Proceedings of the 35th International Conference on Ocean, Offshore & Arctic Engineering
OMAE2016
June 19-24, 2016, Busan, South Korea

OMAE2016-54865

ESTABLISHMENT OF A VALIDATION AND BENCHMARK DATABASE FOR THE ASSESSMENT OF SHIP OPERATION IN ADVERSE CONDITIONS

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ABSTRACT

The Energy Efficiency Design Index (EEDI), introduced by the IMO [1] is applicable for various types of new-built ships since January 2013. Despite the release of an interim guideline [2], concerns regarding the sufficiency of propulsion power and steering devices to maintain manoeuvrability of ships in adverse conditions were raised. This was the motivation for the EU research project SHOPERA (Energy Efficient Safe SHip OPERAtion, 2013-2016 [3-6]). The aim of the project is the development of suitable methods, tools and guidelines to effectively address these concerns and to enable safe and green shipping. Within the framework of SHOPERA, a comprehensive test program consisting of more than 1,300 different model tests for three ship hulls of different geometry and hydrodynamic characteristics has been conducted by four of the leading European maritime experimental research institutes: MARINTEK, CEHIPAR, Flanders Hydraulics Research and Technische Universität Berlin. The hull types encompass two public domain designs, namely the KVLCC2 tanker (KRISO VLCC, developed by KRISO) and the DTC container ship (Duisburg Test Case, developed by Universität Duisburg-Essen) as well as a RoPax ferry design, which is a proprietary hull design of a member of the SHOPERA consortium. The tests have been distributed among the four research institutes to benefit from the unique possibilities of each facility and to gain added value by establishing data sets for the same hull model and test type at different under keel clearances (ukc). This publication presents the scope of the SHOPERA model test program for the two public domain hull models – the KVLCC2 and the DTC. The main particulars and loading conditions for the two vessels as well as the experimental setup is provided to support the interpretation of the examples of experimental data that are discussed. The focus lies on added resistance at moderate speed and drift force tests in high and steep regular head, following and oblique waves. These climates have been selected to check the applicability of numerical models in adverse wave conditions and to cover possible non-linear effects. The obtained test results with the KVLCC2 model in deep water at CEHIPAR are discussed and compared against the results obtained in shallow water at Flanders Hydraulics Research. The DTC model has been tested at MARINTEK in deep water and at Technische Universität Berlin and Flanders Hydraulics Research in intermediate/shallow water in different set-ups. Added resistance and drift force measurements from these facilities are discussed and compared. Examples of experimental data is also presented for manoeuvring in waves. At MARINTEK, turning circle and zig-zag tests have been performed with the DTC in regular waves. Parameters of variation are the initial heading, the wave period and height.

INTRODUCTION

The background of the presented research work is the implementation of the Energy Efficiency Design Index (EEDI)

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by the IMO in January 2013 and the associated requirement for each new-built vessel to meet reference lines for vessel emissions. An obvious way to fulfill these requirements is to reduce the installed power. This approach may however lead to significant safety issues for some ship types since manoeuvring capabilities in adverse conditions might not be sufficient anymore. MARINTEK is leading the comprehensive model testing program of the project with more than 1,300 different tests for three hull designs of different hydrodynamic characteristics (DTC post-panamax container vessel, KVLCC2 tanker and a RoPax ferry, which is not part of this publication). The workload is shared with CEHIPAR, Flanders Hydraulics Research (FHR) and Technische Universität Berlin (TUB). The aim of the model tests in SHOPERA is to close gaps in available benchmark data and broaden the database test results for manoeuvring in waves and seakeeping. By selecting the three hull model types and exploiting the unique possibilities of the participating model test facilities, valuable insights into seakeeping and manoeuvring characteristics have been gained. All results are contributing to a database for validation of software tools and empirical methods that are developed within the framework of the EU research project SHOPERA. On this basis, it is possible to develop a procedure to perform a holistic assessment of ship performance and to formulate minimum powering requirements to ensure safe ship operation in adverse weather conditions, while keeping the right balance between ship economy, efficiency and safety.

The Ship Models

The KVLCC2 is a VLCC-type vessel, representing the second variant of a modern tanker design developed by the Korean Institute of Ship & Ocean Engineering (KRISO) with bulbous bow and U-shaped stern lines (see Figure 1 and [7]). The hull lines have been exclusively developed for testing and benchmarking and no full scale ships of that type exist. The KVLCC2 design features a horn rudder of 273.3 m^2 rudder area and a lateral area of 136.7 m^2. The tanker is equipped with a fixed-pitch 4 bladed propeller of 9.86 m full scale diameter and a pitch ratio of $P/D_{0.7} = 0.721$. The direction of rotation is right-handed, looking in the positive x-direction. The main particulars of this vessel and the loading conditions of the model for scantling draught and heavy ballast are given in Table 1 in full scale. Within the SHOPERA project, the KVLCC2 design has been tested in deep water at CEHIPAR (scale 1:80) and in shallow water at Flanders Hydraulics (scale 1:75).

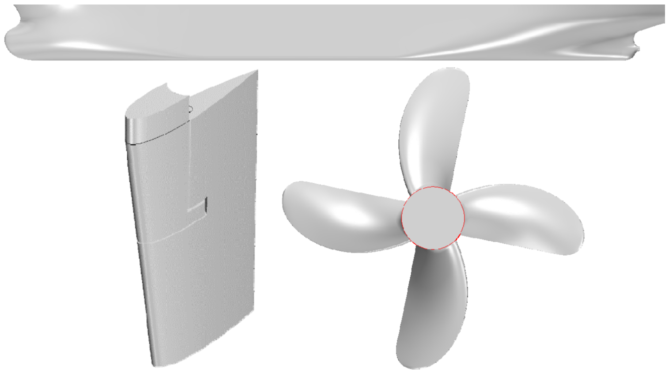

Figure 1: View of the KVLCC2 hull (top), the rudder (bottom, left) and the propeller (bottom, right)

The Duisburg Test Case (DTC) design is a post-panamax 14000 TEU container vessel. It has been developed at the Institute of Ship Technology, Ocean Engineering and Transport Systems (ISMT) of the University of Duisburg-Essen for benchmarking and validation of numerical methods and its lines are available to the public (see Figure 2 and [8]). The DTC design features a twisted rudder with Costa bulb and a NACA 0018 base profile (see Figure 2, bottom left). The projected area of the movable part of the rudder is 95.1 m^2. Figure 2 (bottom, right) shows the fixed-pitch five-bladed propeller of 8.911 m full scale diameter with a pitch ration of $P/D_{0.7} = 0.959$. The direction of rotation is right-handed, looking in positive x-direction. On each side of the vessel, a segmented bilge keel is placed symmetrically around the midship section, consisting of five segments, each with 14.85 m length and 0.4 m profile height. The gap width between the segments is 3.0 m. The main particulars of this vessel and the loading conditions of the model for the design draught and light ballast are given in Table 1 in full scale. Within the SHOPERA project, the DTC design has been tested in deep water at MARINTEK (scale 1:63.65) and in shallow/intermediate water at TUB and FHR (scale 1:89.11).

