INLAND NAVIGATION: ASSESSING THE MANOEUVRING BEHAVIOUR FOR REAL-TIME SIMULATION PURPOSES

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Abstract: The European inland waterway network is under investigation. Solving missing links between waterways in different countries (e.g. Seine-Scheldt) and upgrading of existing waterways for larger vessels are two main project types that require a solid fundamental background on the behaviour of inland vessels in shallow and confined water. During the last three years Flanders Hydraulics Research (FHR) has been investing in experimental research in the Towing Tank for Manoeuvres in Shallow Water (co-operation FHR – Ghent University) and an inland navigation simulator so that mathematical models and real-time simulation techniques can be combined for the evaluation of inland waterway design.

1. INLAND NAVIGATION CHANNELS VERSUS SHIP SIZE

For the concept design of inland navigation channels empirical methods (e.g. Richtlijnen Vaarwegen RVW2011 [1]) exist for estimating the required channel dimensions, taking account of the design ship’s dimensions and characteristics. For inland fairways a distinction is made between normal and confined two-way or one-way channel profiles.

For assessing the feasibility of increasing the maximum dimensions of ships making use of an existing channel other methods, mainly based on simulation techniques, have to be applied. As an example a feasibility study for the upgrading of the river Dender in Belgium for CEMT class IV inland vessels revealed a bottleneck for the passage of the Zeeberg Bridge in Aalst, Belgium (Figures 1-2).

Fig. 1: The Zeeberg bridge in Aalst, Belgium, downstream view

This paper gives an overview of the fundamental experimental and practical simulation research that has been executed during the last three years at Flanders Hydraulics Research in co-operation with other departments of the Flemish Government.
2. CONCEPT DESIGN METHODS

In the concept design stage of either a new access channel or the adaptation of an existing channel for new shipping traffic, initial estimates of the overall physical parameters of the proposed channel – width, depth, alignment – are determined based on physical environment data and other information available at the outset. For inland waterways the Dutch guidelines [1] are often used as a start for the design and evaluation of the ship-waterway relation. The Inland Navigation Commission InCom of PIANC (Permanent International Association of Navigation Congresses) documents and summarizes guidelines for inland waterway design and installed in 2009 the InCom Working Group 141 Design Guidelines for Inland Waterways.

The Dutch Guidelines for inland waterways divide the waterways for commercial shipping according to the traffic density in [2]:

- Normal cross-section (high traffic density): two laden design ships are able to meet at speed, and a laden design ship can be overtaken with caution by another such vessel.
- Narrow cross-section (medium traffic density): two laden design ships are able to meet with caution and an unladen design ship can overtake a laden design ship with caution.
- One-way traffic cross-section (low traffic density): a laden design ship is able to pass through this cross-section in only one direction.

In Flanders (Belgium) most waterways are designed or operated as narrow cross-sections and more often a waterway is adjusted as a one-way traffic cross-section with passing spaces at regular intervals along the waterway.

In the Dutch guidelines the waterway is furthermore characterized by:

- a water depth: water depth to draft ratio of 1.4 for a normal and 1.3 for a narrow and one-way traffic section compared to the Mean Low Water level.
- a width in straight sections and bends with a width allowance for cross-winds: the width of the channel is composed of a manœuvreing lane for each individual ship, a safety width for passing ships and at both sides of the channel for bank effects. The width at the bottom must be one ship’s beam for a one-way cross-section and two ship’s beams for the narrow and normal section. The width in the keel of the laden design ship is increased to respectively two, three and four times the ship’s beam for a one-way, narrow and normal cross-section. For unladen ships an additional width for cross-winds has to be considered and due to the sway motion and thus drift angle during a bend manoeuvre an additional width is introduced in bends.
- a bend radius: the minimal bend radius for a normal cross-section is 6L with L the ship length and for a narrow cross-section 4L.

No other guidelines are so complete as the Dutch guidelines but it should be emphasized that these guidelines must not be considered as rules or standards. Concept design methods provide a rapid estimation of the main channel characteristics based on a limited amount of input data. Mostly methods of this kind are considered to be conservative or belonging to an ideal world compared to the economic and environmental restraints of the waterway under investigation. In the following chapters some examples will be given to show the advantages of real-time simulations in waterway design.

