CAPTIVE MODEL TESTING FOR SHIP-TO-SHIP OPERATIONS

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In the frame of the research project entitled *"Investigating Hydrodynamic Aspects and Control Strategies for Ship-to-Ship Operations"* [1], co-ordinated by MARINTEK (Trondheim, Norway) and supported financially by the Research Council of Norway, a captive model test program has been carried out at the *Towing Tank for Manoeuvres in Shallow Water* (co-operation Flanders Hydraulics Research – Ghent University) in Antwerp, Belgium. The present paper will give an overview of the entire model test program. For a limited amount of tests all measured data will be made available, free to use.

1. INTRODUCTION

Through their large capacity, very (VLCC) and ultra (ULCC) large crude carriers offer the advantage to transport huge quantities of crude oil per voyage, which reduces the transport cost considerably. On the other hand, they suffer from different disadvantages such as the limited access to harbours due to their size or governmental restrictions that want to preserve the safety and environment in coastal areas. To unload the cargo in harbours it must be transferred to smaller service ships, with a typical capacity of 100,000 ton. This operation, called lightering, typically takes place in open sea and at a certain ahead speed. The application of ship-to-ship operations for liquid cargo transfer, will be increasing in the future, not only for crude oil, but also for liquefied natural gas (LNG). Moreover, such operations are expected to take place in more severe environmental conditions.

The main objective of the research project entitled *"Investigating Hydrodynamic Aspects and Control Strategies for Ship-to-Ship Operations"* is to improve existing simulator based training activities for crews, mooring masters and other experts involved in complex ship-to-ship operations in open seas through increased knowledge and understanding of the complex water flow between two ships operating in close proximity. As a final goal, a new generation simulation tools for ship-to-ship operations incorporating up-to-date knowledge of fluid dynamics has to be established. The research project consists of four work packages: Computational Fluid Dynamics (CFD); Particle Image Velocimetry (PIV); Mathematical models for simulators; and Nautical safety and control aspects.

In the frame of the third work package, captive model tests have been carried out at the *Towing Tank for Manoeuvres in Shallow Water* (co-operation Flanders Hydraulics Research – Ghent University) in Antwerp, Belgium. The model of an Aframax tanker is attached to the computer controlled planar motion carriage and a VLCC model is attached to the main carriage of this mechanism. Two types of tests are considered: steady state tests, during which the main tests parameters (ships' speed, relative longitudinal and lateral position, propeller rates, drift angle of the Aframax tanker, rudder angle) are kept constant, and dynamic tests, characterised by a varying rudder angle, lateral distance and/or heading. Horizontal forces and moments, propeller thrust and torque, and vertical motions are measured on both ship models, while the vertical motions of the free surface are monitored at three fixed points in the towing tank.

For five steady state tests and one dynamic test the measured data will be made available. This data contains all measurements of forces, moments and motions on both models and includes the registered wave pattern by all three wave gauges.

2. TEST PROGRAM

2.1 Test facilities

At present the shallow water towing tank, with main dimensions 88 x 7 x 0.5 m^3, is equipped with a planar motion carriage, a wave generator and an auxiliary carriage for ship-to-ship interaction tests for ships at different forward speeds. Thanks to full computer control, the facilities are operated in an unmanned way, so experimental programs are running day and night, 7 days a week. An average of 35 tests a day can be carried out.

One ship model is connected to the carriage by means of a mechanism which allows free heave and pitch; roll can be restrained or free. In the horizontal plane, a rigid connection is provided. The three horizontal motion modes, the wave generator, rudders, propulsions, the auxiliary carriage and other external devices are controlled by a PC and six DIOCs (Direct Input Output Control). The DIOCs also assure the sampling of the analogue input signals.

A secondary beam is added to the main carriage of the towing tank to be able to perform ship-to-ship interaction tests for ships with a zero longitudinal speed difference. This secondary beam is a construction of Rose+Krieger profiles with a length of 6.0 m in the longitudinal direction of the tank. The second ship model is connected to this secondary beam in two points by means of a system of rods and hinges that allows heave and trim. Both connection points are equipped with longitudinal and lateral force gauges; principally the longitudinal force between the carriage and the ship model applies in the most forward connection point only. This setup is shown in Figure 1.

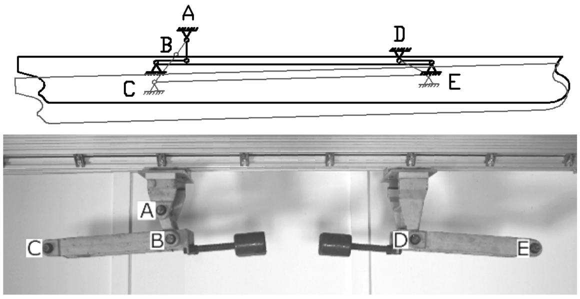

Figure 1 Schematic setup of the connection ship - secondary beam

The transversal position of the ship attached to the secondary beam can be adjusted manually over a range of about 3.00m. During this project the position of the centre line of this ship is fixed at 1.007m out of the centre of the towing tank. The vertical position can be changed so the connection blocks do not induce forces on the model at different combinations of water depth and draft.

