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River Rhine - hydraulic and ship dynamic modelling

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ABSTRACT: The navigation of an inland vessel on a free flowing river is a complex physical process. To help in understanding and in operations, the hydrodynamic and ship models of the Federal Waterways Engineering and Research Institute (BAW) will be combined to create a unified model, whose bases are discussed in the following article. Using the River Rhine as an example, virtual navigation capabilities are demonstrated, as are computational verifications using the ECDIS platform contained in the model.

Keywords: Numerical hydraulic model, Ship dynamic, Inland vessel, Navigation

1 INTRODUCTION

Lake Toma, situated at the Oberalp pass in the Gotthard massif at a height of 2344 m, is officially considered to be the source of the River Rhine.

When leaving Lake Constance at the bridge in Constance the division of the River Rhine into river flow kilometres begins with km 0 and ends in the delta of the River Rhine in the west of Rotterdam with km 1033. Today the navigational River Rhine begins near Basel at Rhine-km 150.

Although the catchment area around Basel is not even a quarter of the total catchment area, the river already conveys nearly half of its total discharge at this location. The discharge is relatively well-balanced over the seasons compared with other rivers. With an average rainfall of 900 mm, the catchment of the River Rhine is considered a water rich area in Europe. With a yearly average discharge of about 2,300 m^3/s (measured at the German-Dutch border), the river is favourable for shipping.

The River Rhine is one of the most navigated large rivers in Europe. In the year 2008, 207.5 million tons of goods were transported on this river. Near Emmerich, 278 ships per day were counted as an average (Statistisches Bundesamt, 2009).

As a technical and scientific consultant of the Federal Waterways and Shipping Administration, the BAW is involved in all main navigational and nautical projects on the River Rhine. One focus is put on the ship dynamic investigations. The coupling of numerical hydraulic models with ship dynamic models is seen as an important field with the aim to develop Hydraulic and Ship Dynamic models (HSD). This article outlines the main features of the HSD-models. Furthermore, a case study is presented for the River Rhine, showing the improvements regarding river navigation analysis, for example, to recognize a nautical bottleneck, to derive necessary methods to optimize the navigability of the waterway.

Finally, the development and application of a navigation simulator is described to predict and resolve operational problems for river navigation.

2 HYDRAULIC AND SHIP DYNAMIC MODEL

The HSD-model of the River Rhein consists of four basic components: The first comprises a hydrodynamic discharge model, which computes water depths and flow velocities and their distribution over the navigable reach of the waterway for the respective discharges, based on the geometry of the waterway. The second component describes the dynamics of an inland vessel, considering the local flow velocities. The third component is a virtual navigation system, which generates the navigation course lines in the waterway, considering the local hydraulic and nautical boundary conditions as well as the regulations of the river navigation. The fourth component is a tracking routing, which allows a track management and an evaluation of the traffic.

2.1 *Hydrodynamic numerical 1D/2D river modelling*

Since 2007 the BAW has operated a one-dimensional (1D) model of the free flowing River Rhine between Iffezheim (km 334) and the Dutch border (km 865) (Figure 1).