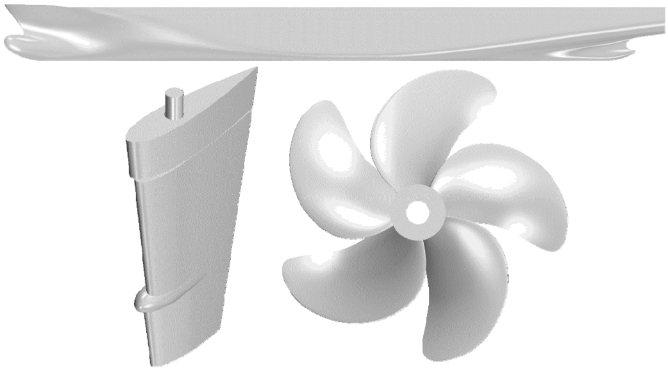

Figure 2: View of the DTC hull (top), the rudder (bottom, left) and the propeller (bottom, right)

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Table 1: Main particulars and loading conditions for the KVLCC2 and DTC (all values refer to the origin located at [AP/CL/BL])

		KVLCC2		DTC	
L_{pp}	[m]	320.0		355.0	
B	[m]	58.0		51.0	
CB	[-]	0.8098		0.661	
		Scantling Draught	Heavy Ballast	Design Draught	Light Ballast
T_{FP}/T_{AP}	[m]	20.8/20.8	8.2/11.5	14.5/14.5	7.8/11.0
∇	[t]	320438	133186	173468	104102
LCG	[m]	171.1	169.0	174.059	170.460
VCG	[m]	18.56	11.17	19.851	16.56
GM_T	[m]	5.71	21.4	5.1	12.4
r_{xx}	[m]	23.2	23.2	20.3	20.1
r_{yy}	[m]	80.0	80.0	87.3	95.9
r_{zz}	[m]	80.0	80.0	87.4	96.9

ADDED RESISTANCE AND DRIFT FORCES

The added resistance and drift force tests have been conducted in steep regular waves and selected irregular sea states that are not presented here. The wave climates have been generated along the limiting curves of the wave makers in the test facilities in a range of $0.1 \leq \lambda/L_{pp} \leq 1.2$. Individual adjustments of the wave heights have been made during testing to guarantee the safety of the hull models and measuring equipment. At the peak of the RAOs and for the shortest wave lengths, two additional wave amplitudes have been tested to account for possible nonlinear effects. Due to the high wave steepness and the extension of the testing range into oblique seas and the short relative wave length region (diffraction dominant domain), the results offer valuable insights and contribute to an enhanced benchmark and validation database compared to the currently available state-of-the-art.

MARINTEK

For the added resistance tests at MARINTEK, the DTC model was captive in a soft-mooring arrangement as visualized in Figure 3 and towed by the carriage at constant speed. Light weight lines were used and the spring stiffness has been chosen such that the eigenfrequency of the mooring in the relevant direction is less than 1/6th of the lowest wave encounter frequency. A transverse beam with attached force transducers was mounted on deck at $L_{pp}/2$ and the connection point for the lines was at [2.789m, ±0.995m, -0.448m] model scale, relative to [AP, CL, BL]. A supplementary set of force transducers was installed in the aft and fore joints of the lines to ensure consistency in the measurements.

For the drift force tests at MARINTEK, the DTC model was captive in a soft-mooring arrangement as visualized in Figure 3 and held at position/towed by the gondola at constant speed. Light weight lines were used and the spring stiffness has been chosen such that the eigenfrequency of the mooring in the relevant direction is less than 1/6th of the lowest wave encounter frequency. At the same time, the aim was to minimize the yaw drift angle (it was kept within ±2°). A transverse beam was mounted to the gondola and the lines were deflected by low friction pulleys to align and attach the springs vertically. Force transducers were mounted forward of the bow and behind the stern at CL and KG. A supplementary set of force transducers was installed in the lines to ensure consistency in the measurements. The model was fitted with segmented bilge keels, rudder (fixed at 0° rudder angle) and rudder box during this set of tests.

All wave environments have been measured without the presence of the model for reference. For drift force tests, the gauge was located at the model position and for added resistance in a representative location between starting position and wave maker.

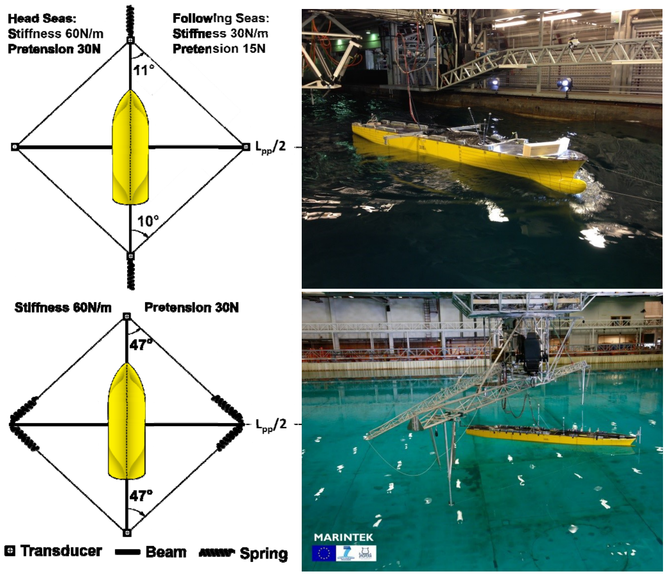

Figure 3: DTC model in soft-mooring arrangement for added resistance (top) and drift force tests (bottom) at MARINTEK (left: schematic sketches, right: impressions from model tests)

CEHIPAR

To measure the mean drift forces in regular waves and deep water conditions at CEHIPAR, the model was restrained with a soft mooring system consisting in four lines arranged in the shape of a diamond in the horizontal plane. The geometry of the system is given in Figure 4 (left). Each line was made of a thin steel wire 3780 mm in length. Two lines are attached to points a little forward of the bow and the other two were attached a little aft of the stern. The two lines at starboard are connected to one vertical pole fixed to the turret of the CPMC (Computerized Planar Motion Carriage), the two port ones are connected to a symmetric pole in the opposite side. The two poles are aligned with the midship section which is slightly aft of the longitudinal COG. The points of connection of the lines

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with the model are at the same height as the COG to reduce the influence in rolling. The lines were almost horizontal. At each connection to the poles, a spring with a stiffness of 107 N/m was attached.

The objective of the soft mooring is to be able to measure the drift forces while keeping the orientation of the model and influencing its motions the minimum possible. To this purpose, the mooring was designed such that the natural resonance periods in surge, sway and yaw were well above the period of the largest wave to be tested. By decay tests, it has been confirmed that the natural periods for surge and sway are 7 to 17 times higher than the tested wave periods while for yaw this ratio is between 3 and 6.