2.2 Ship models

Two ship models have been used: a model of a VLCC and an Aframax tanker, both on a scale of 1/75.


Figure 2 Shallow water towing tank (empty) at Flanders Hydraulics Research with secondary beam

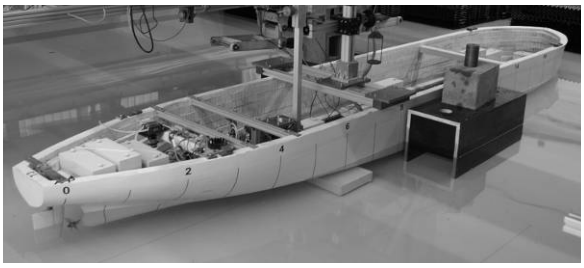
Figure 3 STBL model being prepared for tests

The ship to be lightered (STBL) is a VLCC, for which the MOERI Tanker KVLCC2 has been selected. This is the second variant of the MOERI tanker with more U-shaped stern frame-lines. The hull, propeller and rudder geometry are made available at Simman 2008 [2] and [3].

The STBL model has been constructed in wood by BSHC (Varna, Bulgaria). The main dimensions are shown in Table 1. Tests have been carried out at two different drafts: fully loaded and the draft corresponding to the draft after the second off loading.

During the model test series, the STBL model was attached to the secondary beam.

Table 1 Main dimensions of the STBL

	STBL	
	Full Scale	Model scale
Scale	1	1/75
Hull		
L_{PP}(m)	320.0	4.267
L_{WL} (m)	325.5	4.340
B (m)	58.0	0.773
Design condition		
T_F (m)	20.8	0.277
T_A (m)	20.8	0.277
∇ (m³)	312622	0.741
Loading condition after 2nd off load		
T_F (m)	12.8	0.171
T_A (m)	12.8	0.171
∇ (m³)	182941	0.434
Rudder		
Type	Horn	
Wetted surface (m²)	273.3	0.048
Lateral area (m²)	136.7	0.024
Propeller		
Type	Fixed	
No. of blades	4	4
D (m)	9.86	0.131
P/D (0.7R)	0.721	0.721
Ae/A0	0.431	0.431
Rotation	Right	Right

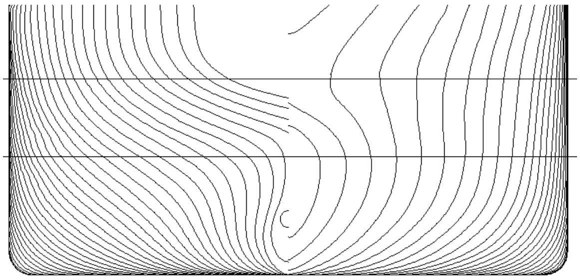

Figure 4 Body plan of the ship to be lightered (STBL) including both water lines at tested drafts.

The service ship (SS) is a scaled model of an Aframax tanker. The hull and rudder geometry and the main properties of the propeller are provided by Marintek. This model was built at Zeydon (Arendonk, Belgium) in fibre glass reinforced vinyl ester to have a rigid but very light ship model. The model is constructed using a female mould and vacuum infusion. This Aframax tanker is tested at two loading conditions: design and ballast (Table 2). During the model test series, the Aframax model was attached to the main beam of the towing carriage.

Table 2 Main dimensions of the SS

	SS model	
	Full Scale	Model scale
Scale	1	1/75
Hull		
L_{PP}(m)	231.4	3.085
L_{WL} (m)	233.92	3.119
B (m)	42.0	0.560
Design condition		
T_F (m)	15.0	0.100
T_A (m)	15.0	0.100
∇ (m³)	109139	0.259
Ballast condition		
T_F (m)	7.5	0.100
T_A (m)	9.1	0.121
∇ (m³)	58456	0.139
Rudder		
Type	Ocean Mariner Schilling	
Wetted surface (m²)	156.1	0.028
Lateral area (m²)	57.9	0.010
Propeller		
Type	Fixed	
No. of blades	5	5
D (m)	6.825	0.091
P/D (0.7R)	0.744	0.744
Ae/A0	0.610	0.610
Rotation	Right	Right

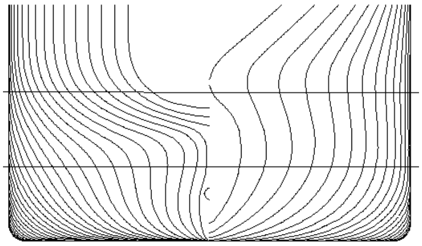

Figure 5 Body plan of the service ship (SS) including both water lines at tested drafts.

Figure 6 Stern and stem section of the SS model in fibre glass reinforced vinyl ester.

2.3 Model tests

The self propulsion point has been defined for both ship models. During the self propulsion tests, each ship has been towed at speeds of 2.0, 4.0 and 6.0 knots full scale, while the propeller rate was changed continuously according to a harmonic time series from zero up to 100% rpm (78.0 rpm full scale) back to zero. The zero-crossing of the longitudinal force that was measured during these tests reveals the model self-propulsion point.

