Paper 50 – Numerical modeling of hydrodynamic interaction forces during entering of a sea lock for Real Time Simulations

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ABSTRACT: To assess the nautical design of the asymmetrical entrance of the new IJmuiden sea lock in the Netherlands Real Time Simulations have been performed by Deltares and MARIN. To enhance the hydrodynamic modeling of the Real Time Simulator (RTS) with advanced lock interaction effects two extra mathematical models have been coupled to the RTS to account for the longitudinal and lateral interaction forces. Validation of the models for seagoing vessels confirmed the model validity. Examples of verification tests are presented to show the correct functioning of the coupled models.

1 INTRODUCTION

In order to be able to receive seagoing vessels of ever increasing size in the port of Amsterdam, Rijkswaterstaat (the executive body of the Dutch Ministry of Infrastructure and the Environment) plans to build a new large sea lock at IJmuiden that is capable of doing so. The new lock will be situated in between two existing locks, which leads to an asymmetric approach on the sea side of the new lock. To assess the minimal required nautical space at the sea side approach of the new lock, Real Time Simulations have been performed at MARIN.

During a lock entry, large vessels experience high forces and moments caused by the induced hydrodynamics. In general, the hydrodynamic models underlying a Real Time Simulator (RTS) only account for (undisturbed) time-varying hydrodynamic influences, like currents, but do not account for the hydrodynamic phenomena induced by the presence of a vessel (i.e. vessel and geometry induced currents, translation waves and their reflections). As there is a strong coupling between the (longitudinal) propulsion forces of the entering vessel and the rudder forces (lateral forces and turning moments), longitudinal forces, as well as lateral forces and turning moments due to hydrodynamic interaction, play an important role.

To account for the longitudinal forces on a vessel caused by the aforementioned phenomena and to realise a proper nautical safety assessment of the new lock design, Deltares coupled the 1D numerical model WAROS (Vrijburcht, 1991) to the RTS. Since WAROS is a 1D model it does not account for the lateral forces and turning moments working on a ship. To account for these the potential flow model DELPASS (Pinkster, 2004, Pinkster and Bhawsinka, 2013), developed by PMH, was coupled to the RTS as well by MARIN. Since DELPASS is a potential flow model, it does not account for viscous effects and can thus not be used to calculate the longitudinal forces working on a ship. The combination of two separate models therefore enhances the hydrodynamic modelling of the RTS significantly.

WAROS has been developed in the eighties to calculate ship and water movements during entering, leaving or sailing through symmetrical locks by inland vessels. The model is an extended version of the mathematical model of Vrijburcht (1986). During the studies for the new sea lock, WAROS has been validated with scale model tests of seagoing vessels entering asymmetrical locks performed by Flanders Hydraulics Research.

The present paper mainly focusses on the validation of WAROS for seagoing vessels (Section 3), the conceptual functioning of the coupling of WAROS to the RTS (Section 4) and the verification of the coupling (Section 5). Additionally, this paper also describes briefly the coupling of the potential flow model DELPASS to the RTS to account for the lateral forces on a vessel due to the asymmetrical approach of the new lock design. Results of the coupled simulations with the RTS of the IJmuiden sea lock are not presented here due to confidentiality of the project.

2 BACKGROUND OF NUMERICAL MODELS

2.1 *WAROS*

WAROS is a one-dimensional (1D) model that was developed by Delft Hydraulics (presently Deltares) for the Dutch Ministry of Public Works (Rijkswaterstaat) to simulate the ship motions (surge, heave and pitch) and water motions during entering, exiting or sailing through a lock (Vrijburcht, 1991). During these maneuvers, the ship and the lock itself have a two-way interaction. They therefor have to be assessed as two components in one system.

The model is an extended version of the mathematical model of Vrijburcht (1986) in which a ship enters a lock through a rectangular or funnel-shaped entrance based on a predefined propeller thrust.

The starting points of WAROS are the following:

- The water movement is based on the complete 1D Navier-Stokes equations for long waves.
- The ship movements are modelled by 3 motion equations for surge, heave and pitch.
- The fairway consists of one branch with different cross sections. For example, the branch can consist of a prismatic entrance channel followed by a lock chamber. A permanent flow can be added to the fairway.
- The shape of the ship can be defined by a certain number of cross sections. The values of the propeller thrust are defined as a function of time or space.

The input of WAROS consists of:

- the geometry of the fairway,
- the geometry, draft and coefficients of the vessel,
- engine power as function of time or space,
- initial and stop conditions (initial and end position of the ship),
- boundary conditions (water levels and flow rates).

The output of WAROS consists of:

- position and velocity of the ship,
- trim and keel clearance at the bow and stern of the ship,
- time series of the water levels and flow velocities in predefined output points.

