistance for the bare hull, and oscillates with the harmonic motion as do the lateral force Y, the yaw moment N and the roll moment K.

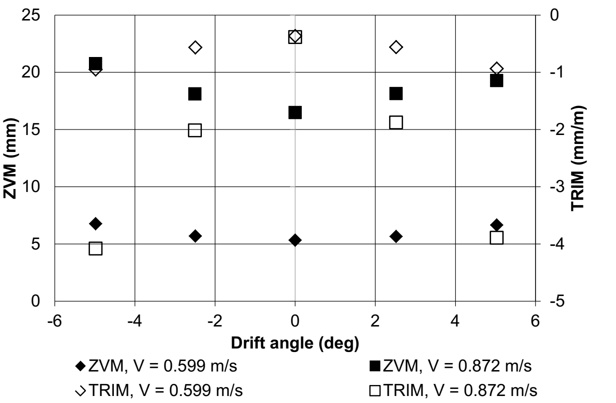

Figure 4. Mean sinkage and trim at stationary tests with the bare hull (V = model speed)

3 STATIONARY TEST DATA

Stationary tests have been executed at the same two Froude numbers as mentioned in section 2.5 with and without drift angle. The results for the mean sinkage and the trim are shown in Figure 4 for the bare hull and in Figure 5 for the appended hull (propeller and rudder attached) with zero propeller rate and according to self-propulsion. The following conclusions can be summarised based on Figure 4:

- The mean sinkage at Fr = 0.096 and zero drift angle is 5 mm.

- The mean sinkage at Fr = 0.139 and zero drift angle is 16.5 mm. The sinkage increases with drift and reaches values of 19.3 mm and 20.7 mm, for positive and negative drift angles, respectively.
- The trim is always negative or thus bow down for both Froude numbers and increases considerably (more negative values) with increasing drift (for example a value of approximately -4 mm/m at +/- 5 degrees drift for the largest Fr).

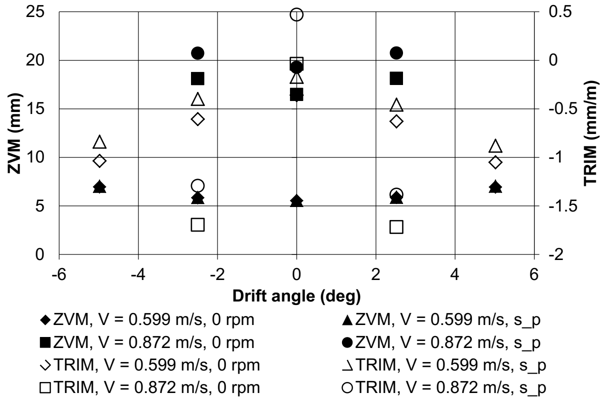

Figure 5. Mean sinkage and trim at stationary tests, appended hull, 0 rpm and model self-propulsion point (s_p)

Some differences between the results for the appended (Figure 5) and the bare hull can be observed:
- The +/- 5 degrees drift for the largest Fr is not carried out with the appended hull.
- Compared to tests at zero propeller rate, tests at the model self-propulsion points, generate higher values for the mean sinkage and more positive values for the trim.

4 BENCHMARK DATA

The harmonic yaw and sway tests with bare hull are referenced with 2016 as prefix (Table 4). The test names differ according to the test conditions:
- harmonic yaw or sway;
- model speed 0.599 m/s or 0.872 m/s;
- test type specific parameters (Table 5 and Table 6).