The SS model in ballast condition (T_F=7.5m, T_A=9.08m) has been towed at three different water depths (h/T=3.93; 3.09 and 1.90). An overview of the self propulsion points is given in Table 3.

Table 3 Tested propeller rates of the SS model at ballast condition

	Propeller rates SS model at model scale	
	Ballast (rpm)	Fully loaded (rpm)
2 kts	137	140
4 kts	274	310
6 kts	411	465
Half	589	589
Slow	433	433

Table 4 Self propulsion propeller rates of the STBL

	Propeller rates STBL at model scale (rpm)
	Loading condition after 2nd off load
2 kts	137
4 kts	250
6 kts	345

The STBL model is towed at the highest water level (h/T=1.87) and at her smallest displacement (T_F=12.8m, T_A=12.8m). The results are shown in Table 4. These propeller rates have been used for all loading conditions and water depths.

All tests carried out with the STBL attached to the secondary carriage and the SS model attached to the main planar motion carriage of the towing tank are referred to as ship-to-ship interaction tests. The SS model is always located at the port side of the STBL (Figure 7). Two types of tests can be distinguished: steady state tests and dynamic tests. At the end of the program 1981 steady state tests and 162 dynamic tests were carried out.

The following combinations of loading conditions for both models have been carried out:

- $SS_{ballasted}$ - $STBL_{2nd\ off\ load}$
- $SS_{ballasted}$ - $STBL_{design}$
- SS_{design} - $STBL_{2nd\ off\ load}$

Two water depths were selected for each combination of displacements. The maximal water depth is 0.475m due to the restrictions of the towing tank. The lowest water level is chosen in such a way that the vessel with the deepest draft has a gross under keel clearance of 35% of the draft. An overview of the absolute values of the water depth in the towing tank is given in Table 5.

Because of the test setup both ships have exactly the same speed in the longitudinal direction of the towing tank. Three speed values have been selected: 2.0, 4.0 and 6.0 knots full scale. As the forces measured during the earliest tests carried out at 2 knots appeared to show a very low absolute value, the number of tests at this speed has been decreased in the test program. A limited amount of tests has been carried out at 5 knots.

Table 5 Experimented water depths

	Water depth [m]	
	UKC 35%	**max**
$SS_{ballasted}$-$STBL_{2nd\ off\ load}$	0.270	0.475
$SS_{ballasted}$- $STBL_{design}$	0.374	0.475
SS_{design}- $STBL_{2nd\ off\ load}$	0.230	0.475

Figure 7 Ship-to-ship interaction tests

The propeller rate of the STBL is always at the self propulsion point as defined in Table 4. The SS model is systematically tested at the self propulsion point (see Table 3) and at the telegraph positions 'slow' and 'half'.

During the test program, the STBL has been towed at zero drift angle only. The drift angle of the SS model in both loading conditions has been varied during the test program: values of 0°, -1°, -2°, -3° and -5° have been applied. The majority of tests are executed with the service ship's bow directed towards the STBL. Only for a very limited amount of tests with the ballasted SS model her bow was directed away from the STBL.

The relative distance between the SS and STBL has been varied. Five lateral distances between the sides of the ships have been selected: 4, 10, 25, 50 and 100m full scale. This range is based on lightering practice: in the beginning of the operation, both ships sail at the same speed and heading at a lateral distance of about 100m before the SS model starts her approach to the STBL. When moored to each other both ships are separated by 4m which is about the size of the fenders between both ships.

Tests have been carried out at different relative longitudinal positions between both midship sections. Three standard positions have been selected: both midship sections at the same longitudinal position

(0%), the SS model half a ship length (Lpp_{SS}) fore of the STBL (+50%), and the SS model half a ship length aft of the STBL (-50%).

A short series of tests has been carried out at a wide range of longitudinal positions between both ships. Figure 8 shows the results of such a series for the (non dimensional) yaw moment of the SS model. When the midship section of the SS model is located in front of the midship section of the STBL a yaw moment is induced on the SS directed with her bow towards the STBL. When the midship of the STBL is in front of the SS model the yaw moment on the SS is directed with her bow away from the STBL. The highest magnitude of the yaw moment occurs when the bow of the SS and the stern of the STBL, and vice versa, are about the same longitudinal position.

All parameters varied during the systematic steady state tests are summarized in Table 6.

During the dynamic tests the values of one or more parameters are varied harmonically as a function of time, while other parameters are kept constant. The following types of dynamic tests have been executed:

- harmonic sway tests
- harmonic yaw tests
- harmonic rudder angle tests.

