The improvement of navigational simulator training performance for inland waterways navigators

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Abstract. Nowadays, the issue of navigational safety support for the inland waterways navigation is very acute. However, it is much more difficult to make a safety assessment when navigating a river due to the limited systematic results of ship research in these navigational conditions. The most advanced method for navigational safety assessment when navigating in difficult navigational conditions is the use of mathematical modeling of the controlled of ship and towing barge motion, taking into account the effects of real hydrometeorological factors. In this work, the method of choosing a design vessel for navigational simulator training performance for inland waterways navigators using ship handling in difficult navigational conditions by means of mathematical models of the controlled motion of ships and towing barges. A similar method was used to determine a typical model for performing calculations using a navigation simulator as part of an international INFUTURE project. Verification of the results confirmed the high efficiency when using such methods.

1. Introduction

Shipping is a high-quality organizational and technical system consisting of three main components: the navigator, the vessel and the environment. Perhaps the most vital component to assess is the navigator.

To assess the practical ship handling capabilities of navigators in difficult navigation conditions computer and mathematical modeling methods are successfully applied (IMO 2003; Chambers and Main 2016; Sellberg 2017; Chen et al 2018). The mathematical modeling method based on information technology to reproduce virtual reality. This reality normally includes the visualization of the navigation area with all stationary and temporary objects of the navigation equipment of the navigation area, a virtual system of navigation and hydrographic conditions (fields of depths, fairways, beacons and buoys, leading lights, etc.), as well as the possibility of imitating hydrometeorological conditions, waves, visibility, currents, etc.).

Mathematical models of navigation include ships themselves, which are described by forth-order differential equations and also include basic and auxiliary control systems with appropriate interfaces. The mathematical modeling method is based on the following:
- special databases on ship models formation;
- electronic navigation chart and information display system (ECDIS) databases;
- databases on the visual surface situation in the expected navigation area with the aim of sharing them in virtual information systems on «bridge» for making decisions on ship handling in virtual reality navigation conditions.
Such information systems are very widely used for assessment practical ship handling competencies using ECDIS associated with various external information sensors, such as GNSS, ARPA, AIS, etc. (Longo et al 2013; Abramowicz-Gerigk and Hejmlich 2015).

Recently, this kind of simulation models are increasingly used to assess the navigation safety and the assessment of navigation risks (Li et al 2012; Mazaheri et al 2015).

The advantages of information systems include:
1. The ability to use the mathematical model of the vessel, taking into account the main features: the nonlinearity of the elements of the ship’s dynamics, the nonlinearity of the influence of wind, waves, currents, etc. The adequacy of mathematical models can be checked by comparing its maneuvering characteristics (acceleration and deceleration characteristics) with the original.
2. An almost complete presentation of cartographic information corresponding to current measurements, the position of dangerous isobaths, the configuration of the navigation equipment system of the navigation area, etc.
3. Formalization of the concept of characteristic winds, currents along suitable recommended tracks.
4. Skilled navigators, pilots, trainer instructors and other experts can be employed as captains (watch assistants) of virtual ships for solving various types of applied tasks.
5. Mathematical modeling, as a rule, precedes the full-scale tests of prototypes of marine equipment, since it makes it possible to reveal the basic properties of the analyzed systems in more economically justified ways.
6. Mathematical modeling does not at all exclude the carrying out of field experiments, however, it allows one to identify in advance the strengths of the analyzed organizational and technical system of vessel control (Berg and Ringen 2011).

The creation of mathematical models is a complex labor-intensive process caused by the following:
1. Required high accuracy and completeness of reproduction navigation-hydrographic and hydrometeorological conditions of the navigation area.
2. The complexity of holistic description of the ship model, disturbing factors and their influence on the ship’s dynamics (Eloot 2006).
3. Difficulties in the formation of the psychological and physiological environment of the bridge of a real vessel, i.e. such properties of the environment, which are characterized by responsibility for decisions made on the maneuver, speed of reaction, susceptibility of information all that distinguishes the real picture of the actions of the operator on the bridge from the virtual bridge (Power MacDonald et al 2011).