2.1.1 *Equations of water movement with a ship*

The base of WAROS is formed by the 1D momentum equation and continuity equation derived for a control volume of water between two transects with a relative distance of dx. Both equations are extended with terms to include the influence of a ship on the water movement (e.g. translation waves or return flows). All extensions of the momentum equation have a large influence on the gradient of the water level in time and thereby on the position and velocity of the ship. The momentum equation and the continuity equation are:

Momentum equation with ship (1):

$$\rho\,\partial Q/\partial t + r_c \rho\,\partial/\partial x\{Q^2/A\} + \rho g A^*\,\partial h/\partial x + \rho g Q|Q|/(C^2 A R) - f_p - f_f - f_h + f_r = 0$$

Continuity equation with ship (2):

$$B\,\partial h/\partial t + \partial Q/\partial x + B_s\,dy_m/dt + B_s x_s\,d\theta/dt + v_s\,dA_s/dx_s = 0$$

in which:

Q	=	$Q(x,t)$ = flow rate	[m^3/s]
h	=	$h(x,t)$ = water level w.r.t. CD	[mCD]
B	=	B_k-B_s = wet width at the water line	[m]
B_k	=	fairway width = $B_k(x)$	[m]
B_s	=	width of the ship = $B_s(x_s)$	[m]
x	=	length coordinate (earth fixed reference frame)	[m]
x_s	=	longitudinal coordinate with respect to the ship's mass center	[m]
t	=	time	[s]
ρ	=	density of water	[kg/m^3]
g	=	gravitation	[m/s^2]
C	=	Chezy coefficient = 18 log(12R/k)	[$m^{1/2}/s$]
R	=	hydraulic radius fairway = A_k/O_k	[m]
O_k	=	wet perimeter of cross section	[m]
k	=	bed (and wall) roughness	[m]
A	=	A_k-A_s = wet cross section	[m^2]
A_k	=	cross section channel	[m^2]
A_s	=	cross section ship	[m^2]
A_e	=	= artificial cross section for detached, decelerating flow	[m^2]
A^*	=	A_k-A_s = wet cross section for accelerating flow or decelerating, attached flow, or	[m^2]
	=	A_e-A_s = net cross section at the point where the flow re-attaches	[m^2]
f_p	=	local pressure resistance term	[N/m]
f_f	=	local friction resistance term	[N/m]
f_h	=	local energy loss term at the stern	[N/m]
f_r	=	local propeller thrust term	[N/m]
y_m	=	vertical position of the ship	[m]
θ	=	trim angle of the ship	[rad]
v_s	=	ship's longitudinal velocity	[m/s]

The first term of equation (1) is the change of impulse in time in the control volume. The second term is the convection term. The third term is the pressure term and describes the change of hydrostatic pressure at the boundaries of the control volume. The fourth term describes the friction effect between the water and the bottom/walls of the fairway in the control volume.

The first term of equation (2) describes the vertical velocity of the water level. The second term represents the change of flow rate in longitudinal direction through the boundaries of the control volume. The third term represents the vertical movement of the ship. The fourth term describes the trim velocity of the ship. The fifth term is the influence of the change in cross section of the ship in longitudinal direction.

2.1.2 *Motion equations of the ship*

Next to the momentum equation (1) and continuity equation (2), three equations are needed which describe the ship motions in longitudinal, vertical and trim direction. Note that the three motion equations are essentially a representation of the second law of Newton (F=ma) in the three considered degrees of freedom. The motion equation in longitudinal direction (surge) is:

Motion equation in longitudinal direction (3):

$$(m_s + a_x)\, dv_s/dt + F_p + F_f - F_r + \rho g \int_L A_s\, \partial h/\partial x\, dx_s = 0$$

in which:

m_s =	ship's mass	[kg]
a_x =	added mass in x-direction	[kg]
=	$\rho\, ¼\, \pi\, A_s\, T_{max}$	
T_{max} =	maximum draft	[m]
F_p =	pressure resistance of the ship	[N]
F_f =	friction resistance of the ship	[N]
F_r =	propeller thrust	[N]

The first term of equation (3) is the ship inertia force. The fifth term is the resulting pressure force on the ship's hull in longitudinal direction, which is determined by the water level gradient along the ship. This term contains the influence of the local energy loss term f_h (see equation (2)).

The motion equation in vertical direction (heave) is:

Motion equation in vertical direction (4):

$$(m_s + a_y)\, d^2y_m/dt^2 + \rho g \int_L B_s(y_m - y_0 + \theta x_s)dx_s - \rho g \int_L B_s(h - h_0)dx_s = 0$$

in which:

y_0 =	initial vertical position of the ship	[m]
h_0 =	initial still water level w.r.t. CD	[mCD]
a_y =	added mass in y-direction	[kg]
=	$\rho\, L\, B_s^3 / (8(h_0 - d - T_{max}))$	
d =	bottom depth	[mCD]

The first term of equation (4) is the ship inertia force of the ship. The second term is the resulting vertical force on the ship's hull due to the difference in vertical position of the ship with respect to the initial vertical position of the ship. The third term describes the resulting vertical force on the ship's hull due to the difference in water level with respect to the initial water level. Both the second and third term are integrals along the hull of the ship in longitudinal direction.

The motion equation in trim direction (pitch) around the center of gravity of the ship M is:

Motion equation in trim direction (5):

$$J_s\, d^2\theta/dt^2 + \rho g \int_L B_s(y_m - y_0 + \theta x_s)x_s dx_s - \rho g \int_L B_s(h - h_0)x_s dx_s + a_m F_r = 0$$

in which:

J_s =	inertia moment of the ship with respect to the ship's center of gravity (CoG)	[kgm^2]
a_m =	vertical distance between the working line of the propeller thrust force and the ship's center of gravity (CoG)	[m]

The first term of equation (5) describes the inertia moment of the ship (approximately equal to $m_s L^2/12$). The second term is the resulting moment on the ship's hull due to the difference in vertical position with respect to the initial vertical position of the ship. The third term describes the resulting vertical moment on the ship's hull due to the difference in water level with respect to the initial water level. The fourth term represents the moment on the ship's hull due to the arm of the propeller thrust with respect to the ship's mass center.