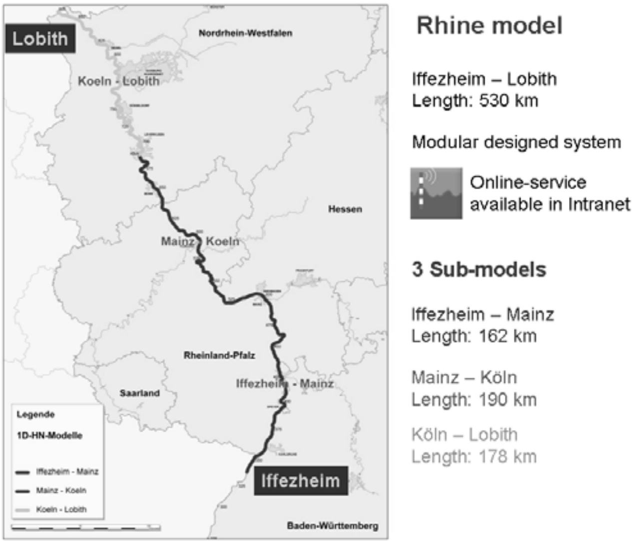

Figure 1: Model of the River Rhine between Iffezheim and the German-Dutch border

The model has been developed and operated by the BAW using the in-house software CasCade, a one-dimensional, hydro-numeric modelling system for unsteady, unconfined flow conditions in branched or meshed networks of rivers, canals and flood fields (Blenninger, T. et al, 2006). CasCade models can easily be connected to the River Rhine water gauge online-database, which is continuously updated with real-time data. Unsteady model runs include the previous flow history and use the actual water level time-series as boundary conditions at open boundaries. Additional water gauge data furthermore allows for a real-time model accuracy check. The model computes all parameters which are necessary for an evaluation of the ship dynamics, such as water depths and flow velocities for each flowrate and cross-section.

To be able to model reaches which have a strong two-dimensional flow field, such as river confluences or complex flood plain flows, two-dimensional (2D) numerical hydraulic models are applied and coupled to the 1D ship model.

2.2 *Modelling ship dynamics*

The ship dynamic model is a 1D-procedure, in which the calculation of the navigational width is taken for granted, which means that the ship is on a stationary circle trip (Figure 2). Additionally a 2D-model exists, in which this limitation is cancelled and the ship moves in a stationary 2D depths averaged flow field.

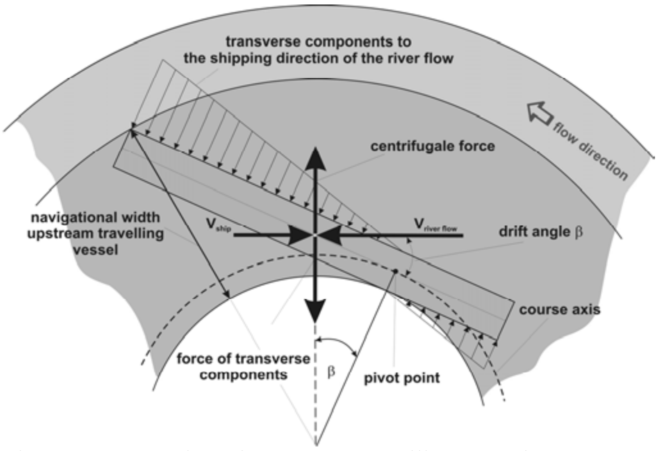

Figure 2: Dynamics of upstream travelling vessels

Both model procedures are based on the dynamic equations of Kirchhoff (Table 1). Professor Gustav Kirchhoff is known for his discoveries in the area of electro-technology and spectroscopy. He developed the general motion equations for a ship during his professorship at the University of Berlin, in the context of his work on mathematical physics (Lamb, H., 1932).

Table 1: Equations of Kirchhoff for the movement of a rigid body in a fluid

$$F_X = m\frac{\partial V_X}{\partial t} + m \cdot \omega_Y \cdot V_Z - m \cdot \omega_Z \cdot V_Y$$

$$F_Y = m\frac{\partial V_Y}{\partial t} + m \cdot \omega_Z \cdot V_X - m \cdot \omega_X \cdot V_Z$$

$$F_Z = m\frac{\partial V_Z}{\partial t} + m \cdot \omega_X \cdot V_Y - m \cdot \omega_Y \cdot V_X$$

$$M_X = I_X \cdot \frac{\partial \omega_X}{\partial t} + I_Z \cdot \omega_Z \cdot \omega_Y - I_Y \cdot \omega_Y \cdot \omega_Z + m \cdot V_Z \cdot V_Y - m \cdot V_Y \cdot V_Z$$

$$M_Y = I_Y \cdot \frac{\partial \omega_Y}{\partial t} + I_X \cdot \omega_X \cdot \omega_Z - I_Z \cdot \omega_Z \cdot \omega_X + m \cdot V_X \cdot V_Z - m \cdot V_Z \cdot V_X$$

$$M_Z = I_Z \cdot \frac{\partial \omega_Z}{\partial t} + I_Y \cdot \omega_Y \cdot \omega_X - I_X \cdot \omega_X \cdot \omega_Y + m \cdot V_Y \cdot V_X - m \cdot V_X \cdot V_Y$$

where F_x,F_y,F_z – external longitudinal forces, external transversal forces, external vertical forces, I_x,I_y,I_z – moment of inertia about the x-axis, the y-axis, the z-axis (including the added Moments of inertia), m – ship mass (including added mass), M_x,M_y.M_z – external momentum about the x-axis, the y-axis, the z-axis, V_x,V_y,V_z – longitudinal speed, transversal speed, vertical speed, ω_x, ω_y, ω_z – rolling, pitching, yawing (Table 1).