Since complexity and labor-intensiveness of mathematical models’ creation process, it is necessary to make balanced assessment of mathematical models required. The following is the methodology of numerical calculation a design vessel for simulator training for navigators to work in difficult navigational conditions typical of inland waterways.

2. **The optimal criterion estimation.**

The estimation of a design vessel should be based on a characteristic that is a criterion for assessing the ability of a vessel to follow a given section and that takes into account the influence of all external factors on the vessel. The most suitable criteria on the basis of which it is possible to form groups of vessels are the maneuvering lane width and the angle of drift.

The causes of the drift will be considered later and their calculation is carried out in accordance with the standard recommendations. The width of the maneuvering lane is a new concept that needs to be discussed in more detail.

2.1. **Basic maneuvering lane.**

The dynamics of ship motion is such that with manual control (usually used on approaches to the port and passing narrows), they go in a winding course in the absence of external influences from wind, waves and currents, occupying the track with a width exceeding the width of the vessel. This is due to the speed of the navigator’s response to navigational aids, which makes it possible to determine the position of the vessel and her reaction to steering forces. The zone of such movement of the vessel is
called the maneuvering lane shunting and depends on a number of factors, the main of which are the following:

- design maneuverability of the vessel (depending on the ratio of the depth and draft);
- navigator’s qualification;
- visual aids of navigation equipment;
- general visibility.

2.2. Vessel’s maneuverability.

It is often difficult to classify rationally a ship’s maneuverability; this requires analysis of a large number of criteria. Vessel can be considered highly maneuverable at open sea if she follows the course at the calculated speed. However, the same qualities that allow the vessel to follow the course strictly do not work in conditions of rapid maneuvering or motion along narrow reach of the approach channel or fairway.

The maneuverability of a ship changes dramatically in narrows. When changing the ratio of depth and draft to 1.3-1.5, the vessel may become less stable relative to her course and move in jerks. If the depth to draft ratio continues to decrease, the vessel follows the intended course more clearly until the depth margin under the keel becomes very small (the depth to draft ratio reaches 1.05-1.10) and the vessel maneuvers very slowly. This improvement in ship stability relative to course is an advantage in straight reaches of the channel.

However, the poor maneuverability of the vessel can cause problems associated with ship handling, therefore, additional space is necessary for maneuvering. The general classification of ship maneuverability depends on the natural and operational conditions. The following points can be used as rough approximate recommendations.

Long and narrow vessels (L/B > 6.5) more clearly follow the course than short (L/B < 6). The latter is easier to maneuver in narrow corners.

In shallow water (h/T ≤ 1.5), the maneuverability of vessels of all types is reduced.

The maneuverability of the vessel at low speed can significantly differ from the maneuverability at the design speed for which she was built (McBride et al 2014).

Single-shaft vessels with one rudder will maneuver quite well, but, as experience shows, the propeller has a side effect of transverse motion (motion due to transverse motion of the stern, which is caused by propeller operation, which makes compensating rudder force necessary).

Single-shaft vessels with pitch propeller, in practice, there is a side effect of transverse motion of the propeller, even when the propeller pitch corresponds to the position of a small or zero thrust.

Twin-shaft ships with two rudders usually have good maneuverability at any speed.

Twin-shaft ships with one rudder may have good maneuverability at design speed, but maneuverability drops at low speeds.

Vessels with bow thrusters have high maneuverability at low speed. Vessels equipped with azimuth thrusters also have high maneuverability at low speed.

2.3. Basic maneuvering lane margins.

From the ship handling theory it is known that the vessel maneuverable lane width is determined by the ratio (Snopkov 2004):

\[ B = L_c \sin C + B_c \cos C, \]

where:
- \( L_c \) – vessel length;
- \( B_c \) – vessel breadth;
- \( C \) – drift angle.

An additional width is added to the width of the basic maneuvering lane, taking into account the possible effects of wind, current, shallow water etc.