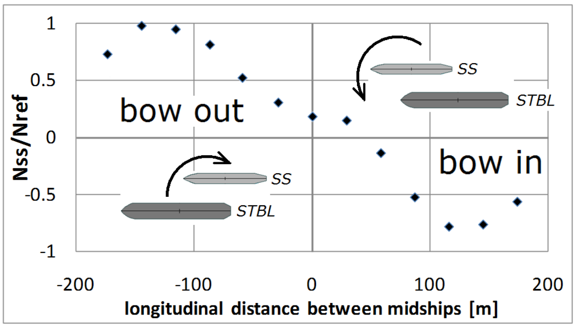

Figure 8 Yaw moment of SS at one lateral distance and different longitudinal distances to the STBL

Table 6 Overview of the variation of all tested parameters during steady state tests. (Grey box indicates not tested at all combinations.)

h	T_{STBL}	n_{STBL}	V	T_{SS}	ψ_{SS}	n_{SS}	δy	δx
[m]	[m]	[]	[kts]	[m]	[deg]	[]	[m]	[m]
h_{max}	20.8	self	2.0	7.5	180	slow	4	0
1.35 T_{STBL}	12.8		4.0	15	179	half	10	L/2
			5.0		178	self	25	-L/2
			6.0		177		50	
					175		100	

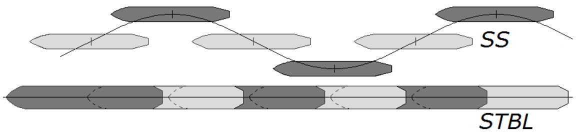

Figure 9 Harmonic sway test

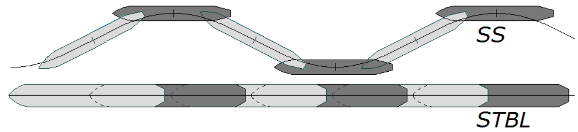

Figure 10 Harmonic yaw test

During a harmonic sway test the main carriage moves with a constant forward speed, while the SS model performs a sway motion with a harmonically varying lateral speed (Figure 9). The heading is always parallel to the longitudinal axis of the towing tank, and therefore equal to the STBL's heading. At the beginning of the tests, the lateral distance between the sides of both models is 100m full scale, the closest distance between both ships' sides is 4m and at the end of the test the lateral separation between both ships is again 100m.

During a harmonic yaw test, the SS model performs a motion characterised by a constant longitudinal ship speed component, a zero drift angle and a harmonically varying heading angle (Figure 10). The lateral separation between the sides of both models also varies between a maximum of 100m and a minimum of 4m full scale. In order to obtain a constant velocity component along the SS model's longitudinal axis the main carriage speed is not constant but contains higher harmonics because of the harmonic motion of the yawing table. As a result, the forward speed of the STBL slightly oscillates during harmonic yaw tests.

Finally tests have been carried out with a harmonic variation of the SS model's rudder angle. During these tests the relative lateral distance between both ship sides is kept constant at 10.0m full scale. The rudder angle changes harmonically as a function of time between -40° and +40°.

3. OPEN STS DATA

For five steady state tests and one dynamic test the forces, moments and motions are made available. All different coordinate systems used in this project are summed up and the position of their origin and orientation of relevant axes explained. Figure 11 shows the test setup and the three rectangular, right-handed coordinate systems of importance:

- $O_0x_0y_0z_0$ (fixed to towing tank)
- $O_{SS}x_{SS}y_{SS}z_{SS}$ (fixed to SS model)
- $O_{STBL}x_{STBL}y_{STBL}z_{STBL}$ (fixed to STBL model)

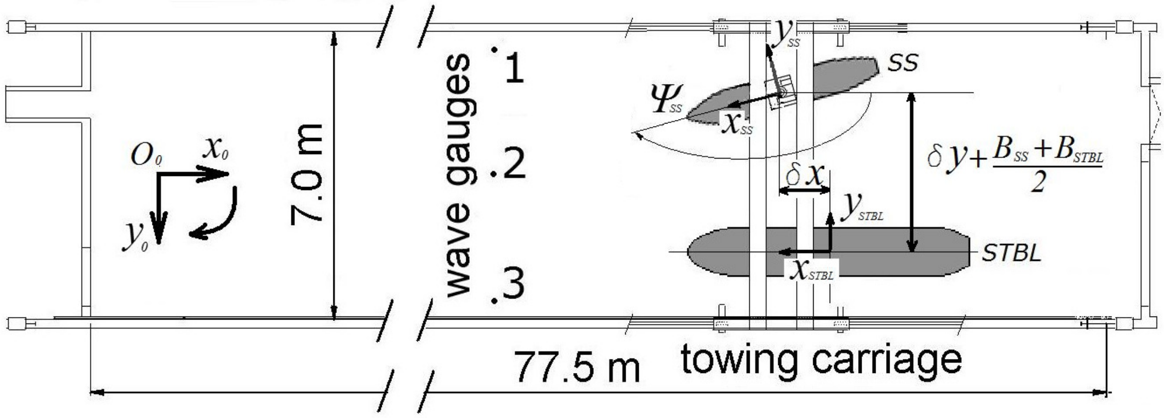

Figure 11 Test setup and coordinate systems of importance.

3.1 Measured forces, moments and motions

During the captive model tests the ship models are free to heave and pitch but are rigidly connected to the carriage according to the other degrees of freedom. The following items have been measured during the tests.