These six equations are strictly derived for a submarine, that moves in all-side unlimited water. For the 1D-model, the movement equation transverse to the shipping direction was solved. The flow velocity of the waterway is considered to be averaged in the profiles. In the longitudinal direction of the ship a fixed velocity against the water is given per section. This procedure can be calculated very quickly on a customary PC and is suitable for large-scale investigations. Additionally it is used as a tool to calculate navigational tracks in rivers depending on the water level.

For the description of the movement within the 2D depth-averaged velocity distribution, the Kirchhoff-equations, which take into account all forces transverse to the ship's movement and the torque-equation around the high axis, were calculated; contrary to the one-dimensional model the unsteady parts were derived. In longitudinal direction the 1D-approach was chosen, which considers besides the efficiency of the propulsion, parts of the ship parameter as the proportion of the part of hull in the water, cross-section of the river, water level slope, etc.

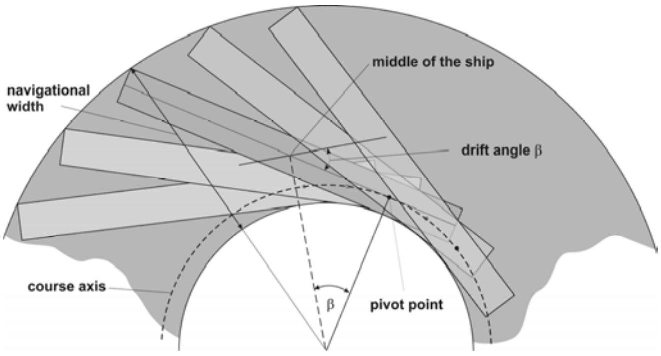

Figure 3: The track of a ship (phase images)

In the Kirchhoff equations the inertia effects of the fluid are modelled as hydrodynamic mass, which are determined potential-theoretically in both procedures. The determination of the lateral forces caused by a velocity distribution oblique to the hull is based on the theory of fine bodies, in which the forces are calculated by means of a local pulse analyzer in the control room near the hull. The resulting shape of the lateral forces, which will not change anymore during the investigation, is calculated and integrated in a preprocessor within the 1D-model. Within the 2D-model this is performed unsteadily during the operating time. For both procedures phase images are generated (Figure 3). In the 1D procedure the ship's positions are calculated at regular distances along a given course line. The local drift angle and the position of the pivot point will be calculate by solving the movement equations. The pivot point marks the position, where the cross flow direction along the ship changes its sign (Figure 2). This point has the specific feature, that the drift angle has the value zero. If the course line describes the way of the pivot point, the symbol for the ship can be placed tangentially to the course line.

In the 2D procedure the ship is navigated by a virtual navigator along a given course. The position of the following ship symbol is given by evaluating the forces from the local field of currents and the movements of the steering wheel.

2.3 *Navigation course line generator*

As described above, course lines are required for the ship dynamic model to generate a phase image. In a broad river with heterogeneous bed geometry, like the River Rhine, position and shape of the course line depend on numerous boundary conditions. Besides the regulations of the river navigation, passages of bridges, distributions of the flow velocities and water depths play an important role regarding the position of the course line. A ship going upstream will always try to navigate within the reaches of the profile with the smallest flow velocity; a ship going downstream, however, will navigate in reaches with the largest flow velocity. Additionally, both ships are looking for deep water, because there they can navigate with the highest load and consequently with highest profit. These boundary conditions are modelled for each cross-section. The cross-section interval usually has a distance of 100 m. The composition of the boundary conditions manages the individual course line.