Table 4. Test names and general parameters of bare hull tests

	Type	u	v_A	r_A
Test name		(m/s)	(m/s)	(deg/s)
2016_A	Yaw	0.599	0	3.8
2016_B	Yaw	0.872	0	3.8
2016_C	Sway	0.599	0.063	0
2016_D	Sway	0.872	0.063	0

4.1 HARMONIC YAW TEST

The harmonic yaw test parameters are summarised in Table 5. During this type of test, the ship's longitudinal speed component u takes a constant value, while the lateral speed component v is equal to zero; therefore, the drift angle is zero. The heading is varying harmonically as a function of time with a large yaw amplitude ψ_A of 15 degrees, equation (2).

$$\Psi(t+\Delta t) = \Psi(t) - \Psi_A \frac{2\pi}{T} \sin\left[\frac{2\pi(t-t_{harm})}{T}\right] \Delta t \qquad (2)$$

The course / yaw angle change during the tests at both ship velocities are presented in Figure 6 as function of the longitudinal position in the towing tank. This position gives a time dependence taking into account the constant longitudinal velocity component u.

Table 5. Test parameters of harmonic yaw tests

	u	v	Ψ_A	T
Test name	(m/s)	(m/s)	(deg)	(s)
2016_A	0.599	0	15	25
2016_B	0.872	0	15	25

The following important conclusions can be made:
- Considering the entire harmonic test run the influence of the harmonic varying course, rate of turn and yaw acceleration on the mean sinkage and trim are minor.
- In the first half period of the harmonic yaw test the mean sinkage increases considerably, especially at the largest Froude number. The trim is small, positive (bow up) at the start of the test (after the acceleration phase) and negative (bow down) while the harmonic yaw test is proceeding.

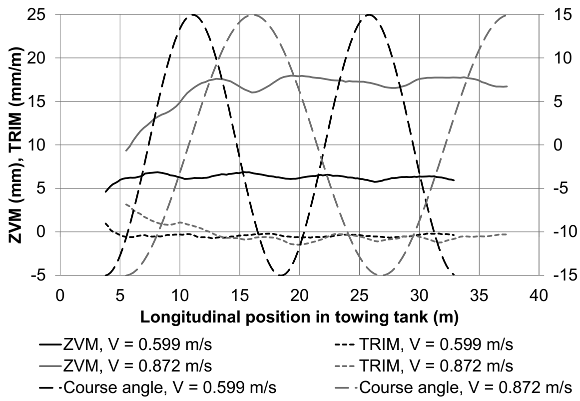

Figure 6. Time series for mean sinkage and trim at harmonic yaw

As the influence of the harmonic yaw motion on the sinkage is small, the values, once a kind of regime in oscillation is obtained after the acceleration phase, could be compared with stationary tests.

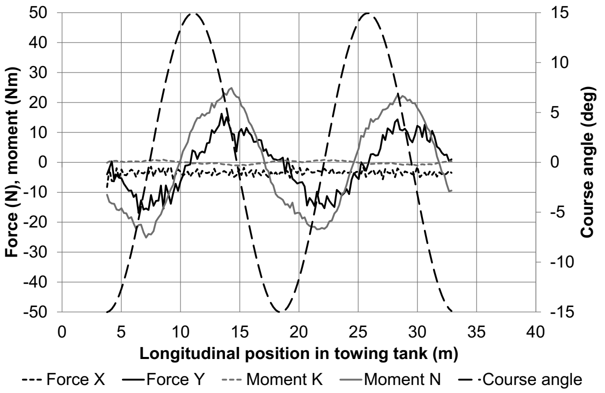

Figure 7. Time series for forces and moments at harmonic yaw and model speed 0.599 m/s

The measured forces and moments are shown in Figure 7 for Fr = 0.096 and in Figure 8 for Fr = 0.139. The longitudinal force X (resistance for bare hull) and the roll moment K have small values, while the lateral force Y and the yaw moment N clearly oscillate with the harmonic motion. Nevertheless, no stable oscillatory force and moment are measured especially for the largest Froude number, so that a Fourier analysis is disregarded. For the lateral force, in particular, the positive peak value, running at the larger velocity, has a significantly larger magnitude compared to the negative peak value. For the yaw moment, on the other hand, the opposite is observed. At maximum yaw angle / yaw acceleration, the lateral force and moment cross the zero ordinate line, so that maximum forces and moments are measured around maximum yaw velocity.