3. EXPERIMENTAL RESEARCH

3.1 Open water manœuvring

Model tests

To offer a realistic simulation environment the manœuvring characteristics of the vessels had to be known. This is realised by experimental research being conducted at Flanders Hydraulics’ shallow water towing tank (Figure 3 - co-operation with the Maritime Technology Division of Ghent University) with a 1/25 scale model of an inland container vessel (length: 110 m, beam: 11.45 m, design draft: 3.65 m, block coefficient Cb 0.89) equipped with a ducted
propeller (5 blades, left-handed, propeller diameter \( D_p \) 1.81 m, pitch ratio \( P/D_p \) 1.19, area ratio \( AEP \) 1.0) and two coupled rudders (max. rudder angle 75/58 deg).

The ship model was tested at different drafts and in different water depths (Table I). Open water tests have been executed with the ducted propeller and the rudders.

Table I. Test conditions (full scale values)

<table>
<thead>
<tr>
<th>Draft</th>
<th>Under Keel Clearance (% Draft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.65 m</td>
<td>200  35  20  10*</td>
</tr>
<tr>
<td>2.85 m</td>
<td>200  35  20</td>
</tr>
</tbody>
</table>

The Bulgarian Ship Hydrodynamics Centre (Varna) performed open water tests with two different scale models of 1/25 and 1/10 to evaluate the influence of scale effects on the propeller characteristics (Figure 4). Four quadrant open water curves for thrust (propeller and nozzle) and torque have been determined. Large spread is recognised for the thrust (Figure 5) and torque coefficients for the smallest propeller if the tests are repeated four times (scale effect, low Reynolds number, lower range of dynamometer capacity). Finally the results with the 1/10 scale model have been used for modelling.

Open water lift and drag coefficients for the rudders have been determined at Flanders Hydraulics Research (FHR) using multi-modal tests with linear varying inflow angle \( \alpha_R \) and constant inflow velocity \( V_R \). In Figure 6 the lift coefficient is shown for the starboard rudder in a single setup without port rudder and in a setup with two rudders with and without a rudder deflection of 15 degrees between both interacting rudders (Figure 6: red triangle for port rudder and green triangle for starboard rudder with rudder deflection angle).

A lift coefficient is measured at zero inflow angle due to the asymmetric profile of an individual rudder. Combining both rudders the stall on the starboard rudder occurs more pronounced at positive inflow angles (i.e. rudder to port) while the maximum lift coefficient at negative inflow angle (rudder to starboard) is increased by the presence of the port rudder.

The modelling of the single propeller - twin rudder system was a real challenge as the inflow to the rudders is strongly dependent on the propeller action (Figure 7), the ship motion and the twin rudder interaction.
The model velocities tested in the towing tank had to be adjusted compared to the real velocities of a class Va vessel to take into account the hydrodynamic restrictions of the towing tank based on blockage – speed relation. Model speeds higher than 0.9 m/s (16.2 km/h full scale) are within the critical speed range for the model test setup at FHR. The wave profile of a 0.72 m/s (13 km/h full scale) model test is shown in Figure 8. A large decrease of the waterline in the vicinity of the ship model midship can be recognised. In addition the ship resistance and the angle between the Kelvin wave pattern and the ship’s longitudinal axis are increasing considerably.

**Squat in open water**

The change of the primary wave system with speed and under keel clearance reveals varying sinkages at bow and stern. These sinkages, referred to as ship squat, reduce the gross under keel clearance in open water and must be taken into account during the design process to prevent grounding or damages to the ship’s keel or propeller-rudder system.

In Figure 9 the non-dimensional sinkages at the fore and aft perpendicular for the class Va vessel with a full scale draft of 3.65 m are presented as a function of the Froude number and in percentage of the gross under keel clearance. In medium deep water (200% UKC) the sinkages are negligible and restricted to approximately 5% of the gross UKC, even at maximum Froude number or a full scale speed of 22.7 km/h. In shallow water (35% UKC) the bow down trim ($z_{VF} > z_{VA}$) and sinkage are increasing with increasing vessel speed (3.2, 6.5, 13, 16.2 km/h) while at $Fr = 0.194$ or 22.7 km/h (in the critical speed range) the UKC is reduced with 65% of the gross UKC at the aft peak while a change of trim occurs and gives a bow up trim with small sinkages at the bow. In very shallow water (10 and 20% UKC) the gross UKC is reduced with 40% at a full scale speed of 13 km/h and $h/T = 1.2$ while an even larger loss of UKC is seen for $h/T = 1.1$ at a speed of 9.7 km/h.