- Hull: For both models the longitudinal and lateral components of the horizontal forces acting between the ship model and the mechanism in two measuring posts located aft and fore in the ship model are registered and converted to a longitudinal force *X*, a lateral force *Y* and a yawing moment *N*, expressed in each ship model's coordinate system ($O_{SS}x_{SS}y_{SS}z_{SS}$, $O_{STBL}x_{STBL}y_{STBL}z_{STBL}$). The roll moment *K*, preventing rotation around the *Ox*-axis, is measured separately for the SS model. The vertical motion of the latter is measured in four points (fore/aft, port/starboard) and converted into z_F and z_A, the vertical motion of the fore and aft perpendiculars, respectively, considered to be positive in case of a downwards motion.

- Propeller: the thrust T_P is positive from stern to stem (as the propeller pushes the ship forward) and the propeller rate *n* is positive turning clockwise (for a right-handed propeller when looking forward). When the propeller generates a positive thrust having a positive propeller rate the torque Q_P on the propeller shaft is considered to be positive.

- Rudder (see Figure 12): the tangential force F_{TR} is positive from trailing towards the leading edge of the rudder, the normal force F_{NR} is positive towards the starboard side. The rudder angle δ is positive if resulting into a turning manoeuvre to port.

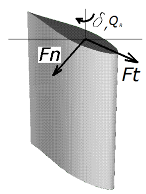

Figure 12: Orientation of normal and tangential forces on rudder and rudder angle and torque

- Water surface level: an increasing water level generates an increasing value of the wave gauge signals.

For the SS model these items have been measured:

Hull:		
Sinkage fore and aft	$z_{F,SS}$ $z_{A,SS}$	[m]
Longitudinal force	X_{SS}	[N]
Sway force	Y_{SS}	[N]
Yaw moment	N_{SS}	[Nm]
Roll moment	K_{SS}	[Nm]
Propeller:		
Propeller thrust	$T_{p,SS}$	[N]
Propeller torque	$Q_{p,SS}$	[Nm]
Propeller rate	n_{SS}	[rpm]
Rudder:		
Rudder normal force	Fn_{SS}	[N]
Rudder tangential force	Ft_{SS}	[N]
Rudder torque	$Q_{r,SS}$	[Nm]
Rudder angle	δ_{SS}	[deg]

and for the STBL:

Hull:		
Longitudinal force	X_{STBL}	[N]
Sway force	Y_{STBL}	[N]
Yaw moment	N_{STBL}	[Nm]
Propeller:		
Propeller thrust	$T_{p, STBL}$	[N]
Propeller torque	$Q_{p, STBL}$	[Nm]
Propeller rate	n_{STBL}	[rpm]

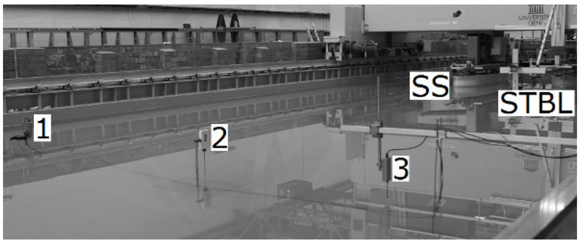

Figure 13 The three wave gauges (*1* at starboard SS, *2* between ships and *3* at port side STBL)

Furthermore three wave gauges were installed to register the wave pattern. One wave gauge is installed between the ship models (*2* in Figure 13), one at the port side of the STBL (*3* in Figure 13) and one at the starboard side of the SS (*1* in Figure 13). The exact position of the wave gauges is given in Table 7.

Table 7 Position of the wave gauges

Wave gauge	x_0 [m]	y_0 [m]
1	50.00	-1.834
2	50.00	0.595
3	50.00	2.166

3.2 Data

For six tests all measured data is made available free to use. All tests are carried out with the SS model sailing at the starboard side of the STBL. The STBL sails with zero drift angle or heading $\psi_{STBL} = 180°$ because a test run starts at the end of the towing tank in the direction of the origin of the earth bound coordinate system. During the test named E the SS sails with her midship half a ship length δx in front of the STBL's midship.

The water depth h, drafts T_{SS}, T_{STBL}, headings ψ_{SS}, ψ_{STBL}, the lateral position of the SS in the towing tank y_0, distance between both ship sides δy, forward and lateral speed u, v, propeller rates n_{SS}, n_{STBL} and rudder angles δ_{SS}, δ_{STBL} are summarized for all tests in Table 8.

The registration of the wave gauges is given in Figure 14, Figure 15, Figure 16 and Figure 18. On the abscissa the longitudinal distance between the midship of the SS model and the wave gauges is given (50.00 - x_0), the ordinate shows the water level depression relative to the still water level. A negative value on the abscissa means the midship did not pass the gauges yet.