2.1.3 *Solving the equations*

The unknowns in the above set of equations (1 to 5) are the flow rate Q and the water level h as function of time and location, the ship velocity v_s, the vertical position of the ship y_m and the trim angle of the ship θ as function of time. The five differential equations are solved in the time domain using a time loop: for every numerical time step a new water level and flow rate in the entire domain are computed and a new ship velocity v_s (7) and ship movement in y- and θ-direction (8 and 9) are calculated. With this, the new position of the ship (x, y, θ) can be determined.

2.2 DELPASS

Delpass is a program that computes the forces on multiple sailing and moored vessels in deep or restricted water for arbitrary motion velocities and positions of ships and waterway. A waterway may be modelled schematically by means of quays and sloping banks with a constant water depth or with varying water depth based on measured bathymetric data. The computations are based on 3D potential flow theory making use of the double-body assumption. With double-body flow computations it is assumed that the vessels are travelling at low to moderate speeds and that the main component of the interactions between the vessels and the surrounding bathymetry is due to so-called 'draw-down' effects. These effects are related to the primary flow around a sailing vessel. Wash waves, or secondary wave effects, are neglected since these are relatively short waves which do not influence larger sailing vessels significantly.

Use is made of zero-order (flat) panels to describe the 3D shapes of vessels and bathymetry. Flow equations involving up to several thousand unknowns are solved at each time-step making use of parallelized code running on a Graphical Processing Unit (GPU) with about 2000 computing cores.

3 VALIDATION OF WAROS FOR SEAGOING VESSELS

The big advantage of WAROS is that the 1D schematisation of a complex fairway makes the calculation times small. Because the model calculates much faster than real-time, it is very suitable to couple it to a RTS. A drawback of the 1D fairway schematization is that in principle only symmetric fairway profiles can be considered. This is disadvantageous for the asymmetric IJmuiden lock approach. Moreover, WAROS has been developed and validated for inland locks and inland vessels and not for seagoing vessels. Before coupling WAROS to a RTS, WAROS therefore had to be validated for seagoing vessels and asymmetric fairway profiles. This has been done by using scale model tests performed by Flanders Hydraulic Research (Delefortrie *et al.*, 2013, Vantorre *et al.*, 2012)

3.1 *Considered model tests*

For the validation of WAROS for asymmetric approaches and seagoing vessels the following tests were used:

- Three scale model tests for the new sea lock of IJmuiden (Delefortrie *et al.*, 2013)
- Captive scale model tests for the Pierre Vandamme lock in Zeebrugge (Vantorre *et al.*, 2012)
- Two scale model tests for the new Panama locks (Vantorre *et al.*, 2012)

The results of one of the IJmuiden scale model tests (test 029), one of the Zeebrugge scale model tests (test G) and one of the Panama scale model tests (test B) are presented in this paper. No full scale tests were considered. Due to the small scale of the scale model tests viscous effects could be somewhat overestimated within the model tests. Measured (scaled) longitudinal forces might therefore be a bit larger than in reality. This effect has not been considered in the real time simulations.

3.1.1 *IJmuiden scale model tests (test 029)*

This scale model test was specifically performed for the new sea lock of IJmuiden. A bulk carrier with dimensions 351.8x58.4x13.75 m was considered for these tests. The keel clearance in this test was equal to 25% of the draft of the ship. The entrance velocity of the ship was equal to 1.25 knots and was maintained by using the ship propeller as well as by two tugs (two fans on top of the ship).

The lower panel of Figure 1 shows the considered symmetrical fairway schematization in WAROS of the asymmetric fairway layout used in the measurements (upper panel). The distribution of the wet cross sections along the track of the WAROS schematization is equal to the scale model.

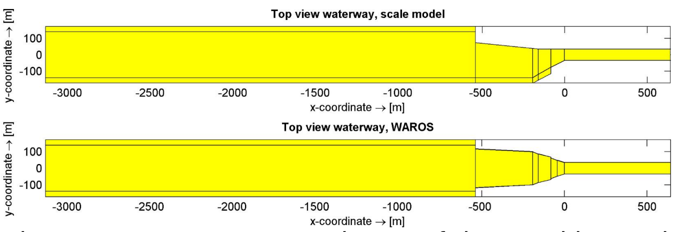

Figure 1: Upper: Waterway layout of the IJmuiden scale model tests. Lower: Symmetrical waterway schematization of WAROS.

The measured forces (propeller thrust and tug forces) have been converted into a theoretical series of engine power. The propeller thrust and tug forces were considered as a single force. The forces in the scale model test were such that a constant ship velocity was maintained. This means that the forces increased when the ship slowed down too much or when it entered the lock (lower panel of Figure 2). The resulting ship velocity is shown in the upper panel of Figure 2, with the measured velocity in red and the calculated velocity in black. Note that the saw tooth pattern in the velocity is caused by the feedback loop of the tugs to maintain a constant velocity. This is reproduced with WAROS.