When determining the limiting hydrometeorological factors affecting the possibility of passing through areas difficult for navigation, the influence of the water level is considered first. This is due to the fact that when the ship moves in shallow water, an increase in draft is observed, which creates the danger of hull hitting the ground.
The phenomenon of vessel draft increasing during her motion is called squat. The squat depends on the ratio of speed, depth, and ship’s draught. To reduce the squat when proceeding in shallow water, it is necessary to reduce the speed in this area. The speed of movement in shallow areas should be such that the water flow supply under the housing, taking into account the squat, is maintained at least as specified.

The wave margin is not taken into account, assuming that the wave is negligible or that, regardless of the direction and height of the waves, the selected level is ensured.

3. Design vessel selection

3.1. Initial data

The data on the main characteristics of the vessels operating in the area are taken, from the reference manual for serial vessels and are summarized in Table 1, where the following notation is used:

- $L$, $B$, $T$ – extreme length, breadth and draught respectively;
- $H$ – moulded depth;
- $D$ – mass displacement;
- $v_{\text{MAX}}$ – maximum design speed of the vessel;
- $\delta$ – coefficient of fullness of displacement.

| Project | No. | $L$ (m) | $B$ (m) | $T$ (m) | $H$ (m) | $D$ (m) | $v_{\text{MAX}}$ (m/s) | $\delta$ |
|---------|-----|---------|---------|---------|---------|---------|----------------------|---------|
| No. 488/A | 1 | 112.5 | 13.0 | 3.7 | 6.0 | 4572 | 5.8 | 0.845 |
| No. 1743 | 2 | 105.0 | 14.8 | 2.51 | 5.0 | 3225 | 5.44 | 0.827 |
| No. 613 | 3 | 90.2 | 13.0 | 3.65 | 5.5 | 3252 | 6.42 | 0.76 |
| P25B | 4 | 96.0 | 12.5 | 2.44 | 3.4 | 2663 | 5.44 | 0.76 |
| P97 | 5 | 90.0 | 15.0 | 2.25 | 2.8 | 2543 | 4.66 | 0.833 |
| No. 19610 | 6 | 134.0 | 16.4 | 3.7 | 6.7 | 6740 | 5.72 | 0.828 |
| No. 19611 | 7 | 111.5 | 16.4 | 3.7 | 6.7 | 5393 | 5.83 | 0.795 |
| No. 050-74M | 8 | 136.0 | 16.5 | 3.7 | 5.5 | 8132 | 5.27 | 0.979 |
| No. 92-040 | 9 | 112.4 | 13.0 | 3.7 | 6.0 | 4648 | 5.27 | 0.859 |
| No.1743.1 | 10 | 105.0 | 14.8 | 2.62 | 5.0 | 3770 | 5.38 | 0.925 |
| P32.3.2. | 11 | 108.6 | 14.8 | 3.3 | 4.3 | 4510 | 5.0 | 0.842 |
| No. 0225 | 12 | 121.73 | 15.6 | 3.2 | 5.45 | 4868 | 5.42 | 0.849 |
| No. 292 | 13 | 124.0 | 15.4 | 3.0 | 5.45 | 4868 | 5.42 | 0.849 |
| P97T | 14 | 90.0 | 15.0 | 2.25 | 2.8 | 2543 | 4.66 | 0.833 |
| No. 630 | 15 | 134.12 | 16.5 | 3.7 | 6.4 | 6984 | 5.27 | 0.853 |
| No. 621 | 16 | 117.72 | 14.8 | 2.53 | 5.2 | 3680 | 5.27 | 0.846 |
| P32 | 17 | 96.9 | 14.8 | 3.0 | 4.3 | 3536 | 5.27 | 0.823 |
| No. 2-95A | 18 | 110.0 | 13.0 | 3.44 | 5.5 | 4062 | 5.55 | 0.825 |
| No. 791 | 19 | 110.0 | 13.0 | 3.35 | 5.5 | 3920 | 5.19 | 0.816 |
| No. 21-88 | 20 | 100.0 | 12.2 | 2.81 | 4.9 | 2800 | 5.55 | 0.818 |
| No. 576 | 21 | 90.0 | 13.0 | 2.85 | 4.8 | 2740 | 5.33 | 0.837 |
| No. 1557 | 22 | 128.6 | 16.5 | 3.62 | 5.5 | 6513 | 5.55 | 0.845 |
| No.578 | 23 | 107.5 | 13.4 | 3.55 | 4.8 | 4330 | 5.0 | 0.872 |
| No.576T | 24 | 107.2 | 13 | 3.5 | 4.8 | 4200 | 5.22 | 0.861 |
| No.16530 | 25 | 112.5 | 13.4 | 3.7 | 6.2 | 4618 | 6.22 | 0.828 |
| No.05074A | 26 | 103.8 | 16.5 | 3.7 | 5.5 | 5406 | 5.88 | 0.853 |
| No.15790 | 27 | 122.1 | 13.5 | 3.7 | 6.5 | 4269 | 5.66 | 0.7 |
3.2 Limiting hydrometeorological factors