Reducing the full scale draft of the vessel to 2.85 m shows an increase of the sinkage at bow and stern in terms of percentage compared to the sinkages for the maximum draft of 3.65 m (Figure 10). As deterministic accessibility issues often work with minimal gross UKC values in terms of percentage the
UKC for a 2.85 m draft will in absolute terms be smaller than the UKC for a 3.65 m draft. This lower absolute UKC together with a modified loading condition clearly give increased sinkages at the same vessel speeds as for the maximum draft in open water and thus less reserve to grounding.

In concept design methods a minimum value for the water depth-draft ratio h/T of 1.3 or 30% UKC is used. Based on Figure 9 the gross UKC reduces with 40 (FPP) to 50% (APP) for common full scale vessel speeds of respectively 16.2 and 20 km/h. It can be concluded that based on the UKC reduction due to sinkage in open water and the additional sinkages measured nearby banks [3] and due to ship-ship interaction [4], frequently occurring on inland waterways, the design UKC of a waterway can only be decreased if the maximum operating speed on the waterway is reduced too.

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The non-dimensional lateral hull force $Y'(\beta)$ as function of the drift angle is shown in Figure 11 for deep and shallow water in four quadrants. $Y'(\beta)$ increases considerably in shallow and very shallow water. This will have an effect on course stability, which is observed to increase with decreasing water depth.

Validation of the mathematical models is based on a comparison between measurement and model of additional multi-modal tests, on standard manoeuvres measured during free-running model tests (Figure 14) and finally on feedback of a boat master executing real-time simulations on the inland simulator.

3.2 Ship-bank and ship-ship interaction

Ship-ship interaction between two or more inland vessels has not been examined in the towing tank so far. For simulation purposes the generalized mathematical model deducted from model tests with sea-going ships can be used. In Figure 15 the passage of two class IV inland vessels on a section of the Upper-Seascheldt is shown. Taking into account the narrow cross-section of the river, encounters cause not only forces between the interacting vessels but each vessel is additionally influenced by bank effects. The slopes of the banks in Figure 15 are in between 1:3 and 1:4.

To model these bank effects ship-bank interaction has been examined executing captive model tests with four types of banks (vertical wall, 1:1, 1:3, 1:4, Figure 16). These tests have been executed at full
loaded condition and all UKC values as for the open water tests except 10% UKC (Figure 17). Model speed, lateral distance to the bank and propeller rate (no propeller action and self propulsion) have been varied to determine the influence of these parameters on longitudinal, lateral force and yawing moment due to ship – bank interaction.

\[ Y_F = \frac{1}{2} \rho V_T (u + \beta_1 V_T)^2 \left( \frac{1}{d_{2b}} \right) ^{\beta_2} \]

\[ Y_A = \frac{1}{2} \rho V_T (u + \beta_1 V_T)^2 \text{sign} \left( \frac{1}{d_{2b}} \right) \left( \frac{1}{d_{2b}} \right) ^{\beta_2} \]

with \( V_T \) a propeller thrust dependent parameter defined as:

\[ V_T = \text{sign}(T_p) \left( \frac{\theta_{Tp}}{\rho n D^{\beta_2}} \right) \]

The coefficients \( \beta_1 \) and \( \beta_2 \) have been determined in two ways: as regression coefficients function of an effective UKC and as tabular coefficients function of the longitudinal speed \( u \) for \( \beta_1 \) and function of \( u \) and a mean UKC for \( \beta_2 \). The tabular model gives over all a better agreement between measurements and model.