The arrangement allows to easily change the orientation of the model with respect to the waves just by slowly rotating the turret of the CPMC.

The same arrangement was used for the added resistance tests in regular and irregular waves by moving the carriage at the desired speed. In this case it was necessary to make the acceleration phase very smooth with very low acceleration to reduce the excitation of the soft mooring resonances as much as possible.

The incoming wave has been measured by a wave probe forward of the model. This measurement is affected by the wave reflections from the model. The undisturbed reference wave height has also been measured in absence of the model. The vessel motions in six degrees of freedom have been measured by an optical tracking system (Krypton). Wave forces have been measured by two six component dynamometers, one at the bow and one at the stern at the points of attachment of the mooring lines. Additional load cells were mounted in each line.

Both the dynamometers and the load cells can be combined separately to give two different estimates of the surge and sway forces and the yaw moment so giving some redundancy. The results from the load cells gave similar results to those of the dynamometers except that they are slightly lower due, probably, to friction at the pulleys used to connect the wires to the springs and load cells. All results presented in the following are direct measurements from the dynamometers.

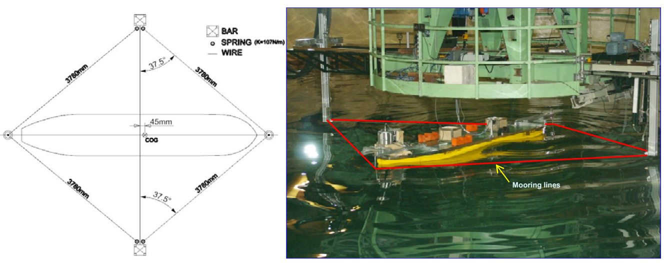

Figure 4: Mooring arrangement for the drift force tests with the KLVCC2 model at CEHIPAR

Flanders Hydraulics Research

At FHR, captive model tests have been performed with a 1:75 scale model of the KVLCC2 and a 1:89.11 scale model of the DTC in the Towing Tank for Manoeuvres in Shallow Water (co-operation with Ghent University, see Figure 5and [9] for more information). The usable dimensions of the tank are 68 x 7 x 0.5 m³. The KVLCC2 was tested at scantling and heavy ballast draught and the DTC at design loading condition, see Table 1.

The considered under keel clearances are expressed as a percentage of the draft at the aft perpendicular and have the following magnitude:

- 30% and 20% for the KVLCC2, the latter only at scantling draft;
- 100% and 20% for the DTC.

The sailing speeds were 0, 6 and 12 knots full scale for the KVLCC2 and 0, 6 and 16 knots for the DTC. At 0 kn, the drift angles were varied for the KVLCC2 (30% ukc only) to investigate various incoming wave angles (0 to 150° in steps of 30°, which corresponds with the interval from head to stern quartering waves).

Figure 5: Impression of the KVLCC2 (top) and DTC model (bottom) in the captive test setup at FHR

At FHR the tests have been performed with fully restrained surge, sway and yaw, while heave, roll and pitch were free. During the tests the wave climate was measured at the four positions in the Towing Tank, as shown in Figure 6.

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Name	Longitudinal coordinate	Lateral coordinate
WG1	$x_0 = 66.29$ m	$y_0 = 0.00$ m
WG2	$x_0 = 44.00$ m	$y_0 = 2.60$ m
WG3	$x_0 = 24.00$ m	$y_0 = 2.60$ m
WG4	$x_0 = 4.03$ m (rel. to ship)	$y_0 = -0.65$ m

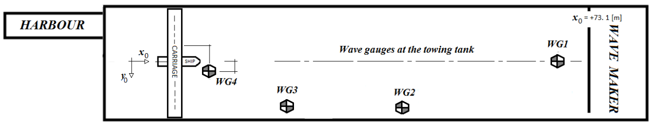

Figure 6: Position of wave gauges in the towing tank at FHR

Waves were varied in length between 0.2 and 1.2 λ/L_{pp}. The possible wave height is strongly dependent of the shallow water effects, which put a limit on the maximal wave height that can be tested. Moreover to avoid transient effects, the ship velocity may further reduce the maximal achievable wave height. For a selection of wave lengths, 50% and 70% of the wave heights listed in Table 2 were also tested.

Table 2: Base prototype wave heights at FHR

Ship	ukc	Velocity [kn]	Wave height [m]
KVLCC2 - scantling	30%	0 – 12 kn	2.25
	20%	0 – 12 kn	1.50
KVLCC2 – ballast	30%	0 – 12 kn	1.50
DTC	100%	0 – 16 kn	5.00
	20%	0 – 6 kn	2.00
		16 kn	1.20

Technische Universität Berlin

At TUB, added resistance and drift force tests have been performed in the seakeeping basin (former Berlin Model Basin VWS) with the DTC model at scale 1:89.11 at an intermediate water depth of 1 m (89.11 m water depth at full scale). The basin is 120 m long with a maximum testing length of 90 m and a width of 8 m.

All tests have been performed with an especially developed measurement platform (see Figure 7), built to determine hydrodynamic forces and moments as well as 6-DOF motions of ship models in waves. The measuring platform is composed of two nested slides (front and back) that can move in horizontal direction. Each slide consists of a Δy-slide for transverse motion and a nested Δx-slide that moves in longitudinal direction, both displacing with low friction linear ball bearings on steel rails. The slides are bound to a mean position by springs connected to each slide. By combined linear motions of the slides, the model can move in the horizontal plane, only restricted by spring stiffness and a maximum motion amplitude of each slide of 0.2m. Each Δx-slide has a vertical heave rod that is connected to the model via rod ends to allow free heave, roll and pitch motions. Between each rod end and the model a force gauge is placed to measure the forces in these two points in a model fixed manner.

The model motions are measured with a set of ten cable actuated distance sensors in a partially redundant arrangement for minimum motion interference. With the signals of six distance sensors a nonlinear system of equations in the motion parameters can be stated, which is solved iteratively in real time during the tests. The basic idea for the platform has been derived from the work of [10], who used a partially similar arrangement in combination with a PMM device.

The applied test setup therefore allows for free heave, roll and pitch motions and restrains surge, sway and yaw motion with linear springs. For the spring stiffness refer to Table 3.

Table 3: Spring stiffness of the test setup for drift forces and added resistance test with the DTC model at TUB

C_χ [N/m]	C_γ [N/m]	C_ψ [Nm/°]
373.6	792.0	309.4

Tests were performed with seven wave lengths between 0.35 and 1.2 λ/L_{pp}, the wave steepness was kept constant to eliminate the influence of the wave amplitude.

The sailing speeds of the DTC for added resistance tests was 8kn and 16kn. The zero speed drift tests were performed from encountering angles of 0° to 180° in 30° steps. The ukc of the DTC in design draught was 613%.

During all tests at TUB the model was equipped with segmented bilge keels and the rudder. A propeller was not present.