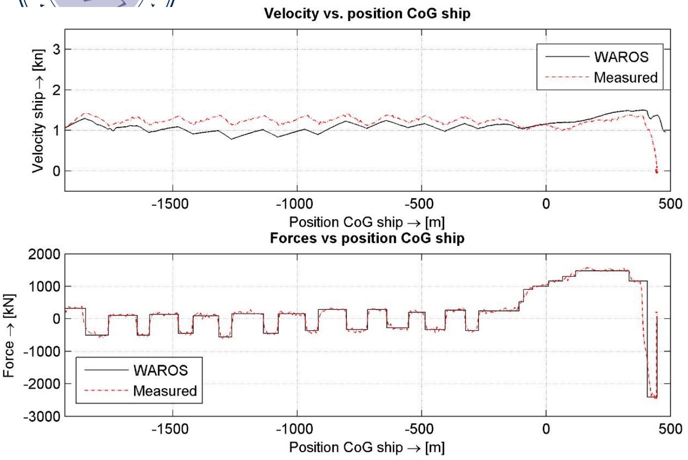

Figure 2: Resulting ship velocity (upper) and forces on the ship (lower) of the IJmuiden scale model test 029.

The goal of this simulation was to tune the coefficients most relevant for seagoing vessels to get the best agreement between the measured and computed forces on the ship and the ship velocity, because the considered situation resembles the foreseen design layout the most.

Within the entrance harbor (x_{CoG} < 150 m) and the lock itself (x_{CoG} > 150 m) the agreement of the velocities is fair, based on the applied engine thrust. This shows that the applied resistance coefficients are realistic and that the effect of the lock (sudden change in geometry) can be simulated well.

Also the hydrodynamics in WAROS showed a good agreement to the measured values. This can also be seen in the sinkage of the ship (Figure 3). The apparent overestimation of the sinkage when the ship is in the lock can be assigned to the schematization in WAROS in which both the tug forces and the propeller thrust are modeled one single force which is working on the propeller. This (for practical reasons chosen) modeling approach leads to a larger return flow aside the ship in WAROS than in de scale model measurements where the tugs were simulated as separate forces by air fans.

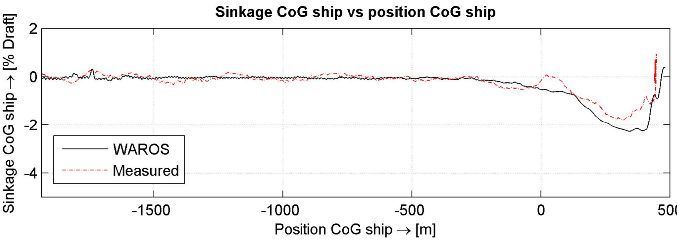

Figure 3: Resulting sinkage of the CoG of the ship of the IJmuiden scale model test 029.

3.1.2 *Panama scale model tests (test B)*

The Panama scale model test B is comparable to the IJmuiden scale model test with respect to the channel layout. Other than for the IJmuiden test a 12000 TEU container vessel (365x49x15.2 m) was used for the Panama test. Next to that, the test started with a higher velocity (2 knots), the keel clearance in this test was equal to 10% of the draft of the ship and the vessel was only propelled by tugs during the entrance of the lock itself; the main propeller was switched off.

Figure 4 shows both the scale model layout (upper panel) as the symmetric WAROS schematization (lower panel). When in the scale model a vertical wall was used on one or both sides of the channel, a vertical wall was used on both sides in WAROS.

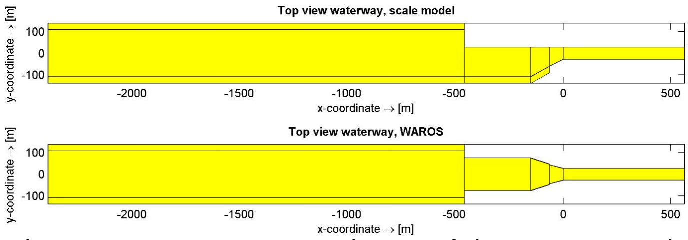

Figure 4: Upper: Waterway layout of the Panama scale model tests. Lower: Symmetrical waterway schematization of WAROS.

The lower panel of Figure 5 shows the measured forces of the scale model test together with the applied force in WAROS. In this test the tug forces are modeled in WAROS as an external force on the ship, with its working point at the same height as the tugs in the scale model test. The upper panel of the figure shows the resulting ship velocities.

In the wide first part of the channel (x_{CoG} < -1000 m) the agreement on the deceleration of the vessel in absence of external forces is good, showing that the still-water-resistance force is well represented in WAROS. In the part between x_{CoG} = -1000 m and -670 m, the vessel response to the decelerating tug forces lags behind in WAROS. This leads to slightly higher calculated velocities here.