Limiting hydrometeorological factors for the possibility of vessel passage through the particular section include:

– water level;
– current action;
– wind action;
– rough-water effect;

When determining the limiting hydrometeorological factors affecting the possibility of passage through the section, the influence of the water level shall be considered first.

This is due to the fact that when the vessel moves in shallow water, an increase in draught is observed, which creates the hazard of hull impact with the ground. The settlement depends on the ratio of speed, draught, and pass depth.

To reduce the settlement when moving in shallow water it is necessary to reduce the speed in this area. The speed of movement in shallow areas shall be such that the under-keel clearance, including the settlement, is maintained at least as specified.

For the unified deep-water system of European Russia (UDWS) the depth of 4m is guaranteed. However, taking into account actual water levels of the Neva River, a level of 1.0 – 2.0 m above the design value can be chosen.

In relation to this level, for each of the selected vessels, let consider the difference between the sum of the static draught of the vessel, under-keel clearance and the vessel settlement, and between the available depth.

The wave tolerance will not be taken into account, assuming that the waves are insignificant or that, regardless of the direction and height of the waves, the specified level is ensured.

3.3 Safe speed calculation

The basis for determining the dynamic settlement of the vessel are dependence diagrams of the relative increase in average vessel draught and its trim on the displacement Froude number at various ratios of depth and vessel draught. These data are shown in Fig. 1 and Fig. 2 and obtained using interpolation formula by the method based on the results of model and full-scale testing carried out by Leningrad Institute of Water Transport. The presented results can be used to calculate the settlement in canals with a small cross section constraint.

The basis of this method is as follows:

dependence graphs of relative increase in average draught on the Froude number for various relations of depth and vessel draught \( h/T \), shown in Fig.1;

dependence graphs of trim \( T_f - T_a / T \) in the form of the relative difference between the bow \( T_f \) and stern \( T_a \) draughts of the Froude number \( Fr_V = v/\sqrt{gV^{1/3}} \) by displacement \( V \) at various ratios of the depth and vessel draught \( h/T \) shown in Fig. 2.

The definition of dynamic settlement is carried out according to Formula 2

\[
\Delta H = C_b T[0.01 \Delta T / T + (T_f - T_a) / T]
\] (2)
Figure 1. The dependence of relative increase in average draught $\Delta T / T$, $\%$ on the Froude number $Fr = v / \sqrt{gL}$ for various relations of depth and vessel draught $h/T$.

Figure 2. The dependence of trim $(T_f - T_a)/T$ on the Froude number for displacement $Fr_V = v / \sqrt{gL}$ at various ratios of the depth and vessel draught $h/T$. 
Table 3. Calculation of the actual under-keel clearance for vessels moving with the maximum design speed.