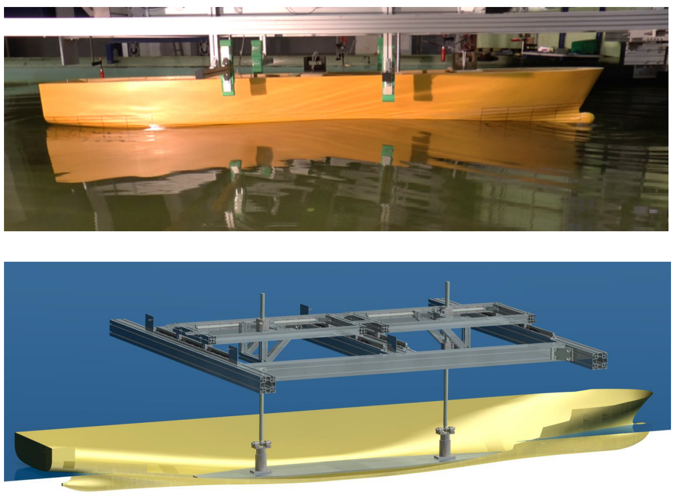

Figure 7: Measurement platform developed and used for added resistance and drift force tests at TUB

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Selected Results - DTC

The added resistance of the DTC hull has been measured in a range of $0.1 \leq \lambda/L_{pp} \leq 1.2$. The choice of force sensors was a delicate procedure since they had to be watertight, lightweight and cover a wide range of force amplitudes with sufficient accuracy. The shortest waves have been measured at MARINTEK, with the wave maker operating at its lower limit and the wave time series reveal that the waves are not as stable as for the other periods. While the measured total longitudinal forces are very similar for the three investigated wave heights at $\lambda/L_{pp} = 0.1$, the RAO data is scattered. This is caused by the normalization with very small values (squared wave amplitudes) that amplify the uncertainties of the experimental data in this range. Due to these uncertainties, this data is not presented in the following graphs. However, there is a tendency that the RAO values for the added resistance increase for shorter relative wave lengths. This range is of particular interest for large vessels since it covers normal operating sea states (for the DTC, $\lambda/L_{pp} = 0.1$ is equal to a wave length of 35.5 m or a wave period of 4.77 s in deep water).

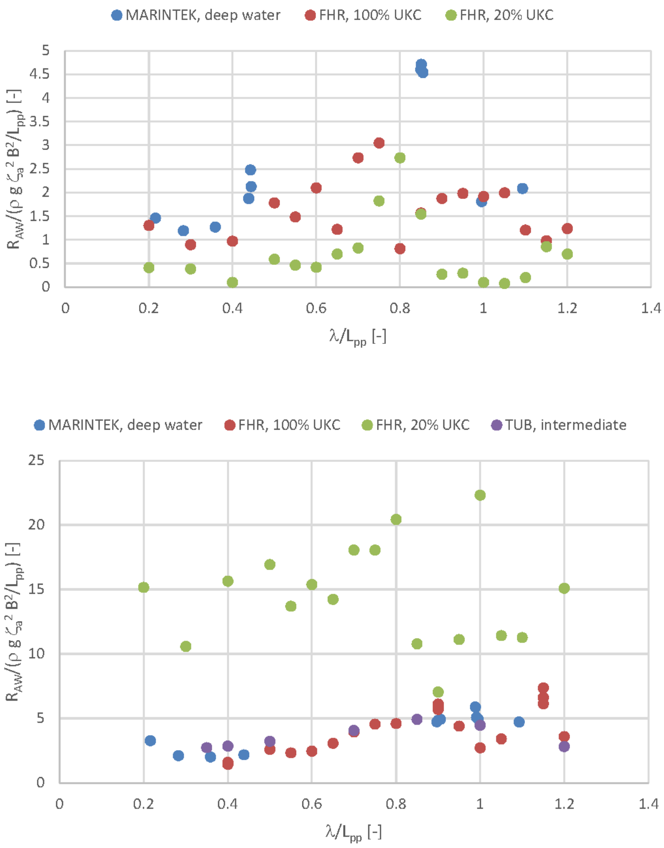

Figure 8: Comparison of normalized added resistance data measured with the DTC model at design draught at 6kn (top) and 16kn forward speed (bottom) in different water depths

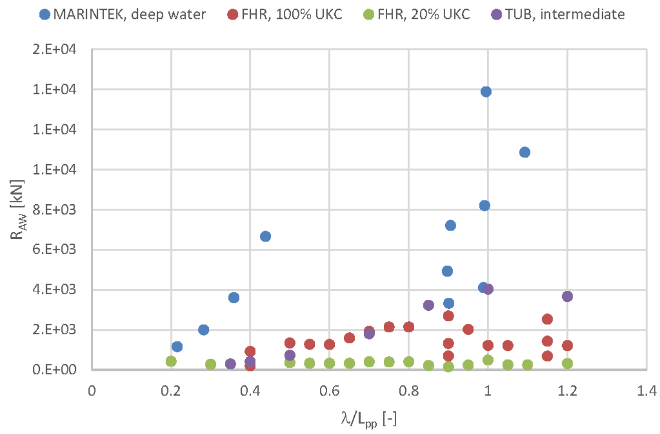

Figure 9: Full scale added resistance for the DTC model at design draught at 16kn forward speed in different water depths

Three different water depths, under keel clearances (ukc) and wave steepness have been considered for the added resistance tests with the DTC hull at design draught at 6 kn and 16 kn forward speed. For 6 kn, the measured normalized added resistance values are increasing with increasing water depth and ukc (see Figure 8, top). While the magnitudes of the RAOs are different, the overall tendencies are similar (as far as evaluable from the data points), the peak of the RAO is located around $\lambda/L_{pp} = 0.8$.

For the 16 kn case, as presented in Figure 8 (bottom), the normalized added resistance RAO values for deep water (636.5 m water depth at full scale, blue), intermediate water depth (89.11 m water depth at full scale, purple) and the 100% ukc condition (29.0 m water depth at full scale, red) are very similar without a clear trend regarding the influence of the water depth. The normalized added resistance at 20% ukc (17.4 m water depth at full scale) is significantly higher for all investigated wave conditions. However, looking at the actual forces presented in full scale in Figure 9, it becomes evident that the values measured for 20% ukc are the smallest. There are several effects that lead to the high normalized values as shown in Figure 8: The static ukc for these runs is 20% (or 3.25 cm at model scale). The sinkage measurements from these runs however reveal squat effects leading to a dynamic ukc of only 10.7% (or 1.75 cm) in calm water and 0.9% (or 0.15 cm) in the presence of waves. This is certainly an extreme condition where the vessel is sailing in the boundary layer of the bottom flow of the towing tank, which is estimated to be 7.6 cm thick, according to Prandtl's law. The effect of this on the added resistance is not known. Due to the very low ukc, the wave amplitudes had to be very small (0.6 m full scale, or 6.7 mm at model scale) in order to avoid that the heave and pitch motions cause bottom contact of the ship model. For very small wave amplitudes, measurements and accuracies are challenging, but also the amplitude-squared relation between incident wave and mean added resistance seems to be questionable, as already

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described for the case of very short waves at MARINTEK. This well-established relation has been found to be valid in the longer wave regime in deeper water, as deducible from Figure 8 and Figure 9. The different force levels in Figure 9 are resulting from different wave amplitudes (steepness) in the tests. At $\lambda/L_{pp} = 1$, the full scale wave amplitudes at MARINTEK (blue dots) are 6.25 m, 4.7 m and 3.1 m. The full scale amplitude at TUB is 3.1 m (purple dots) and at FHR 2.5 m (100% ukc, red dots) and 0.55 m (20% ukc, green dots). The two measured force values for the same wave amplitude are very similar, and the forces for different amplitudes are clearly increasing with the squared-amplitude of the wave.