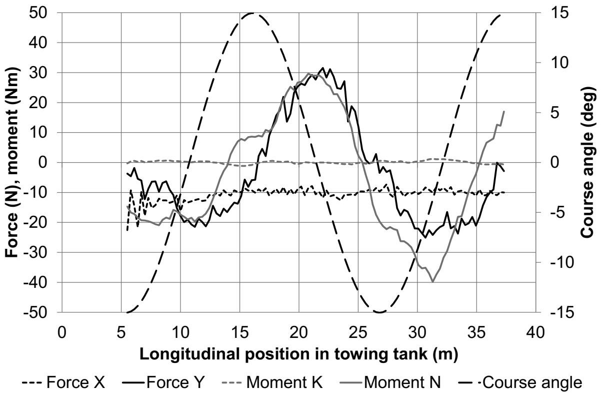

Figure 8. Time series for forces and moments at harmonic yaw and model speed 0.872 m/s

The resulting graphs for sinkages, forces and moment of each benchmark harmonic yaw test are repeated in full form in Appendix 1.

4.2 HARMONIC SWAY TEST

During harmonic sway tests, the ship's longitudinal speed component u takes a constant value, while the lateral speed component v oscillates harmonically as a function of time. The heading is constant and, hence, the rate of turn is zero during the test.

$$y_0(t) = y_{0,A}\cos\frac{2\pi(t-t_{harm})}{T} \quad (2)$$

The harmonic sway tests are summarised in Table 6.

Table 6. Test parameters of harmonic sway tests

	u	v_A	$y_{0,A}$	T	β_A
Test name	(m/s)	(m/s)	(m)	(s)	(deg)
2016_C	0.599	0.063	0.2	20	6.0
2016_D	0.872	0.063	0.2	20	4.1

Sway tests with small sway amplitudes are chosen as in shallow water this results in values for the acceleration dependent derivatives which are less sensitive to the oscillation frequency [7].

The mean sinkage and trim are presented in Figure 9 for the tests at 11 and 16 knots full scale. Even for the lower velocity a clear oscillation in the time series for sinkage and trim occurs. Nevertheless at the higher Froude number 0.139 the magnitude of the oscillating sinkage and trim gradually increases; no steady oscillation is reached before the end of the test run.

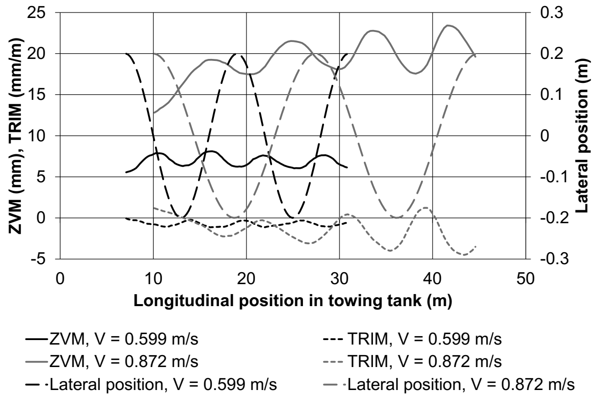

Figure 9. Time series for mean sinkage and trim at harmonic sway

The following important conclusions can be made:

- The peak values of the sinkage and trim occur at non-zero lateral position or thus at a combined non-zero sway velocity and sway acceleration.
- The mean sinkage and trim run in phase so that a maximum sinkage corresponds to a maximum trim magnitude.
- The trim is generally negative and thus bow down.
- For the test run at Fr 0.139 the critical velocity is almost reached which gives an increasing amplitude of the mean sinkage and the trim. Compared to the harmonic yaw test where there is almost no influence of the critical velocity and a mean sinkage of 16 to 17 mm is measured with a trim of -1 to -2 mm/m, for the harmonic sway test the mean sinkage reaches values of 18 to 23 mm (minimum and maximum) at the last

cycle and the trim oscillates between -4.5 and +1.5 mm/m.