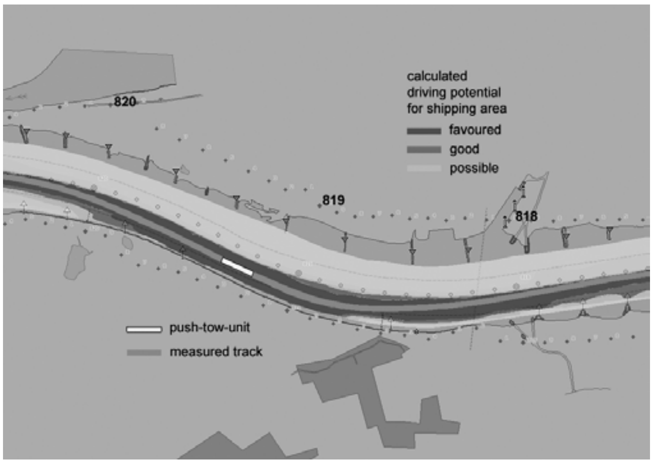

Figure 4: Measured track of a push-tow-unit compared with a calculated potential of navigability

For example, the water depth is much more important for a tanker heavily loaded with hazardous material than for a container ship, which in most cases drives with low draught.

From these boundary conditions and considering all weightings, a potential of the navigability of the river is calculated for each cross-section and from this the passage gates for this profile is determined. Afterwards a course line is designed from the sequence of the passage gates. Algorithms were developed for the calculation and the evaluation of the navigational potential as well as for the design of the course line, which allow a full automatically running of these processes (Figure 4).

2.4 *Ship simulation tracking routine*

All calculations for a single ship were performed assuming the condition of an undisturbed trip. This means that the ship can navigate with optimum speed and that there is no influence of other traffic. By using a time reference it is possible to calculate the relevant place-time curves for each ship.

An example is shown in Figure 5. The track started at 8:00 a.m. At this time, the ship travelling downstream passed the city of Mainz 510 km and the ship travelling upstream passed the city of Koblenz 610 km. The time display in Figure 5 is 10:00 a.m. The downstream ship is located at 550 km the upstream ship is located at 586 km. The passing point will be at 577 km at 10:50 a.m.

Encounter situations with other vessels (oncoming traffic), and overtakings with special traffic situations can be planed and evaluated.

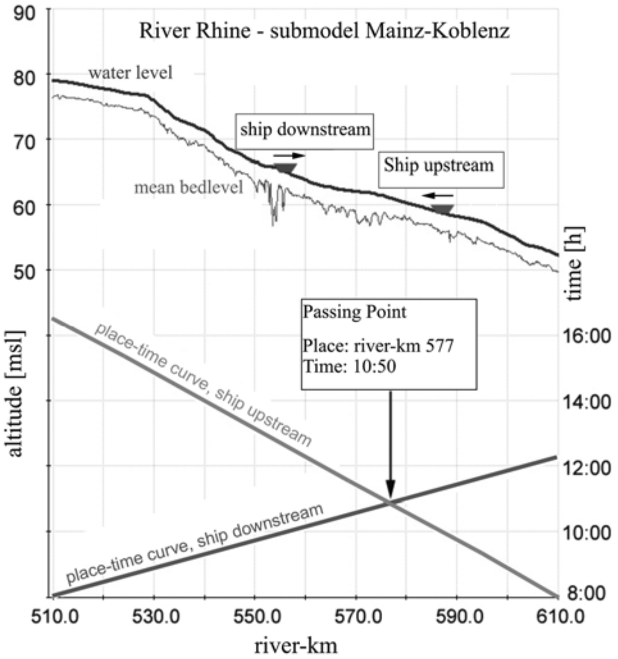

Figure 5: With HSD-model calculated traffic situation

2.5 *Calibration / Verification*

Within the pilot project Argo twelve ships were equipped with advanced navigation installations between October 2000 and February 2002 (WSD Südwest, 2003). During this period, the ships recorded 541 trips (314 upstream and 227 downstream) between Iffezheim and Lobith with the help of GPS-positioning. The data can be demonstrated and interpreted on the platform of Electronic Chart Display and Information System (ECDIS). Additionally, the water levels during the periods were evaluated with the hydraulic numerical model. With these conditions for flow depth and flow velocity, computed course lines could be calibrated and verified.