Further added resistance tests with a lighter loading condition for the DTC (light ballast, c.f. Table 1) have been performed at TUB for 8 kn and 16 kn forward speed. As expected, the non-dimensional added resistance increase with increasing forward speed, accompanied by a shift of the peak towards longer waves (see Figure 10).

Systematic experimental data for added resistance in oblique seas is not easily available. Series of tests with the DTC at design loading condition have been performed at MARINTEK, with varying encounter angle from head (0°) to following seas (180°) in 30° intervals.

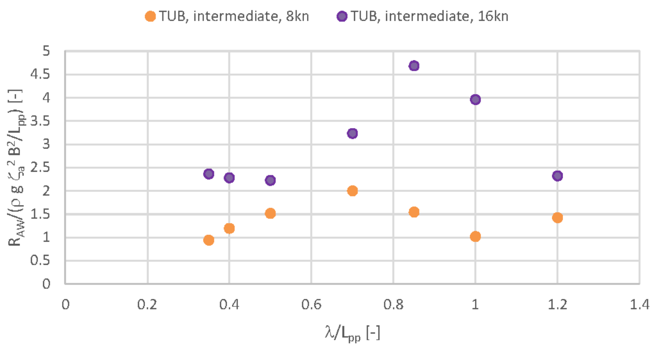


Figure 10: Comparison of added resistance data measured with the DTC model at light ballast draught with 8 and 16kn forward speed in intermediate water depth

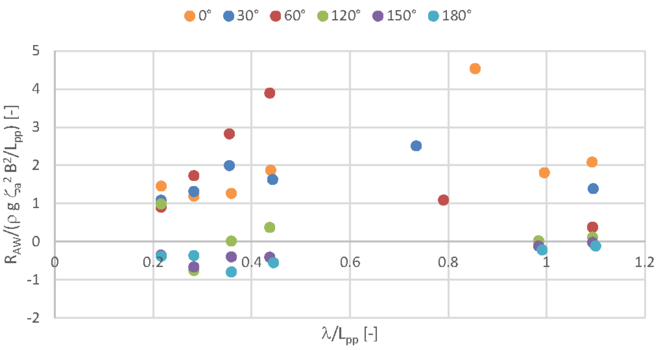


Figure 11: Comparison of added resistance data measured with the DTC model at design draught and 6kn forward speed in deep water and different wave headings (0° denotes head seas, 180° following seas)

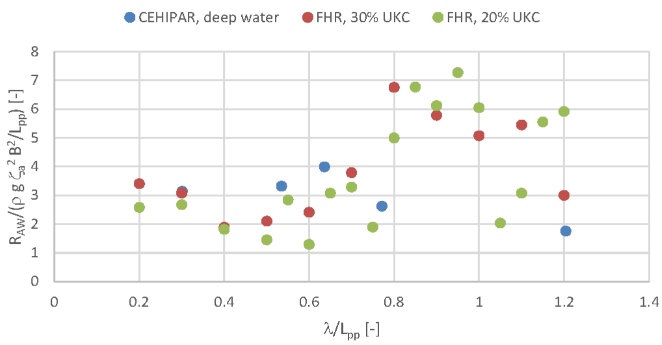
The results are summarized in Figure 11. The highest forces have been measured in head seas and bow quartering seas (waves 60° off the bow), where the peak of the RAO is shifting towards shorter waves for increasing wave encounter angles. In shorter waves $\lambda/L_{pp} < 0.3$, the added resistance is similar for headings from 0° to 60°. At 120°, the measured added resistance is small, changing sign at $\lambda/L_{pp} = 0.25$. From 150° to 180° (stern quartering to following seas), the added resistance becomes negative, i.e. the vessel experiences a pushing effect rather than a resistance caused by the presence of the waves.

The presentation of experimental data for the DTC is not exhaustive but rather provides examples where it is interesting to compare data from different laboratories or testing conditions.

Selected Results – KVLCC2

For the added resistance tests with the KVLCC2 at scantling draught, three different water depths and under keel clearances (ukc) have been considered as well.

In Figure 12 (top), the the measured normalized added resistance values for 6 kn forward speed are shown. A similar tendency as for the DTC results can be observed: the RAO values are increasing with increasing water depth and ukc – apart from the last data point in deep water.



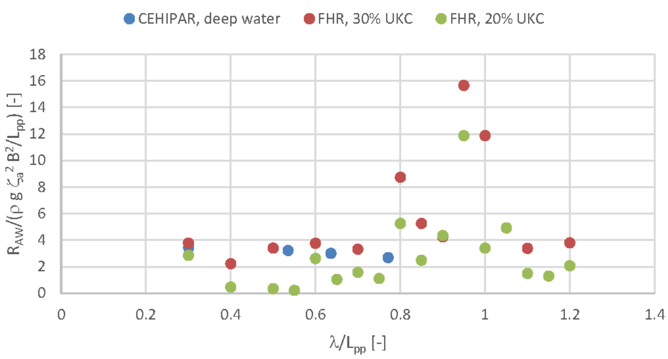


Figure 12: Comparison of added resistance data measured with the KVLCC2 model at scantling draught at 6kn (top) and 12kn forward speed (bottom) in different water depths

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In shallow water, the peak of the RAO is located around $\lambda/L_{pp} = 0.8$, while it appears to be at $\lambda/L_{pp} = 0.65$ in deep water. For the 12 kn case, as presented in Figure 12 (bottom), the added resistance RAO values for deep water (400 m water depth at full scale, blue) and 30% ukc condition (27.0 m water depth at full scale, red) are very similar in the range $0.3 \le \lambda/L_{pp} \le 0.8$. The lowest added resistance values are obtained for the 20% ukc condition (25.0 m water depth at full scale, green).

Another focus of the experimental program of the SHOPERA project lies on the measurement of drift forces in regular waves. For the KVLCC2, numerous drift force tests have been conducted both in deep water at CEHIPAR and in shallow water conditions at FHR.