| №  | d   | B/d | 0.07d | $\frac{v}{\sqrt{gL}}$ | $\frac{v}{\sqrt{g^3V}}$ | $\Delta T/\bar{T}$ | $T_f - T_{af}/\bar{T}$ | ΔH | $\Sigma[1,3,8]$ | H - $\Sigma[1,3,8]$ |
|----|-----|-----|-------|----------------------|----------------------|------------------|------------------------|----|----------------|-------------------|
| [0] | [1] | [2] | [3]   | [4]                  | [5]                  | [6]              | [7]                     | [8] | [9]            | [10]              |
| 1   | 3.7 | 1.5 | 0.26  | 0.17                 | 0.45                 | -4.5             | -0.052                 | 1.8 | 5.76           | 0.26              |
| 2   | 3.65 | 1.5 | 0.26 | 0.22                 | 0.53                 | -8.8             | -0.56                  | 1.5 | 5.71           | 0.21              |
| 3   | 3.7 | 1.5  | 0.26 | 0.16                 | 0.42                 | -3.5             | -0.46                  | 1.5 | 5.46           | 0.04              |
| 4   | 3.71 | 1.5 | 0.26 | 0.18                 | 0.45                 | -5.5             | -0.49                  | 1.6 | 5.57           | 0.07              |
| 5   | 3.7 | 1.5  | 0.26 | 0.14                 | 0.38                 | -1.1             | -0.42                  | 1.6 | 5.56           | 0.06              |
| 6   | 3.7 | 1.5  | 0.26 | 0.16                 | 0.41                 | -3.5             | -0.46                  | 1.6 | 5.56           | 0.06              |
| 7   | 3.7 | 1.5  | 0.26 | 0.15                 | 0.39                 | -1.4             | -0.04                  | 1.5 | 5.46           | 0.04              |
| 8   | 3.44 | 1.6  | 0.24 | 0.17                 | 0.44                 | -4.0             | -0.48                  | 1.5 | 5.18           | 0.32              |
| 9   | 3.62 | 1.5  | 0.26 | 0.16                 | 0.41                 | -3.5             | -0.47                  | 1.6 | 5.48           | 0.02              |
| 10  | 3.55 | 1.6  | 0.25 | 0.15                 | 0.40                 | -2.5             | -0.43                  | 1.5 | 5.3            | 0.2               |
| 11  | 3.5 | 1.6  | 0.25 | 0.16                 | 0.41                 | -3.1             | -0.44                  | 1.5 | 5.2            | 0.25              |
| 12  | 3.7 | 1.5  | 0.26 | 0.19                 | 0.49                 | -6.5             | -0.53                  | 1.8 | 5.76           | -0.26             |
| 13  | 3.7 | 1.5  | 0.26 | 0.18                 | 0.45                 | -5.5             | -0.51                  | 1.7 | 5.66           | -0.16             |
| 14  | 3.7 | 1.5  | 0.26 | 0.16                 | 0.45                 | -3.5             | -0.51                  | 1.5 | 5.46           | 0.04              |
| 15  | 3.3 | 1.7  | 0.23 | 0.15                 | 0.39                 | -1.3             | -0.36                  | 1.1 | 4.63           | 0.87              |
| 16  | 3.2 | 1.7  | 0.23 | 0.15                 | 0.39                 | -1.3             | -0.36                  | 1.1 | 4.53           | 0.97              |
| 17  | 3.0 | 1.8  | 0.21 | 0.15                 | 0.42                 | -1.4             | -0.41                  | 1.1 | 4.31           | 1.9               |
| 18  | 3.0 | 1.8  | 0.21 | 0.17                 | 0.43                 | -3.5             | -0.45                  | 1.2 | 4.41           | 1.09              |
| 19  | 3.35 | 1.6  | 0.24 | 0.16                 | 0.42                 | -3.1             | -0.45                  | 1.3 | 4.89           | 0.61              |
| 20  | 2.81 | 2.0  | 0.2  | 0.18                 | 0.47                 | -3.5             | -0.46                  | 1.2 | 4.21           | 1.29              |
| 21  | 2.85 | 1.9  | 0.2  | 0.18                 | 0.46                 | -3.5             | -0.43                  | 1.2 | 4.25           | 1.25              |
| 22  | 2.51 | 2.2  | 0.18 | 0.17                 | 0.45                 | -1.0             | -0.37                  | 0.8 | 3.49           | 2.01              |
| 23  | 2.44 | 2.3  | 0.17 | 0.18                 | 0.47                 | -2.2             | -0.39                  | 0.9 | 3.51           | 1.99              |
| 24  | 2.25 | 2.4  | 0.16 | 0.17                 | 0.40                 | +1.0             | -0.17                  | 0.3 | 2.71           | 2.79              |
| 25  | 2.62 | 2.1  | 0.18 | 0.17                 | 0.44                 | -1.5             | -0.36                  | 0.9 | 3.7            | 1.8               |
| 26  | 2.25 | 2.4  | 0.16 | 0.15                 | 0.40                 | +1.9             | -0.16                  | 0.3 | 2.71           | 2.79              |
| 27  | 2.53 | 2.2  | 0.18 | 0.16                 | 0.43                 | +0.75            | -0.33                  | 0.7 | 3.41           | 2.09              |