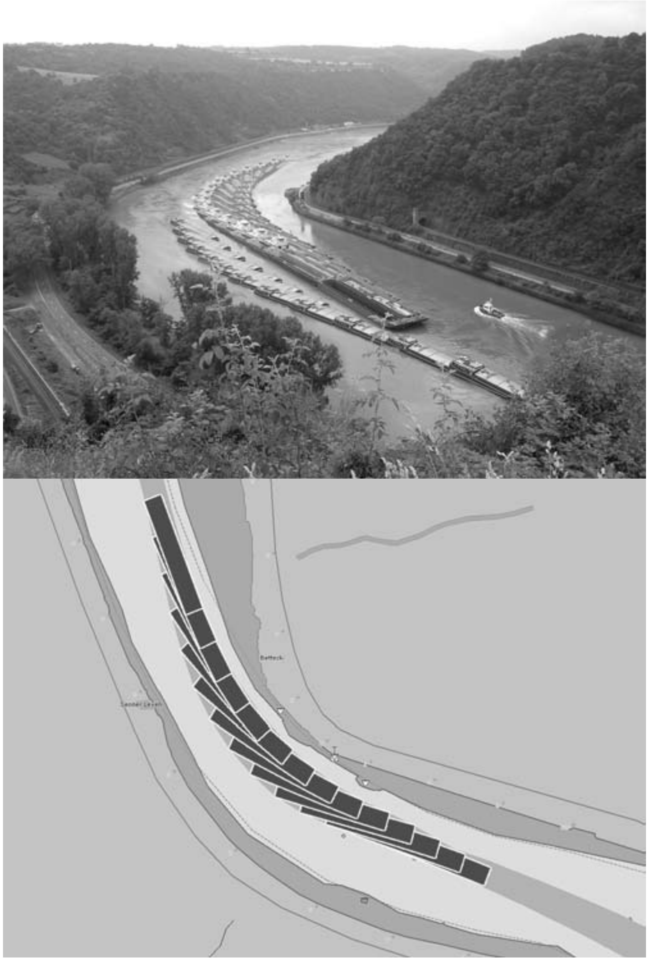

Figure 6: Phase pictures; above: photography, below: measured ship positions of the push tow-unit.

Additionally, results from ship dynamic investigations were available, which BAW performed during the past at different discharge conditions in the reach between Mainz and Koblenz. The results of the model show a good agreement between the calculated and the actual driven course line as well for the calculated lengths of the trips.

In June 2009, a push-tow-unit consisting of four units was instrumented during a trip between Emmerich and Mannheim for going upstream as well as downstream (Figure 6).

In this way the database, which is available for calibrating and verifying the HSD-models, is growing continuously.

3 CASE STUDIES FOR RIVER RHEIN

3.1 *Route planning / Route monitoring*

Ship simulation with time reference is practicable for route planning and route monitoring. When the velocity of the ship relative to the water is known, and the mean velocity of the river within the fairway is calculated, it is easy to combine both velocities to receive the ship velocity above ground. The integration over the river sections produce the time of arrival.

In a typical situation in June 2009, the trip of a push-tow-unit was monitored to verify the ship dynamic model (Figure 6). The ship passed the city of Koblenz (590 km) at 11:42 p.m. and the city of Braubach (580 km) at about 01:15 a.m. next day. The gauge Kaub showed 255 cm, increasing 0.5 cm per hour. The model calculated the ship velocity relative to water as 3.3 m/s.

When the vessel passed the city of Mainz (500 km) at 01:00 p.m., the model forecasted the arrival time at Mannheim (425 km) at about 10:00 p.m. The push-tow-unit arrived at Mannheim at 09:20 p.m. There is still potential for improvement!