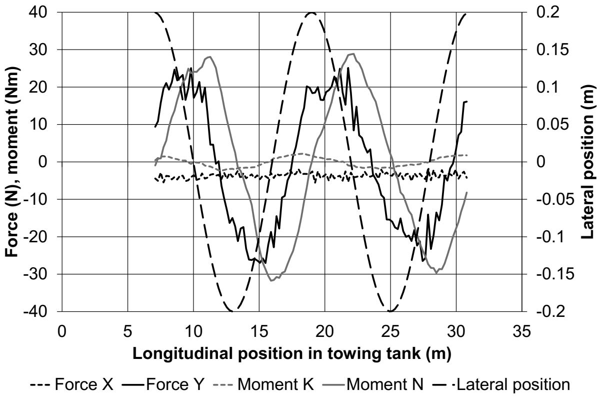

Figure 10. Time series for forces and moments at harmonic sway and model speed 0.599 m/s

The measured forces and moments are shown in Figure 10 for Fr = 0.096 and Figure 11 for Fr = 0.139. The longitudinal force X act similar as the same force during the harmonic yaw tests.

The roll moment K oscillates considerably more than during the harmonic yaw test although the values remain small.

The lateral force Y and the yaw moment N have a stable oscillating pattern at Fr = 0.096 but increase while the test is running with high maximum values at Fr = 0.139 (minimum value lower than -100 Nm). The critical velocity influences the test sequence.

At Fr = 0.096 an peak value for the yaw moment is measured when the ship is at the middle of the tank on the x_0 axis which means that the sway motion and sway acceleration are zero. Zero-crossing of the lateral force occurs at a combined non-zero sway velocity and acceleration.

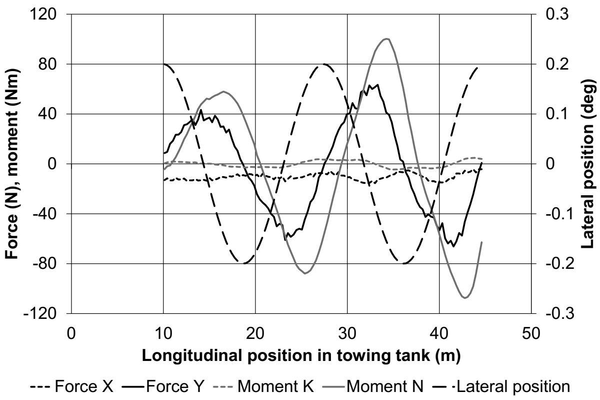

Figure 11. Time series for forces and moments at harmonic sway and model speed 0.872 m/s

The resulting graphs for sinkages, forces and moment of each benchmark harmonic sway test are repeated in full form in Appendix 2.

4.3 COMPARISON WITH STATIONARY TESTS

Comparing the values for sinkage and trim between stationary and harmonic tests, the following conclusions can be made:

- The mean sinkage at Fr = 0.096 and zero drift angle for stationary tests (value of 5 mm) corresponds to the starting value measured at the first period of the harmonic yaw and sway tests. For both yaw and sway tests the mean sinkage then gradually increases to a higher value.
- The mean sinkage at Fr = 0.139 and zero drift angle for stationary tests (value of 16.5 mm) corresponds to the mean value over the complete harmonic yaw test and the minimum value of the harmonic sway test. The sinkage increases with drift and reaches values of 19.3 mm and 20.7 mm. These values are still lower than the values measured during the harmonic sway tests with a maximum drift angle of 4.1 degrees at Fr = 0.139.

5 HARMONIC TEST DATA WITH APPENDED HULL

5.1 HARMONIC YAW TEST

The time series of mean sinkage and trim are shown in Figure 12 for the harmonic yaw tests at both Froude numbers with the fully appended hull and zero propeller rate. The differences with Figure 6 are minor.