Table 3 shows that three groups of vessels can be distinguished depending on draught and settlement. It should also be noted that some vessels will not have the necessary under-keel clearance. Therefore, for further calculation, their speeds will be reduced by a certain amount providing movement with a safe speed. The calculation of speeds is given in Table 4.

Table 4 Calculation of safe speed to ensure the under-keel clearance

| №  | d   | $v_{\text{MAX}}$ | $\frac{v}{\sqrt{gL}}$ | $\frac{v}{\sqrt{g^3V}}$ | $\Delta T/\bar{T}$ | $T_f - T_{af}/\bar{T}$ | ΔH | $\Sigma[1,9,8]$ | H - $\Sigma[1,3,8]$ |
|----|-----|------------------|----------------------|----------------------|------------------|------------------------|----|----------------|-------------------|
| [0] | [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] | [10] |
| 1   | 3.7 | 1.5 | 5.0 | 0.15 | 0.39 | -2.5 | -0.45 | 1.5 | 0.26 | 5.46 | 0.04 |
| 3   | 3.65 | 1.5 | 5.6 | 0.19 | 0.47 | -6.5 | -0.42 | 1.4 | 0.26 | 5.31 | 0.19 |
| 7   | 3.71 | 1.5 | 5.4 | 0.16 | 0.41 | 3.0  | -0.45 | 1.4 | 0.26 | 5.37 | 0.13 |
| 8   | 3.7 | 1.5 | 5.0 | 0.14 | 0.36 | -1.0 | -0.38 | 1.4 | 0.26 | 5.36 | 0.14 |
| 9   | 3.7 | 1.5 | 5.0 | 0.15 | 0.39 | -2.5 | -0.43 | 1.5 | 0.26 | 5.46 | 0.04 |
| 25  | 3.7 | 1.5 | 5.5 | 0.16 | 0.42 | -3.5 | -0.47 | 1.5 | 0.26 | 5.46 | 0.04 |
| 26  | 3.7 | 1.5 | 5.2 | 0.16 | 0.41 | -3.5 | -0.46 | 1.5 | 0.26 | 5.46 | 0.04 |
3.4. Speed calculation in shallow water

When solving practical problems of handling a ship, shallow water is considered as a conditions when depth/draft ratio is $H/d \leq 2–3$. To calculate the speed in shallow water the formula obtained by A.P. Smirnov (Snopkov 2004) can be applied,

$$v_M = k_0 \cdot k_\delta \cdot k_{B/d} \cdot \infty$$  \hspace{1cm} (3)

Where

- $v_M$ – vessel speed in shallow water, m/s;
- $v_\infty$ – vessel speed in deep water, m/s;
- $k_0$ – proportionality factor (see Table 4);
- $k_\delta$ – proportionality factor for displacement coefficient of underwater body (see Table 5);
- $k_{B/d}$ – proportionality factor for ratio vessel breadth/draught $B/d$ (Table 6).