3.2 *Nautical bottlenecks*

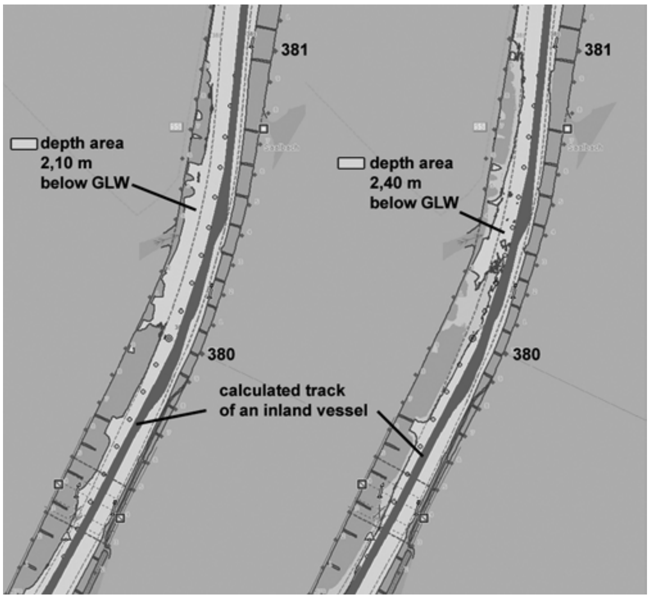

Figure 7: Nautical bottleneck, referenced to a water depth of 2.10 m and 2.40 m

On the left side at a fairway depth of 2.10 m below GlW (**Gl**eichwertiger **W**asserstand means a low water level reference for the River Rhine) is a quiet confortable track. Contrary, the right part of Figure 7 shows the navigational water for a heavily loaded vessel, which makes the most of the water depth, using 2.40 m below GlW.

By increasing the required water depth step by step it is easily seen, where bottlenecks within the navigational track appear first in each reach.

3.3 *Safety aspects*

Another application of HSD-models are the investigation of worst-case scenarios. How large may a push-tow-unit system be to ensure safe navigation in a river section? When should regulations be introduced? The simulation performed with a HSD-model offer possibilities to develop solution approaches and to analyse sections and case specific examples. This is illustrated in Figure 8. A phase picture shows an encounter between a push-tow-unit loaded with containers travelling downstream and a pusher tug-barge going upstream. This river section of navigational risk shortly upstream the Loreley section is regulated for the traffic. Large ships need a special allowance for navigating downstream.

4 ACTUEL DEVELOPMENT

In November 2009 a ship-handling simulator was installed at BAW in Karlsruhe (Figure 9). The main components are the ship-handling bridge characterized by different levels of navigational equipment, various facilities for enhanced visual simulation, an instructor console for session exercises with full digital replay and a console to prepare three dimensional models from ships as well as bathymetry from the Electronic Navigational Charts (ENC).

The simulator is designed modularly and is controlled via a Linux network. This enables further development of the hydraulic and ship dynamic model as well as modular adjustments of the soft- and hardware. Data for the simulations are mostly taken from Inland ENC.

The ship-handling simulator is the logical further development of HSD-models for the evaluation of waterways and shipping.

One of the next steps is to implement procedures which describe the interaction of ship and waterway. This includes the installation of a wave model to calculate and visualize ship induced waves as well as ship’s squat. The ship-handling simulator serves to obtain a better understanding for the requirements of navigation as well as to develop solutions which are in accordance with the hydraulic of the river.

Figur 8: River Rhine near city of Oberwesel, phase picture of a real situation in summer 2009

Figure 9: Ship handling simulator, ship-bridge with view scene of the River Neckar at Heidelberg

5 CONCLUSION

The River Rhine is one of the most navigated large rivers in Europe. As a technical and scientific consultant of the Federal Waterways and Shipping Administration, the BAW is involved in all main navigational and nautical projects on the River Rhine. The coupling of numerical hydraulic models and ship dynamic models to Hydraulic and Ship Dynamic models (HSD) has been accomplished and showed a large field of possible applications to improve river navigation. The developed HSD-model for the River Rhine consist of four basic components:

- Hydrodynamic-numerical 1D/2D river modelling
- Ship dynamic modelling
- Navigation course generator
- Ship tracking simulation with time reference

Some examples for the applicability of the HSD-models are demonstrated for route planning / route monitoring, nautical bottlenecks and safety aspects.

A new ship-handling simulator was installed as a numerical platform for the amendment and development of the navigational dynamic expertise, especially for inland navigation.

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