Table 8 Test conditions for open data

	A	B	C	D	E	F
h [m]	0.230	0.270	0.475	0.374	0.475	0.230
$\mathbf{T_{SS}}$ [m]	0.100	0.200	0.200	0.100	0.100	0.100
$\mathbf{T_{STBL}}$ [m]	0.171	0.171	0.171	0.277	0.277	0.171
ψ_{SS} [°]	180	180	180	178	180	180
ψ_{STBL} [°]	180	180	180	180	180	180
δx [m]	0	0	0	0	1.543	0
$\mathbf{y_{0,SS}}$ [m]	-0.327	-0.327	0.287	0.007	0.007	0.207
δy [m]	0.667	0.667	0.053	0.333	0.333	0.133
$\mathbf{u_{SS}}$ [m/s]	0.356	0.297	0.238	0.237	0.356	0.356
$\mathbf{v_{SS}}$ [m/s]	0.000	0.000	0.000	0.008	0.000	0.000
$\mathbf{n_{SS}}$ [rpm]	588	384	432	273	410	410
$\mathbf{n_{STBL}}$ [rpm]	344	287	249	249	345	345
δ_{SS} [°]	0	0	0	0	0	-40 – +40
δ_{STBL} [°]	0	0	0	0	0	0

The longitudinal force, sway force, yaw moment, trim and sinkages of the SS model are listed in Table 9 as well as the thrust and torque on the propeller shaft and the longitudinal, transversal force and torque on the rudder shaft.

For the STBL the longitudinal and sway force, yaw moment and thrust and torque on the propeller shaft resulted from the steady state tests are shown in Table 10.

For the tests B, D and E three wave gauges registered the wave pattern on a fixed position in the towing tank (Table 7). The registration of the relative water level is shown in Figure 14, Figure 15 and Figure 16.

Table 9 Forces, moments and motions on the service ship

		A	B	C	D	E
$\mathbf{X_{SS}}$	[N]	-0.10	-0.25	-0.13	-0.02	-0.04
$\mathbf{Y_{SS}}$	[N]	-0.30	-1.55	-1.09	-0.81	-1.15
$\mathbf{N_{SS}}$	[Nm]	1.38	0.19	0.73	-0.02	0.11
$\mathbf{K_{SS}}$	[Nm]	0.00	0.01	0.01	0.00	0.00
$\mathbf{z_{F,SS}}$	[mm]	1.1	3.0	0.4	1.0	2.1
$\mathbf{z_{A,SS}}$	[mm]	4.3	-0.3	0.7	0.9	2.1
$\mathbf{T_{p,SS}}$	[N]	0.87	0.62	0.90	0.19	0.64
$\mathbf{Q_{p,SS}}$	[Nmm]	25	15	17	9	13
$\mathbf{Ft_{SS}}$	[N]	-0.05	-0.06	-0.06	-0.01	-0.02
$\mathbf{Fn_{SS}}$	[N]	-0.09	-0.11	-0.11	-0.03	-0.05
$\mathbf{Q_{r,SS}}$	[Nmm]	0.18	-0.17	-0.11	-0.01	0.10

Table 10 Forces and moments measured on the STBL

	A	B	C	D	E
X_{STBL} [N]	1.48	0.21	0.88	0.23	0.06
Y_{STBL} [N]	0.85	1.41	0.86	0.91	0.85
N_{STBL} [Nm]	3.44	-0.68	0.00	-0.28	-0.74
$T_{p,STBL}$ [N]	2.44	1.68	0.98	0.88	2.43
$Q_{p,STBL}$ [Nmm]	37	26	18	23	36

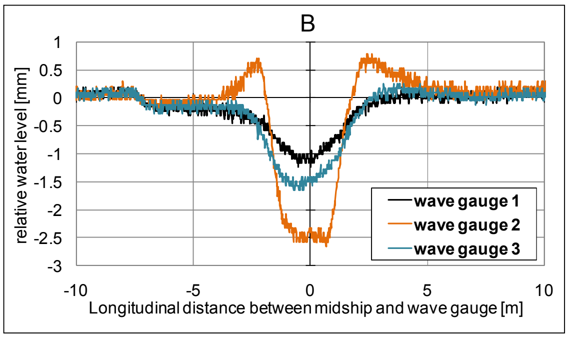

Figure 14 Test B Registration of the wave pattern by three wave gauges

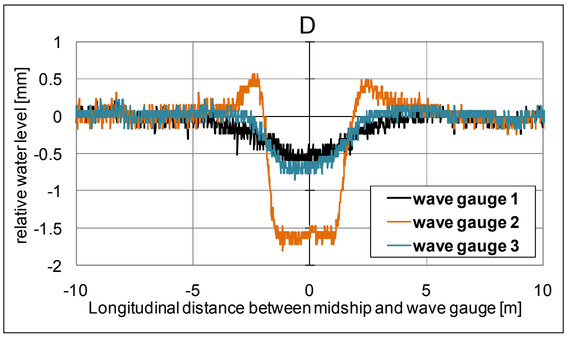

Figure 15 Test D Registration of the wave pattern by three wave gauges

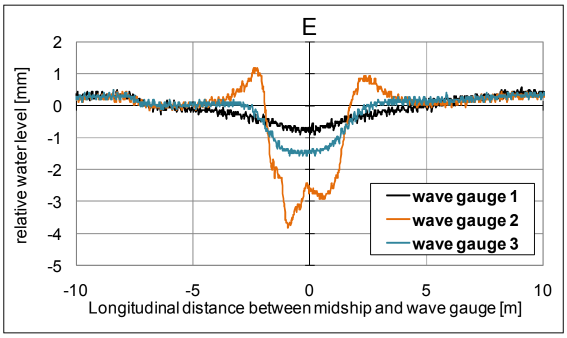

Figure 16 Test E: Registration of the wave pattern by three wave gauges

The rudder angle of the SS varies harmonically (between -40° and +40°) during test F. The results of this test are summarised in Table 11. In Figure 17 the yaw moment on the SS model is shown with varying rudder angle. This graphs shows that a rudder angle of about 10 degrees compensates the yaw moment induced by the proximity of the STBL. This however does not compensate the sway force induced by the STBL. The registration of the wave pattern is added in Figure 18.