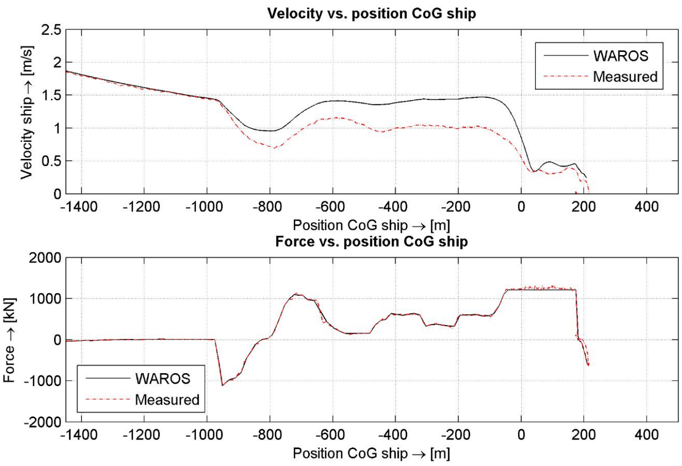

Figure 5: Resulting ship velocity (upper) and forces on the ship (lower) of the Panama scale model test B.

In the smaller part with the vertical walls (between x_{CoG} = -680 m and -180m) the vessel in the scale model test experiences slightly more resistance, which can be seen in the minor acceleration in WAROS and the constant velocity of the scale model test. This is most probably caused by the asymmetric flow around the vessel in the scale model test. Due to the proximity of the vertical wall in the scale model test at one side of the vessel, a strong asymmetric return flow is present. WAROS does not account for these effects. Because the resistance of a ship is (partially) quadratically related to the flow velocity along the vessel hull, a higher return flow will have a relatively larger influence on the velocity.

When the container vessel enters the lock (x_{CoG}> -170 m) the resistance in WAROS is larger than the measured resistance. This is mainly caused by the higher entry velocity of the WAROS simulation, which leads to a (too) high resistance force.

3.1.3 *Zeebrugge scale model tests (test G)*

The Zeebrugge scale model test is different from the aforementioned two tests with respect to the driving of the vessel. This test was performed as a "captive" test, which means that the forces on the ship have been measured directly by restricting all horizontal movements of the ship. The propulsion of the ship is therefore not achieved by means of a propeller or tugs, but by dragging the ship forward with a tow installation. The test was performed with a bulk carrier (265x43x17.3 m) with a constant velocity of 1.3 m/s and an under keel clearance of 20% of the draft.

To mimic the propulsion of the ship in WAROS the effect of the propeller on the water has been disabled. Next to that the action height of the force has been moved to coincide with the action height of the tow installation. This way the applied propeller thrust of WAROS represents the external towing force.

Figure 6 shows both the asymmetric scale model layout (upper panel) as the symmetric WAROS schematization (lower panel). The geometry (wet channel cross sections) of the approach harbour has been altered slightly in WAROS to ensure numerical stability of the model. To correct for this, local loss coefficients have been changed. This way, the tested situation is represented as well as possible.

This specific test has been performed with the version of WAROS that has been altered to be coupled to the RTS. In this version the resistance force (F_{WAROS}) working on the ship is also calculated (see Section 4 for more detail). In the case of a constant velocity, this force should be equal to the measured force working on the ship. The WAROS runs have been set up such that a constant velocity was reached by tuning the applied propeller thrust.

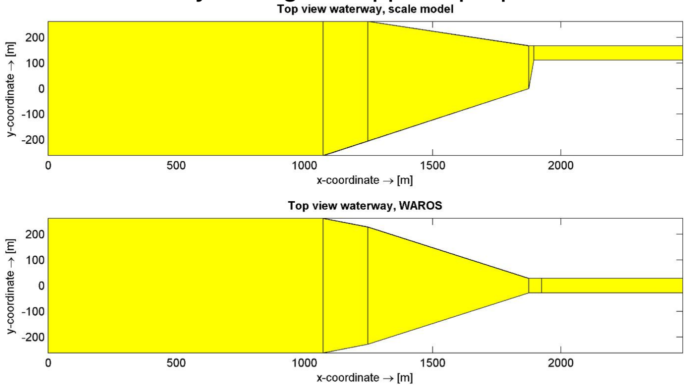

Figure 6: Upper: Waterway layout of the Zeebrugge scale model tests. Lower: Symmetrical waterway schematization of WAROS.

Figure 7 shows the results of test G. The upper panel presents the measured velocity and the calculated velocities of WAROS. The lower panel presents the resulting forces. The measured and calculated forces show a very good agreement, which indicates that WAROS models the resistance force due to the entering of a lock well. For this case the asymmetric approach harbour geometry does not have a dominant influence on the resulting longitudinal forces.

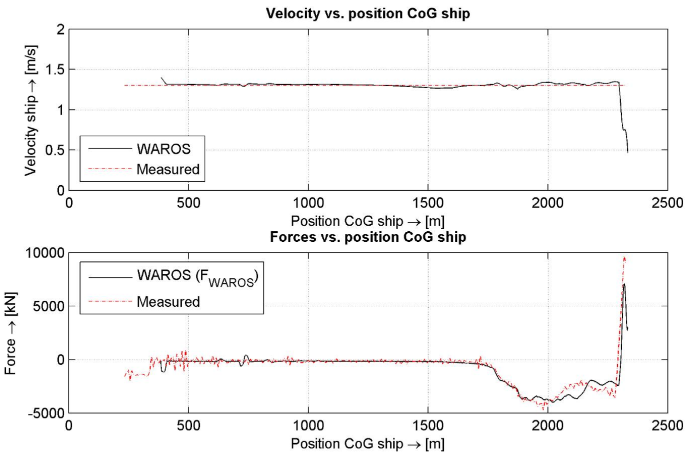

Figure 7: Resulting ship velocity (upper) and resistance forces on the ship (lower) of the Zeebrugge scale model test G.