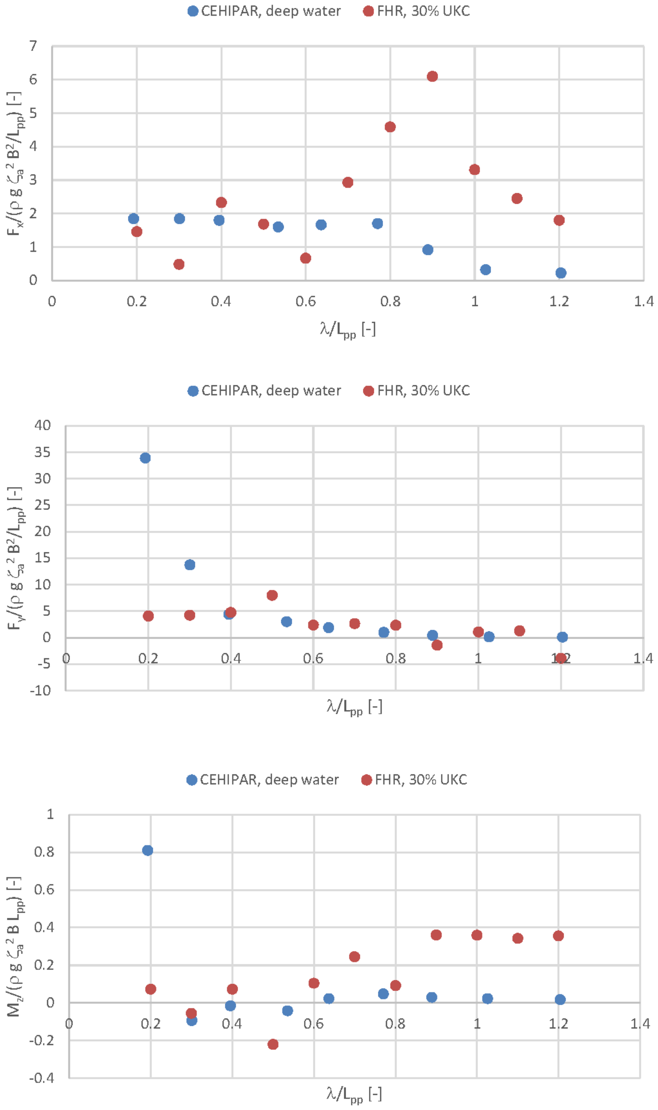

Figure 13: Comparison of measured longitudinal drift forces (top), lateral drift forces (center) and yaw drift moments (bottom) for the KVLCC2 model at scantling draught and in different water depths

An example of the results is presented in Figure 13, where the longitudinal drift forces (top), lateral drift forces (center) and yaw drift moments (bottom) of the KVLCC2 at scantling draught and 0 kn forward speed are compared. The tendencies for the longitudinal forces are similar as for the added resistance results: the RAO values for deep water (400 m water depth at full scale, blue) and 30% ukc condition (27.0 m water depth at full scale, red) are very similar in the range $0.3 \le \lambda/L_{pp} \le 0.8$. For longer waves the forces in shallow water are increasing towards a peak around $\lambda/L_{pp} = 0.9$ while they are decreasing in deep water. The normalized lateral forces for both water depths are very similar for $\lambda/L_{pp} \ge 0.4$. For shorter waves, the RAO values in deep water are increasing while they are almost constant in shallow water. The tendency of the yaw drift moment is very similar for both water depths, with changing signs between $0.2 \le \lambda/L_{pp} \le 0.6$. The magnitude of moments in shallow water is larger than in deep water conditions.

The presentation of experimental data for the KVLCC2 is not exhaustive but rather provides examples where it is interesting to compare data from different laboratories or testing conditions.

MANOEUVRING IN WAVES

The manoeuvrability of ships is addressed by IMO Standards for Ship Manoeuvrability, adopted in 2002 (see [11]), which assess turning ability (the ability of ship to turn using hard-over rudder), initial turning ability (i.e. the course-changing ability), yaw-checking ability, course-keeping ability and emergence stopping ability, which are evaluated in simple manoeuvres in calm water. These standards have been often criticized for not addressing ship manoeuvring characteristics at low speed, in restricted areas and in adverse weather conditions.

Experimental benchmark data for calm water manoeuvres as well as an overview on the capabilities of state-of-the-art numerical methods is available from e.g. the SIMMAN workshops [12].

However, the availability of both, experimental benchmark data and validated numerical methods to assess manoeuvrability in waves in limited. Therefore, special attention has been paid to this test type in the compilation of the model test matrix for the research project SHOPERA.

Calm water manoeuvres such as turning circles and zig-zags have been performed in regular waves of different periods and height with different initial headings. It should be noted that these are not defined IMO conform manoeuvres and the results are not comparable to calm water results in classical quantities such as e.g. the tactical diameter or the overshoot angle. The purpose of these tests is to gain insight into the manoeuvrability of vessels in the presence of waves in a broader and more general sense. First validation results for the numerical methods developed within SHOPERA to predict manoeuvrability in waves are presented in [13].

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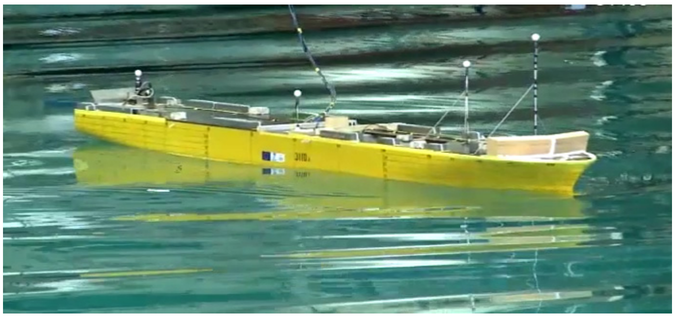

Figure 14: Impression of the free-running DTC model performing manoeuvring tests in waves in MARINTEK's Ocean Basin

Turning circle (35° rudder angle) and 20°/20° zig-zag manoeuvres in calm water and regular waves have been performed with the free-running DTC model (connected by an umbilical to a manually controlled gondola following the model, see Figure 14). Heading and propulsion settings have been controlled by MARINTEK's online autopilot software NEMO, with an applied rudder rate of 3.0°/s model scale (corresponding to 25°/s full scale). The online PD regulator of the autopilot software has been tuned by experienced MARINTEK staff to find the optimum settings (constant RPM approach) for the tests and to achieve the same initial vessel speed (6 kn, full scale) prior to rudder execution. The instrumentation consists of a rudder servo for the autopilot, a dynamometer to measure thrust and torque, the optoelectronic position measuring system OQUS for measurement of motions in 6 DOF and four conductive wave tapes to measure the relative waves elevation at the port side fore shoulder of the hull.