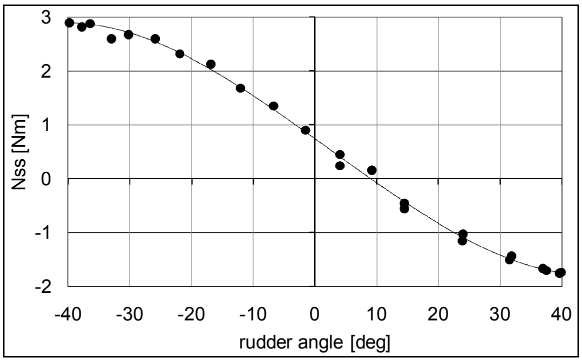

Figure 17 The yaw moment of the SS model with a varying rudder angle.

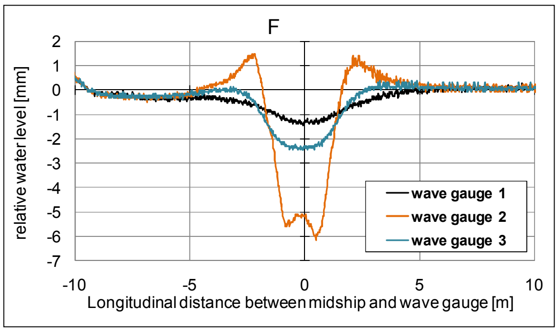

Figure 18 Test F Registration of the wave pattern by three wave gauges

4. CONCLUSION

Because of the increasing interest in and complexity of ship to ship manoeuvres, and the growing importance of simulation as a training and research tool, a research project entitled *"Investigating Hydrodynamic Aspects and Control Strategies for Ship-to-Ship Operations"* has been initiated by MARINTEK (Trondheim, Norway) to obtain more insight into the physical background and improve and extend the existing mathematical simulation models. For one of the work packages of this project an extensive series of model tests are carried out in the *Towing Tank for Manoeuvres in Shallow Water* (co-operation Flanders Hydraulics Research – Ghent University). The present paper gives a description of the test program.

For a very limited selection of tests, all results are made available. These test results are free to use as benchmark data for validation of mathematical models, recalculation by computational methods, calibration or other purposes.

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Norway) and financially supported by the Research Council of Norway.

5. NOMENCLATURE

A_E	[m²]	*expanded area of the propeller*
A_0	[m]	*disc area of the propeller*
B	[m]	*beam of the ship*
D	[m]	*propeller diameter*
F_{NR}	[N]	*rudder normal force*
F_{TR}	[N]	*rudder tangential force*
h	[m]	*water depth*
L_{WL}	[m]	*length on the waterline*
L_{PP}	[m]	*length between perpendiculars*
K	*[Nm]*	*roll moment*
N	[Nm]	*yaw moment*
n	[rpm]	*propeller rate*
P	[m]	*pitch*
Q_P	[Nmm]	*torque on the propeller shaft*
Q_R	[Nmm]	*torque on the rudder shaft*
T_A	[m]	*draft aft*
T_F	[m]	*draft fore*
T_P	[m]	*thrust of the propeller*
UKC	[]	*under keel clearance*
u	[m/s]	*linear velocity along ship x-axis*
v	[m/s]	*linear velocity along ship y-axis*
V	[m/s]	*ship speed*
X	[N]	*longitudinal force*
Y	[N]	*sway force*
z_A	[m]	*sinkage aft*
z_F	[m]	*sinkage fore*
δ	[°]	*rudder angle+*
δx	[m]	*longitudinal distance between midships, (>0 if midship SS is in front of STBL)*
δy	[m]	*lateral distance between ship sides*
ρ	[kg/m³]	*density*
∇	[m³]	*displacement volume*
ψ	[°]	*heading*

Subscripts:

$_{SS}$	[]	*service ship*
$_{STBL}$	[]	*ship to be lightered*

REFERENCES

[1] http://www. sintef.no/Projectweb/STSOps/
[2] http://www.simman2008.dk/KVLCC/KVLCC2/tanker2.html
[3] Simman 2008, Workshop on Verification and Validation of Ship Manoeuvring Simulation Methods, Copenhagen, Denmark, April 14^{th}-16^{th} 2008