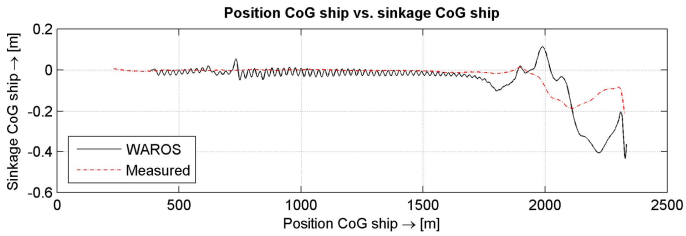

Figure 8: Resulting sinkage of the CoG of the ship of the Zeebrugge scale model test G.

Other than the agreement of the forces, the agreement of the measured and calculated sinkage is less good. This is presented in Figure 8. This difference could be ascribed to the small alteration of the approach harbour geometry in WAROS or the symmetric schematization of the asymmetric geometry. Nevertheless, in general WAROS is capable of representing the physics in this situation with enough accuracy.

3.2 *Conclusions of the WAROS validation*

In general, the validation results show that the longitudinal forces working on a seagoing vessel entering a lock are reasonably well represented by WAROS. When the geometry is not too asymmetric, the symmetrical approach of WAROS offers a good estimate of the forces. The optimization of the different coefficients in WAROS for seagoing vessels, which are normally optimized for inland vessels (e.g. pressure- and friction coefficients), enhanced the results significantly. It was concluded that the physics are represented sufficiently accurately by WAROS to generate a sufficiently realistic longitudinal force on a ship entering a lock when the model is coupled to a RTS. Note that for such tests the precise absolute value is of less importance than the timing and direction of the forces working on the ship. The latter were simulated well with WAROS in the considered validation tests.

4 COUPLING OF MODELS TO THE REAL TIME SIMULATOR

4.1 WAROS

4.1.1 *Requirements of the coupling*

Essentially, in the standard standalone mode as described above WAROS is a 1D-maneuvering simulator that solves the ship's motion equations (longitudinally) in the time domain just as the RTS itself (longitudinally and transversally). To create a coupling between WAROS and the RTS, WAROS has been adjusted such that, given the movement along the track, the longitudinal forces acting on the ship due to the water movements are computed and transmitted to the RTS.

In the coupled configuration the velocity of the vessel is computed by solving the motion equation in longitudinal direction within the RTS (using an expression comparable to equation 3 in Section 2). Each time step the computed ship velocity is given to WAROS as input and a number of force terms related to pressure, friction and water movement are being calculated within WAROS using equation 3, which reduces to equation 6 (F_{WAROS}, see below). These forces are then sent to the RTS as input for the external longitudinal force. The new ship velocity and position at the next time step are then calculated within the RTS and sent to WAROS again. This is an efficient approach for which minimal code changes within the RTS and WAROS were needed and for which the other external forces on the ship (e.g. tug and wind forces) can be taken into account conventionally within the RTS.

Resistance force (6):

$$F_{WAROS} = F_p + F_f + \rho g \int_L A_s \, \partial h/\partial x \, dx_s$$

The other four equations of WAROS are solved in an unchanged manner. These are needed for a correct representation of the vertical ship and water movements, but the results are not sent to the RTS, because it does not need this information.

4.1.2 *Coupling procedure*

The communication between the RTS and WAROS goes according to the UDP Multicast protocol with an update rate of 10 Hz, which means that information is shared 10 times per second between the RTS and WAROS. The RTS leads this communication and sends the data (among others the ship velocity and the propeller thrust) with 10 Hz to WAROS. Below the communication is described point wise and presented schematically in Figure 9:

- The RTS sends the current ship velocity, propeller thrust and position to WAROS.
- WAROS performs calculations for 1 time step (0.1 s) in much less physical time than 0.1 s.
- WAROS directly sends back the calculated resistance force F_{WAROS} to the RTS.
- The RTS automatically selects the most recent value of F_{WAROS} and calculates the new output values.
- After 0.1 s the RTS sends the new ship velocity, propeller thrust and position to the RTS.
- Et cetera…

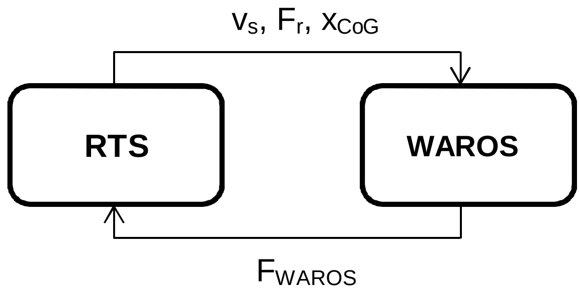

Figure 9: Schematic flowchart of the communication between WAROS and the RTS.

4.1.3 *Some points of consideration*

- To couple WAROS to the RTS a clear distinction has been made between which effects are calculated by WAROS and which by the RTS. Since the forces due to the water on the ship's hull are now computed by WAROS, those contributions (e.g. friction and pressure resistance) need to be switched off in the RTS.