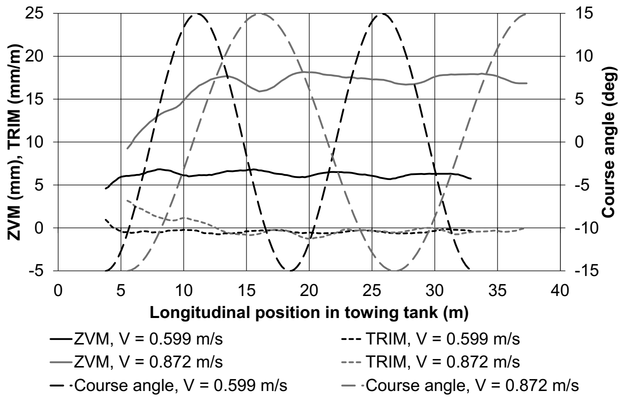

Figure 12. Mean sinkage and trim at harmonic yaw tests, appended hull - 0 rpm

5.2 HARMONIC SWAY TEST

The harmonic sway tests executed with the appended hull are presented in Figure 13. The differences at zero propeller rate are again minor compared to the bare hull results in Figure 9 but the mean sinkage at model speed 0.872 m/s shows more steep variations in the maximum sinkage range. The presence of the propeller and rudder influences the pattern of the time series. If the propeller is running at the model self-propulsion point, slightly higher sinkages are measured and a more regular oscillation pattern is observed.

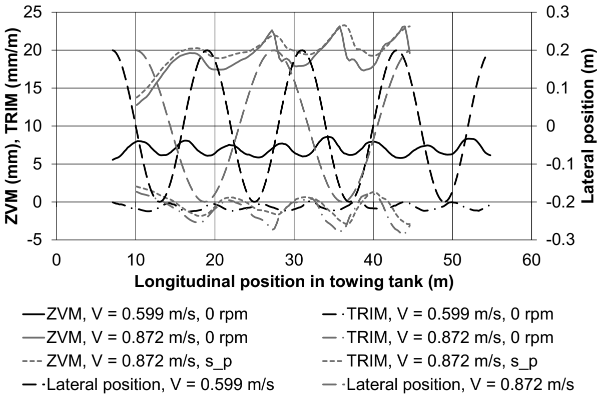

Figure 13. Time series for mean sinkage and trim at harmonic sway, appended hull, 0 rpm and model self-propulsion point

6 CONCLUSIONS

This paper introduces four benchmark tests carried out with the DTC container carrier at 20% under keel clearance. Two speeds were selected, corresponding to 11 and 16 knots full scale, at which both harmonic yaw tests and harmonic sway tests were carried out. The tests at 11 knots show a more consistent behaviour. At 16 knots nearly supercritical effects start to occur in the towing tank.

The data not only present the sinkage and trim during the four benchmark data tests but also the forces and moments. The test results are further considered in a broader test matrix comparing the bare hull benchmark tests with tests executed with the appended hull at zero propeller rate or self-propulsion. Stationary test results additionally show the reference data values for the harmonic test type time series.

The benchmark data are open and digitally available and can be ordered on request at info@shallowwater.be.

7 ACKNOWLEDGEMENTS

The authors would like to thank the SHOPERA consortium for the permission to publish the data and the Flemish Government for the financial support for the maintenance and operation of the Towing Tank for Manoeuvres in Shallow Water (cooperation Flanders Hydraulics Research – Ghent University).

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Katrien Eloot holds the current position of senior expert at Flanders Hydraulics Research, Flemish Government and guest professor at Ghent University. She is responsible for simulation studies and fundamental research related to ship hydrodynamics and especially manoeuvring in shallow and confined water. She is member of PIANC InCom Working Group 141 and AVT-183 and AVT-216 of NATO STO.