Table 11 Results of harmonic rudder tests

Name	x_0	δ_{SS}	X_{SS}	Y_{SS}	K_{SS}	N_{SS}	$z_{A,SS}$	$z_{F,SS}$	$T_{p,SS}$	$Q_{p,SS}$	Ft_{SS}	Fn_{SS}	$Q_{r,SS}$	X_{STBL}	Y_{STBL}	N_{STBL}	$T_{p,STBL}$	$Q_{p,STBL}$
	[m]	[°]	[N]	[N]	[Nm]	[Nm]	[mm]	[mm]	[N]	[Nmm]	[N]	[N]	[Nmm]	[N]	[N]	[Nm]	[N]	[Nmm]
F	61.5	4	-0.32	-2.55	0.01	0.24	4.1	3.9	0.36	14.5	-0.07	0.00	0.0	-0.20	2.00	-2.37	2.12	35.8
F	59.5	14.5	-0.31	-1.80	0.00	-0.56	4.1	4.3	0.37	14.8	-0.12	0.41	0.8	-0.35	2.38	-2.08	2.36	38.4
F	57.5	23.9	-0.25	-1.43	0.00	-1.16	4.1	4.4	0.38	15.1	-0.12	0.77	1.4	-0.06	2.14	-2.26	2.33	38.1
F	55.6	31.5	-0.26	-1.06	0.00	-1.51	4.2	4.3	0.38	15.2	-0.11	1.05	1.8	0.15	2.41	-1.62	2.34	38.3
F	53.6	36.9	-0.32	-0.87	0.00	-1.67	4.1	4.3	0.39	15.2	-0.07	1.19	2.0	0.22	2.41	-1.63	2.36	38.5
F	51.7	39.6	-0.44	-0.83	0.00	-1.76	4.0	4.2	0.39	15.4	-0.06	1.27	2.0	0.14	2.18	-1.74	2.32	38.0
F	49.7	39.9	-0.47	-0.89	0.00	-1.74	4.0	4.1	0.39	15.3	-0.05	1.28	2.0	0.13	2.00	-2.01	2.35	38.4
F	47.7	37.5	-0.42	-0.92	0.00	-1.71	4.0	4.0	0.39	15.2	-0.07	1.23	2.0	0.17	1.92	-2.04	2.36	38.5
F	45.8	31.8	-0.35	-1.08	0.00	-1.44	4.0	4.0	0.38	15.1	-0.10	1.03	1.9	0.05	2.02	-1.98	2.36	38.4
F	43.8	24	-0.22	-1.47	0.01	-1.03	4.0	4.0	0.38	15.0	-0.12	0.75	1.5	0.11	1.94	-2.22	2.36	38.4
F	41.9	14.5	-0.22	-1.91	0.01	-0.46	4.1	3.9	0.39	15.1	-0.12	0.37	0.9	-0.12	1.86	-2.47	2.37	38.5
F	39.9	4	-0.08	-2.53	0.01	0.45	3.9	3.5	0.38	14.8	-0.07	-0.07	0.1	-0.06	2.08	-2.45	2.38	38.7
F	37.9	-6.7	-0.05	-3.05	0.01	1.35	3.6	3.4	0.39	14.9	0.05	-0.50	-0.8	0.11	2.28	-2.27	2.38	38.6
F	36.0	-16.9	-0.07	-3.47	0.01	2.13	3.5	3.7	0.39	15.0	0.20	-0.91	-1.5	0.06	2.45	-2.08	2.38	38.7
F	34.0	-25.9	-0.39	-3.86	0.01	2.60	3.7	4.0	0.40	15.1	0.26	-1.27	-1.4	0.16	2.17	-2.26	2.38	38.8
F	32.1	-33	-0.77	-4.20	0.00	2.60	4.2	4.0	0.40	15.3	0.31	-1.45	-0.9	-0.43	1.48	-3.27	2.36	38.6
F	30.1	-37.8	-0.88	-4.48	0.01	2.82	4.2	3.7	0.40	15.3	0.37	-1.61	-0.7	-0.24	1.62	-3.23	2.38	38.7
F	28.1	-39.8	-0.90	-4.37	0.01	3.05	4.0	3.8	0.39	15.2	0.39	-1.67	-0.6	0.05	2.22	-2.85	2.47	39.7
F	26.2	-39.8	-0.95	-4.26	0.01	2.90	4.0	3.8	0.40	15.3	0.37	-1.63	-0.6	-0.21	2.22	-2.41	2.37	38.6
F	24.2	-36.4	-0.75	-4.18	0.01	2.88	4.0	3.8	0.40	15.2	0.33	-1.55	-0.8	-0.39	2.30	-2.17	2.36	38.6
F	22.3	-30.2	-0.57	-4.03	0.01	2.68	4.0	3.9	0.40	15.2	0.26	-1.38	-1.1	-0.23	2.04	-2.34	2.34	38.4
F	20.3	-21.9	-0.39	-3.93	0.00	2.32	4.0	3.8	0.40	15.0	0.20	-1.13	-1.6	-0.18	1.83	-2.78	2.35	38.5
F	18.3	-12.1	-0.08	-3.50	0.01	1.68	4.0	3.7	0.40	14.8	0.11	-0.73	-1.6	0.21	1.89	-2.73	2.39	39.0
F	16.4	-1.5	0.05	-2.86	0.01	0.90	3.8	3.5	0.40	14.7	-0.04	-0.25	-0.7	0.18	2.00	-2.47	2.40	38.9
F	14.4	9.2	0.08	-2.23	0.01	0.16	3.7	3.5	0.39	14.7	-0.11	0.18	0.2	0.07	2.02	-2.28	2.35	38.3