- The propeller thrust feed of the RTS is only used to calculate the effect of the propeller on the water in WAROS. The velocity and position of the ship are calculated in the RTS.
- The ship position that is sent to WAROS is only meant for verification. WAROS calculates the ship position by integrating the ship velocity of the RTS in time. It was checked after every run whether the ship position of the RTS is the same as the one of WAROS. If the deviation was too large, the test was discarded.
- In the present version of the coupling, WAROS does not account for transverse ship movements of the RTS. For the present simulations it was assumed that the ship sailed in an almost straight line and that the deviations of this track were negligible. This was monitored and if the deviations were small enough (<10m) this was regarded as acceptable, else a test was discarded.
- The communication time step (0.1 s) was equal to the calculation time step of WAROS. This time step should be small enough to assure numerical stability of WAROS. In the stand-alone version of WAROS the time step is adjusted automatically when the courant criterion is exceeded. This was not possible in the coupled situation. The time step of 0.1 s proved to be sufficiently small.
- The RTS does not account for the influence of an enhanced return flow due to the entering of the narrow passage (e.g. lock) for the interaction of the propeller and the water. This information is available from WAROS but is not used yet. The current coupling can therefore be extended by sending this information from WAROS to the RTS.
- In the coupled configuration the WAROS simulation does not start with a ship from standstill. The WAROS simulation is initialised with a still water level. Therefore start-up effects may appear in the WAROS output due to the sudden acceleration of the ship and the water. This may result in translation waves and unrealistic forces on the ship. It was verified that due to a start location at a sufficient distance from the lock these start-up effects did not influence the entering manoeuvre of the lock itself.

  During the simulations the pilots indeed mentioned that at the start of the simulation the ship did not respond realistically. During the entering of the lock the ship did respond correctly. In the future the coupling can be improved by starting a WAROS simulation with a restart file, in which the water movement at initialisation corresponds to the imposed start velocity of the ship. This was not possible within the present project.

4.2 DELPASS

The RTS contains the standard manoeuvring model of the vessels concerned. This model accounts for water depth dependent manoeuvring forces and includes all external forces like wind forces, tug forces and collision forces (when hitting quay or lock walls). Lock interaction forces and moments calculated by DELPASS are solved at each time-step making use of parallelized code running on a Graphical Processing Unit (GPU). As DELPASS runs on a separate PC the time step of DELPASS may differ from the time step of the RTS, without interfering with the main simulation process.

The inputs for the DELPASS computations are the instantaneous position (x, y, heading) and velocities (u, v, r) of the vessels as calculated by the RTS. The outputs are the sway force and yaw moment on each vessel, which are treated as the external force and moment in the RTS.

5 VERIFICATION OF COUPLING

5.1 Verification approach

To check whether the coupling worked properly some basic checks were performed. Verification tests have been performed to check whether the new version of WAROS produced the same results in the standalone configuration as in the coupled configuration, in identical lock entries.

Using the same geometry of the IJmuiden sea lock as was used for the real time simulations, two conditions were considered for verification. One condition (cond01) had a relative spacious under keel clearance of the ship of 20%, the other (cond02) had a smaller under keel clearance of 12.7%. The conditions are summarized in Table 1.

Table 1: Selected condition for the coupling verification

Simulator condition	cond01	cond02
Ship	Bulk carrier T=13.7m	Bulk carrier T=13.7m
Lock width [m]	65	65
Lock depth [mCD]	-18.25	-17.25
Water level [mCD]	-1.75	-1.75
Water depth [m]	16.5	16.5
UKC [%]	20.0	12.7
A_{ship}/A_{lock} [%]	66.7	71.0
Distance to wall* [m]	17.28	17.28
* Distance between ship's hull and the vertical wall of the lock's approach harbour		

5.2 *Presentation of results*

5.2.1 *Constant velocity*

To verify that both configurations of WAROS produced the same results (F_{WAROS}), both conditions were first considered using a constant ship velocity of 1 m/s. In the RTS this was done by using a ship with an infinite mass that is not decelerated by external forces. In WAROS the constant velocity was reached by iteratively tuning the applied engine power. Only the results of cond02 are presented below. The results of cond01 were comparable to the results of cond02.

Figure 10 shows the results for cond02. The upper panel shows nearly equal and constant ship velocities. Because it was not possible in WAROS to set the velocity directly, some minor deviations of the constant value can be seen. These deviations are so small that they had little influence on the results.

The lower panel shows the results of the resistance force F_{WAROS}. In the coupled configuration this is the force that is send to the RTS by WAROS. The RTS uses this force to calculate the new ship velocity. Note that for the 'constant velocity' tests the infinite mass ship of the RTS does not respond to a change in forces. The results are practically equal which indicates that the coupling is implemented correctly.