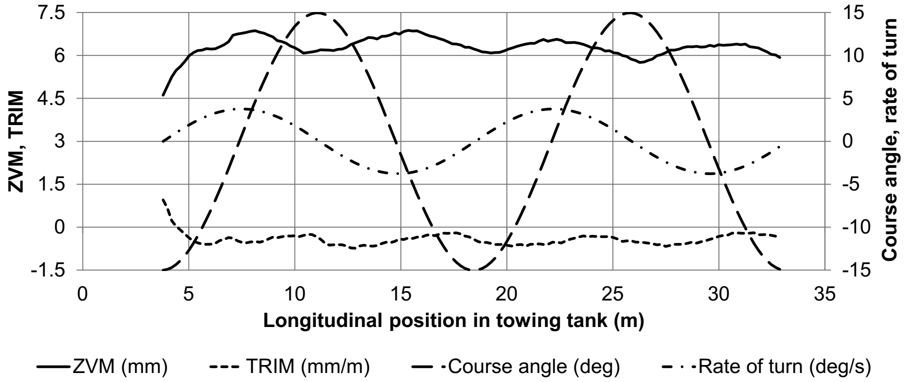
Marc Vantorre, naval architect, is full senior professor of marine hydrodynamics and head of the Maritime Technology Division at Ghent University, Belgium. His research focuses on ship behaviour in shallow and confined waters, mainly in close co-operation with Flanders Hydraulics Research in Antwerp. He is member of PIANC Working Groups and former member of the ITTC Manoeuvring Committee.

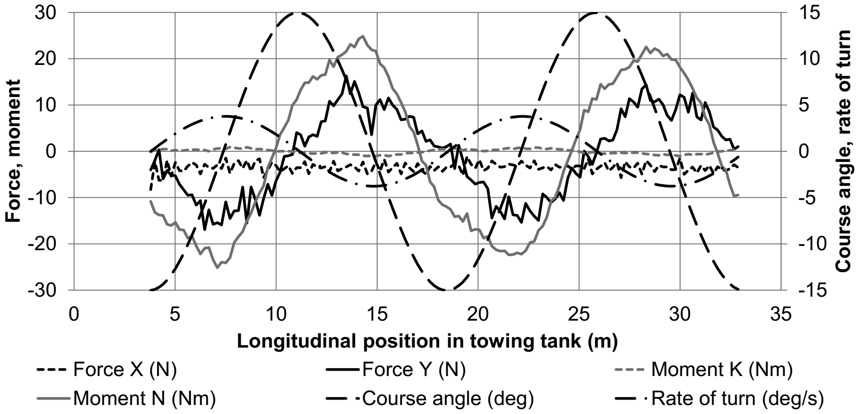
Guillaume Delefortrie is expert nautical research at Flanders Hydraulics Research. He is in charge of the research in the Towing Tank for Manoeuvres in Shallow Water (cooperation Flanders Hydraulics Research – Ghent University) and is secretary of the 27th and 28th ITTC Manoeuvring Committee.