The majority of tests has been performed with the rudder set to starboard. Additional runs have been conducted to investigate the differences in manoeuvring behaviour when the rudder is set to portside, caused by the single screw propeller and twisted rudder setup of the DTC. The evaluation of the test data revealed that the rudder of the DTC model was mounted approx. 3° off the true zero angle towards portside, leading to pronounced differences between manoeuvres over portside and starboard side. Repetitions of the calm water turning circle manoeuvres showed a deviation of less than 1% in tactical diameter and advance.

The test matrix comprises a total of 17 turning circle manoeuvres, two calm water reference runs, 14 runs in regular waves (parameters of variation: initial heading, rudder direction, wave period, wave height) and 1 run in irregular seas.

In addition, five 20°/20° zig-zag manoeuvres have been performed, one calm water reference run and 4 runs in regular head waves (parameters of variation: wave period and timing of rudder execution relative to crest/trough). The comparison of the phasing of the rudder execution revealed a negligible influence on the characteristics of the manoeuvres with differences of 2-3% for overshoot angles and timing. These differences are in the range of accuracy of manoeuvring tests in waves and it is difficult to draw conclusions with respect to the influence of phase shift on the manoeuvring characteristics.

In Figure 16, examples of the influence of the initial wave heading on the trajectory during the manoeuvre is shown. The vessel trajectories in the x-y-plane in waves are compared to a reference run in calm water (black trajectory). The approach speed for all cases is 6 kn (full scale) and the results are synchronized with respect to rudder execution (35° to starboard). In head sea conditions (red trajectory), the first circle requires less space compared to the calm water reference run, and as apparent from Figure 15, it takes the vessel approximately the same time to change heading by 90° as in calm water, while a turn over 180° takes less time than for the calm water case. The head waves push against the bow and thus amplify the effect of the moment produced by the rudder. The vessel is drifting oblique with the direction of wave propagation. This is caused by the wave moment acting against the rudder moment when the ship is turning from 180° to 270°. In following sea conditions, the (blue) trajectory of the vessel is strongly distorted by the pronounced drift motion between consecutive turns, here the wave moment amplifies the effect of the rudder moment when the ship is turning from 180° to 270°. In this condition, it takes approximately the same time to turn 90° as in calm water, while it takes significantly longer to turn by 180° (see Figure 15). When the vessel approaches the manoeuvre in beam seas and initially turns the bow into the waves (green trajectory), it takes slightly longer to turn 90°, while the time required to turn by 180° is approximately the same as in calm water (see Figure 15).

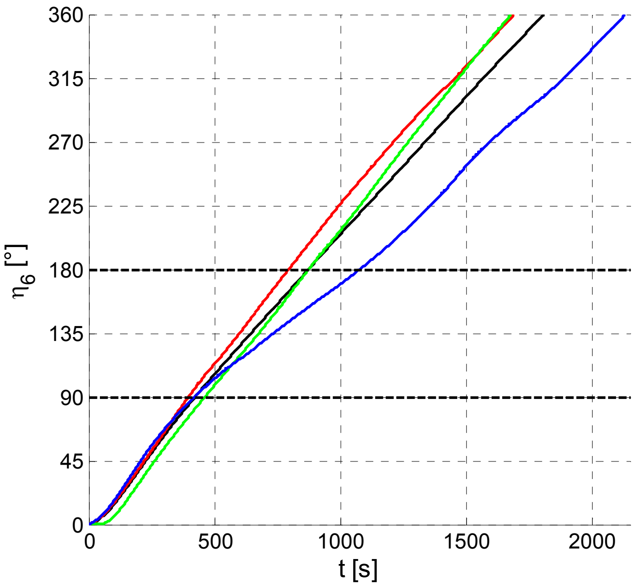

Figure 15: Time series of the vessel heading during the turning circle manoeuvres in calm water (black), head waves (red), beam waves (green) and following waves (blue)

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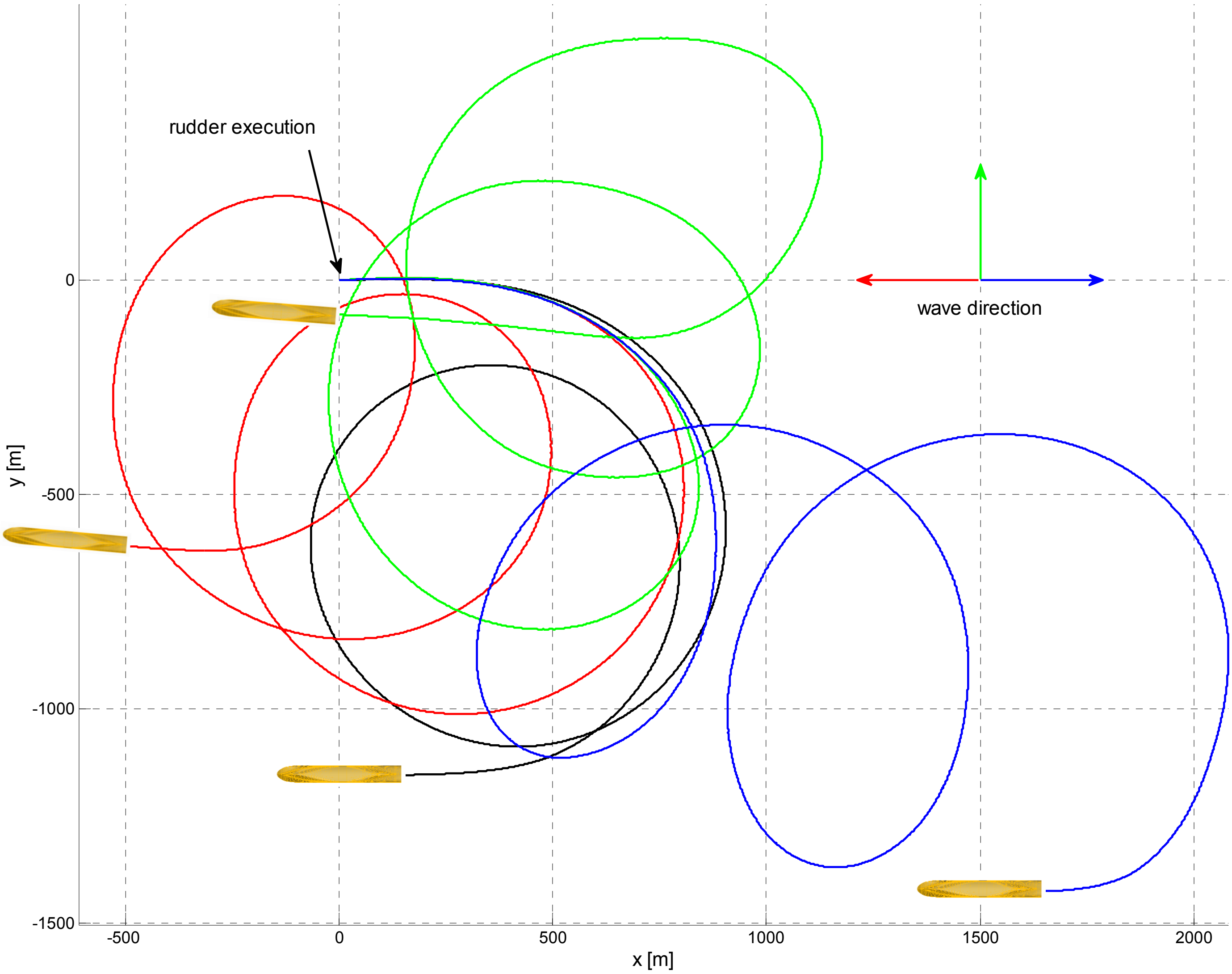