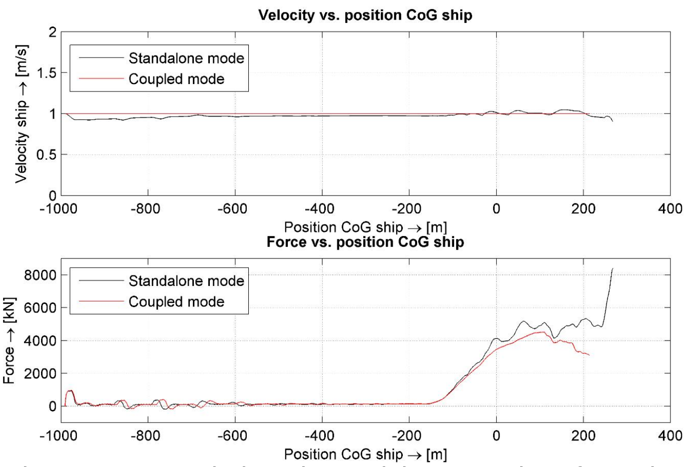

Figure 10: Coupled and standalone results of cond02 with a constant ship velocity.

5.2.2 *Constant thrust*

For the second set of test conditions cond01 and cond02 were rerun with a constant propeller thrust in the standalone version of WAROS. For the coupled configuration this means that a set rpm was imposed to the RTS out of which an "approximately" constant propeller thrust follows. Note that for the second set, the normal ship was used in the RTS which does react to external forces.

Again, the coupled configuration is considered to be working properly when both configurations produce the same results. Here, the velocity is the most important parameter. As for the constant velocity tests only the results of the more complex cond02 are presented here. The performance for cond01 was very comparable to cond02.

The results of cond02 are presented in Figure 11. As expected the velocity decreases when the ship enters the lock, due to an increased value of the interaction forces (F_{WAROS}). In general terms, the results of both configurations are comparable. The results of the standalone version show a somewhat higher velocity than the coupled version. This leads to a somewhat higher value of F_{WAROS} when the ship enters the lock, resulting in a larger deceleration, after which the end velocities are equal.

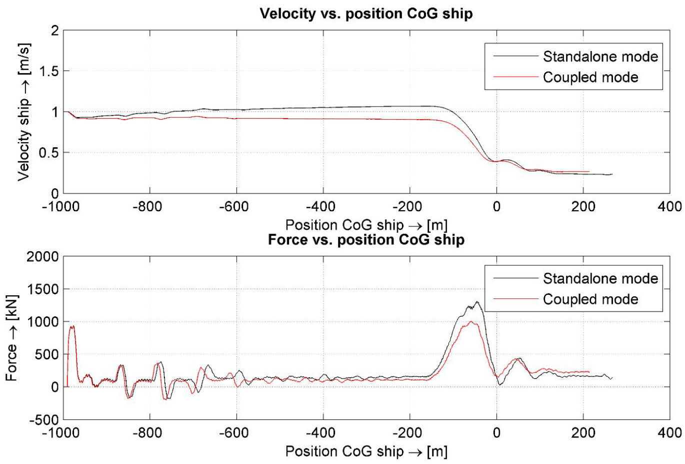

Figure 11: Coupled and standalone results of cond02 with a constant propeller thrust.

Possible causes for the velocity differences between the configurations are:

- The applied propeller thrust is not exactly constant in the coupled mode, while it was constant in the standalone mode.
- The schematizations of the water-propeller interactions are different for WAROS (standalone) and the RTS (coupled).
- Numerical rounding errors in the RTS-WAROS communication lead to a small difference in the ship position of both configurations.

The agreement and the accuracy of the results were assessed as sufficient within the boundaries of the RTS-tests of the entry of the new sea lock of IJmuiden. For such tests the behaviour of a ship is more important than the exact value of the resistance force. It could therefore be concluded that the coupling of WAROS with the RTS worked properly.

6 CONCLUSION

This paper presents a short background of the numerical model, WAROS, together with the validation of the model for seagoing vessels and sea locks. Next to that, the realised coupling of WAROS with the Real Time Simulator (RTS) of MARIN is presented. Within this coupling WAROS calculates an external longitudinal resistance force, F_{WAROS}, which includes the extra resistance due to the ship-lock interaction that is not represented in conventional real time ship simulators. The code of WAROS has been changed such, that given the ship's movement along the track, the forces on the ship due to the water movement are delivered to the RTS.

In general the validation results of WAROS for seagoing vessels (bulk and container vessels) entering a sea lock showed that the longitudinal forces working on the vessels can be described reasonably well by WAROS. When the geometry is not too asymmetric, the symmetrical approach of WAROS can give a good estimation of the resulting forces. Based on the validation results it is concluded that the physics during lock entry are described sufficiently accurately by WAROS to generate a sufficiently realistic force when coupled to a RTS.

The verification tests showed that the realised coupling works properly. Small differences between the coupled and standalone configuration of WAROS can be seen, but these are explainable. Given the goal of the coupling, i.e. real time simulations for the new IJmuiden sea lock, and given the boundary conditions of the project the achieved accuracy of the coupling is assessed as sufficient.

Next to the WAROS model the potential flow model DELPASS was coupled to the RTS to calculate the yaw interaction force and the sway interaction moment. The new IJmuiden sea lock project showed that DELPASS is also a significant add-on to the RTS. As it has been observed, the interaction forces calculated in real time are quite reliable.

In conclusion, the implementation of WAROS and DELPASS in a RTS reduces effort that was initially needed to create interaction forces databases and provides more flexibility to the user in research and training scenarios where interaction forces play an important part. A RTS coupled with WAROS and DELPASS provides its users with the freedom to simulate a wider range of distances and speeds between passing structures.

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