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

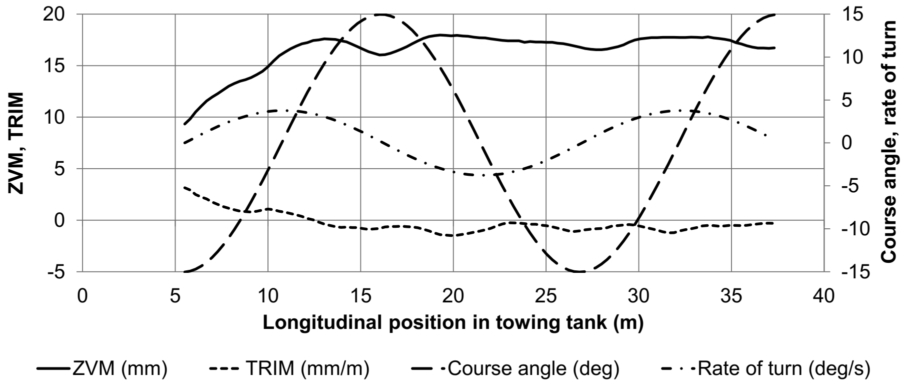
Appendix 1 Benchmark harmonic yaw test

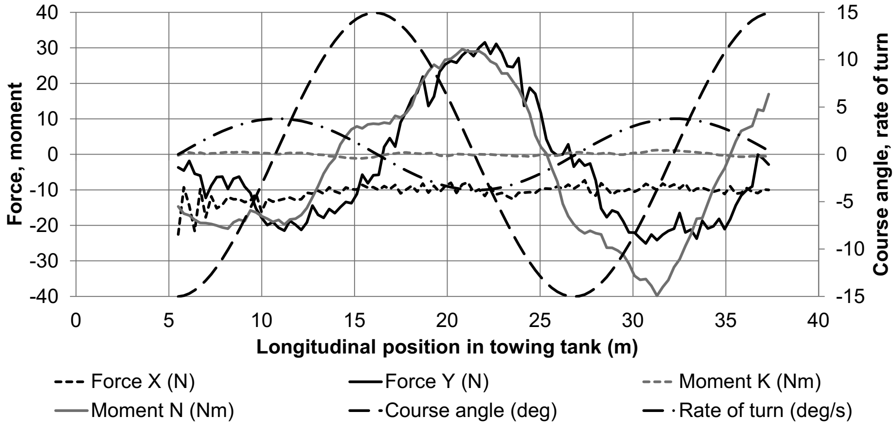
2016_A





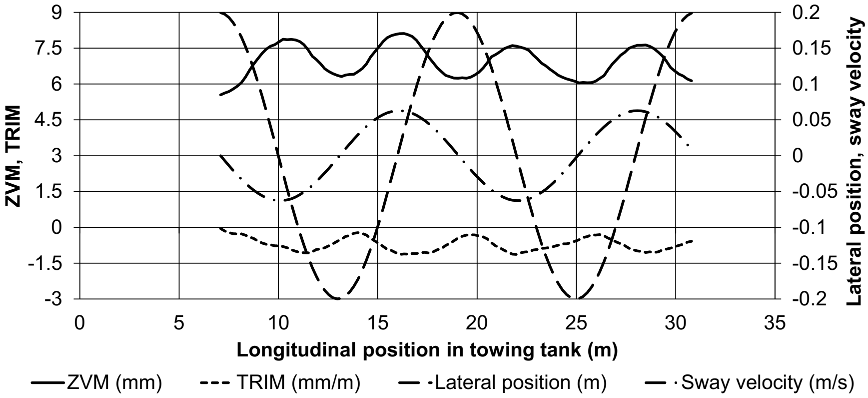
2016_B

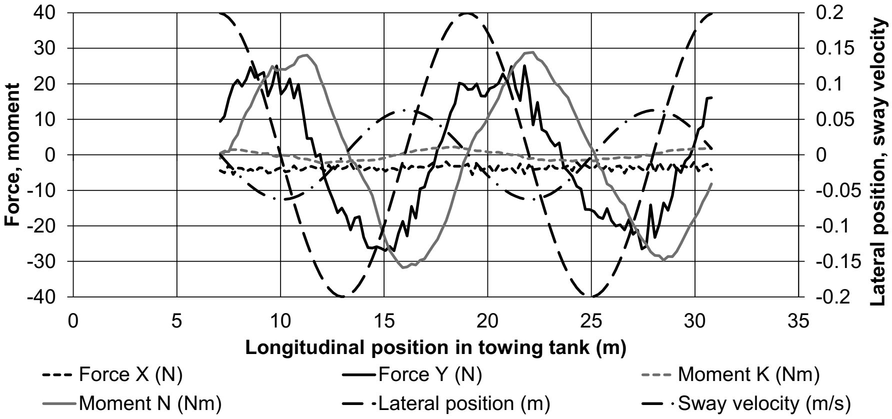




Appendix 2 Benchmark harmonic sway test

2016_C





2016_D