Figure 16: Trajectories of the DTC performing turning circle manoeuvres (rudder 35° to starboard) in MARINTEK's Ocean Basin in calm water (black), head waves (red), beam waves (green) and following waves (blue); tests have been conducted in regular waves with H = 2.0 m and T = 10.6 s (full scale)

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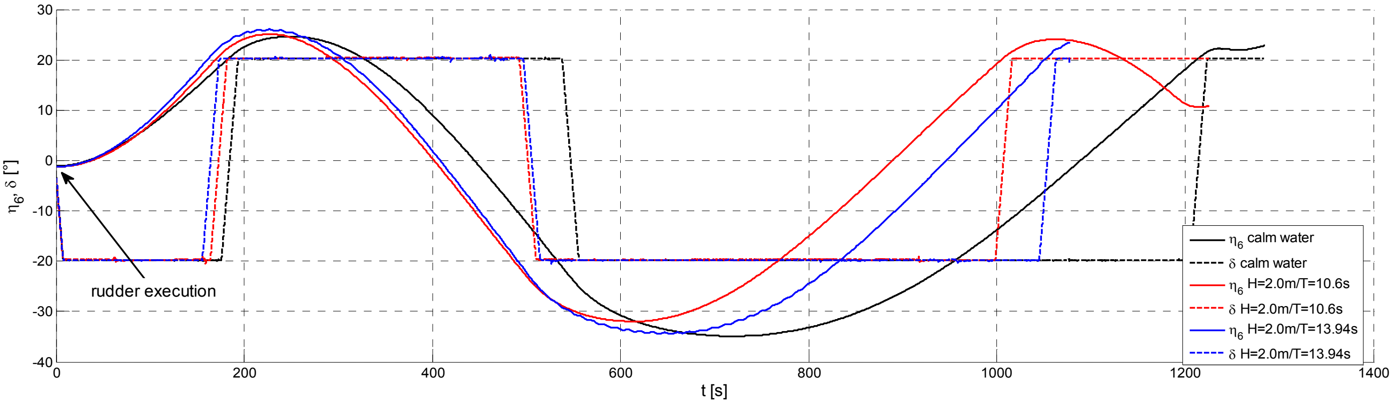

Figure 17: Yaw and rudder angle of the DTC performing 20°/20° zig-zag manoeuvres in MARINTEK's Ocean Basin in calm water (black) and regular head waves with H = 2.0m/T = 10.6 s (red) and H = 2.0m/T = 13.94 s (blue), full scale

An example of the influence of regular head waves on the course changing ability of the DTC vessel is presented in Figure 17, where three 20°/20° zig-zag manoeuvres with 6 kn approach speed are compared. The black lines show the yaw angle (solid) and rudder angle (dashed) as a function of time in calm water (full scale), the red and blue lines represent the regular head wave cases (red: H = 2.0 m/T = 10.6 s, blue: H = 2.0 m/T = 13.94 s). All three cases are synchronized with respect to first rudder execution, which has been performed with wave crest at $L_{pp}/2$ (FP) for the cases with waves. While the first (and second) overshoot angle and initial turning time is similar for all three cases, the differences become more pronounced for reach and time for the complete cycle. In head waves, the vessel requires less time to reach zero heading after the first and third rudder execute. The shortest duration for the completion of the manoeuvre is observed for the longer wave period (T = 13.94 s).

CONCLUSIONS

This paper presents examples of the broad experimental campaign that has been run with two public domain hull models of different hydrodynamic characteristics – the DTC and the KVLCC2 - by four of the leading European maritime experimental research institutes within the framework of the EU research project SHOPERA, namely MARINTEK, CEHIPAR, Flanders Hydraulics Research and Technische Universität Berlin. The purpose of the performed model tests is to contribute to the establishment of a benchmark and validation database that addresses seakeeping and manoeuvring in waves in different environmental conditions and water depths. This database is of paramount importance for the development of procedures to assess ship performance and to formulate minimum powering requirements to ensure safe ship operation in adverse weather conditions, while keeping the right balance between ship economy, efficiency and safety.

The presented data samples have been selected to highlight the influence of wave climate, vessel heading and water depth on added resistance and drift forces for different vessel types. The key findings from the comparison of selected results are:

- An overall fair agreement of results can be observed, with no significant deviations caused by the different test setups of the involved facilities
- Normalized added resistance increases with increasing slightly with increasing water depth
- The squared-amplitude relation for added resistance has been confirmed for longer waves in deep water. For short waves in deep water and for very small ukc regimes, this relation appears to be questionable.
- For large vessels, especially the short relative wave range is of relevance. This leads to challenges for testing facilities when it comes to scales and accuracies for both, waves and forces.
- For the DTC, the added resistance becomes negative at 6 kn over certain period regions in stern quartering and following seas. This means that the vessel actually experiences a pushing effect from the waves.
- The influence of the boundary layer of the bottom flow of the towing tank on added resistance for very small ukc is not known.

Experimental investigations of manoeuvres performed in regular waves with different initial heading illustrate the importance of considering the presence of waves when assessing the manoeuvrability of a vessel. The comparison of results from selected turning circle and zig-zag tests with the DTC model in waves and calm water in MARINTEK's Ocean Basin reveals:

- Turning circles performed in initial head or beam sea conditions require the least space and time, turning circles performed in initial following seas require the most space and time.
- Turning 90° in beam seas takes longer than for all other investigated cases, while a 180° turn takes about the same time as in calm water conditions.
- Turning 180° in head seas requires less time than in calm water.

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- Turning 90° in following seas takes less time than for all other investigated cases, while a 180° turn takes the more time than in all other investigated cases.

ACKNOWLEDGMENTS

The authors acknowledge the contributions of all SHOPERA partners. The work presented in this paper is supported by the Collaborative Project SHOPERA (Energy Efficient Safe SHip OPERAtion), Grant Agreement number 605221, co-funded by the Research DG of the European Commission within the RTD activities of the FP7 Thematic Priority Transport, FP7-SST-2013-RTD-1, Activity 7.2.4 Improving Safety and Security, SST.2013.4-1: Ships in Operation. The European Community and the authors shall not in any way be liable or responsible for the use of any knowledge, information or data of the present paper, or of the consequences thereof. The views expressed in this paper are those of the authors and do not necessary reflect the views and policies of the European Community.

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