Fig. 16: Four types of banks in the towing tank

Fig. 17: Class Va ship model sailing above the 1:1 bank

Fig. 18: Lateral forces due to bank effects at fore and aft gauges as function of 1/d2b for a speed of 10.8 km/h full scale and deep to shallow water, no propeller action, class Va

4. FULL SCALE MEASUREMENTS

To validate the mathematical models for a specific simulation project FHR has invested in an accurate measurement equipment that can be installed in a short time on almost any vessel (Figure 19). The equipment uses a combination of RTK GPS antennas, accelerometers and inclinometers to measure the position and orientation of the vessel in three dimensions with an accuracy up to respectively 2 cm and 0.01°. It consists of a pre-calibrated housing carrying two GPS antennas with separation distance
2 m, sending the measured data wireless to a laptop standing in the bridge house. Furthermore AIS-data from the ship's pilot plug are supplied to the laptop using a pilot plug splitter. During the survey the time evolution of rudder angles and machine orders are registered manually.

The registered trajectory of a class IV vessel (85 m length) on the Upper-Seascheldt and the vessel speed are shown on Figure 20. The Upper-Seascheldt, the most upward tidal part of the river Scheldt from the port of Antwerp to the locks in Merelbeke, is accessible for class IV vessels and under investigation for an upgrade to a class Va waterway. The Dutch design guidelines are not met for two-way traffic straight sections and for the bends. The maximum draft depends on the tidal condition. Different alternative river adaptations have been examined in a multidisciplinary research of which real-time simulations have been used for the nautical evaluation. Speeds over ground of over 20 km/h are measured during a full scale trial although the speeds through water are lower as the tidal wave is actually used for the inbound manoeuvre. This speed through water determines the squat. Upgrading the river for class Va vessels and larger ship’s drafts suppose the availability of a gross under keel clearance of at least 30 to 35% in the axis of the river so that grounding is avoided and ship manoeuvrability is sufficient for taking the bends and counteracting the influence of banks and other ships. This proposed gross UKC value corresponds to the water depth-draft ratio prescribed in the Dutch guidelines.

5. REAL-TIME SIMULATIONS

5.1 Inland Simulator LARA

On December 3rd 2010 the inland simulator LARA (Figure 21) at FHR was inaugurated by the Minister of Mobility and Public Works H. Crevits. The aim of this simulator is to provide the Flemish Government with a tool for research and development on inland navigation.

LARA is based on the hardware and software simulator technology of FHR with following features:

- Full mission bridge with 210° aerial view displayed on seven 52” LCD monitors (Visualisation software Vegaprime Presagis)
- Equipped with ECDIS and radar (Tresco, Alphatron, Sindel)
- Controllable camera views
- Controllable bridge height as on many inland vessels

5.2 Comparison between reality and simulation

The Upper-Seascheldt was implemented in LARA for the execution of the class Va accessibility simulation study. In order to validate the simulator environment a comparison was made between real-time simulation runs on LARA and the measured track of a class IV vessel on the Scheldt reported in chapter 4 (Figure 20). The simulation runs have only been executed at the most difficult conditions (maximum flood or ebb current or lowest water level). Consequently no one to one comparison is possible with the measured inbound voyage as at full loaded condition class IV vessels are forced to use the flood tide avoiding the maximum flood current at the most difficult passages.
6. CONCLUSIONS

To be able to offer a simulation tool for the evaluation of the design of inland waterways, Flanders Hydraulics Research has developed mathematical manoeuvring models. These mathematical models have been based on an extensive experimental program in open water and nearby banks with a ship model of a class Va inland vessel (110 m, 11.45 m). Manoeuvring models have been determined for two loading conditions (3.65 m and 2.85 m) and four water depth to draft ratios (2.0, 1.35, 1.2 and 1.1). Bank effects have only been examined at the largest draft and for h/T ratios of 2.0, 1.35 and 1.2.

The manoeuvring models have been validated by boat masters during simulation runs on the inland navigation simulator LARA. Some modifications to the model coefficients had to be made.

As design guidelines for inland waterways cannot always be met for the adaptation of existing inland waterways due to the existence of urban or natural valuable areas, in-depth research based on real-time simulations can help in defining the limits.

Future research for inland navigation will have to focus on the prediction of the manoeuvring behaviour of push convoys (2012-2013) and estuary ships (2011-2012) in open and confined water and the interaction between inland ships.

7. ACKNOWLEDGEMENTS

The authors want to thank the Flemish Government and the Flemish authorities responsible for the navigation on inland and estuary rivers in Flanders, Waterwegen en Zeehaven nv, Maritime Access Department, nv De Scheepvaart, and the promotional agency Promotie Binnenvaart Vlaanderen for their support in the development of an inland navigation research section at FHR.

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