### Table 4. Values of $k_0$ factor

| $H/d$ | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|-------|---|---|---|---|----|----|----|----|----|----|----|----|
| Speed $v_\infty$ in deep water, knots |
| 3.5  | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.99 | 0.98 | 0.98 | 0.98 | 0.98 | 0.98 | 0.97 |
| 3.0  | 1.00 | 0.99 | 0.98 | 0.98 | 0.97 | 0.97 | 0.96 | 0.96 | 0.96 | 0.95 | 0.94 |   |
| 2.5  | 0.99 | 0.98 | 0.98 | 0.96 | 0.95 | 0.95 | 0.94 | 0.94 | 0.93 | 0.93 | 0.92 | 0.92 |
| 2.0  | 0.98 | 0.97 | 0.97 | 0.95 | 0.94 | 0.93 | 0.92 | 0.90 | 0.90 | 0.89 | 0.88 | 0.88 |
| 1.5  | 0.96 | 0.94 | 0.92 | 0.91 | 0.89 | 0.88 | 0.87 | 0.86 | 0.86 | 0.85 | 0.84 | 0.84 |
| 1.3  | 0.95 | 0.93 | 0.91 | 0.89 | 0.88 | 0.86 | 0.85 | 0.84 | 0.83 | 0.83 | 0.82 | 0.82 |
| 1.25 | 0.94 | 0.92 | 0.91 | 0.89 | 0.87 | 0.86 | 0.85 | 0.84 | 0.83 | 0.82 | 0.81 | 0.81 |
| 1.10 | 0.94 | 0.91 | 0.89 | 0.88 | 0.86 | 0.85 | 0.83 | 0.83 | 0.82 | 0.82 | -    | -    |

### Table 5. Values of $k_\delta$ factor

| $\delta$ | 0.7 – 0.75 | 0.75 – 0.80 | 0.80 – 0.85 |
|----------|------------|-------------|-------------|
| $k_\delta$ | 1          | 0.973       | 0.947       |

### Table 6. Values of $k_{B/d}$ factor

| $B/d$ | 2.0 | 2.5 | 3.0 | 3.5 |
|-------|-----|-----|-----|-----|
| $k_{B/d}$ | 1.026 | 1.0 | 0.973 | 0.947 |

The calculation of vessel speed in shallow water is summarized in Table 7.

### Table 7. Speed calculation in shallow water

| $N_e$ | $H/d$ | $k_0$ | $B$ | $k_{B/d}$ | $k_\delta$ | $v_M$ (m/s) | $N_e$ | $H/d$ | $k_0$ | $B$ | $k_{B/d}$ | $k_\delta$ | $v_M$ (m/s) |
|-------|-------|-------|-----|---------|-----------|-----------|-------|-------|-------|-----|---------|-----------|-----------|
| 1     | 1.5   | 0.88  | 3.5 | 0.947   | 0.947     | 3.9       | 15    | 1.7   | 0.91  | 4.5 | 0.947   | 0.947     | 4.1       |
| 2     | 1.5   | 0.865 | 3.5 | 0.947   | 0.973     | 4.5       | 16    | 1.7   | 0.9   | 4.9 | 0.947   | 0.947     | 4.2       |
| 3     | 1.5   | 0.88  | 4.4 | 0.947   | 0.947     | 4.5       | 17    | 1.8   | 0.925 | 5.1 | 0.947   | 0.947     | 4.5       |
| 4     | 1.5   | 0.877 | 4.4 | 0.947   | 0.973     | 4.4       | 18    | 1.8   | 0.91  | 4.9 | 0.947   | 0.947     | 4.3       |
| 5     | 1.5   | 0.89  | 4.4 | 0.947   | 0.947     | 4.0       | 19    | 1.6   | 0.9   | 3.6 | 0.947   | 0.947     | 4.2       |
| 6     | 1.5   | 0.89  | 3.5 | 0.947   | 0.947     | 4.0       | 20    | 2.0   | 0.92  | 4.3 | 0.947   | 0.947     | 4.3       |
| 7     | 1.5   | 0.89  | 4.5 | 0.947   | 0.947     | 4.2       | 21    | 1.9   | 0.93  | 4.6 | 0.947   | 0.947     | 4.4       |
| 8     | 1.5   | 0.89  | 3.7 | 0.947   | 0.947     | 4.4       | 22    | 2.2   | 0.94  | 5.9 | 0.947   | 0.947     | 4.7       |
| 9     | 1.5   | 0.88  | 4.5 | 0.947   | 0.947     | 4.2       | 23    | 2.3   | 0.94  | 5.1 | 0.947   | 0.947     | 4.6       |
3.5. Calculation of wind and current drift angles

The values of wind drift angles in deep water can be selected from Table 8.

The magnitude of wind drift angle selected from Table 8 at depths a third less than vessel draught is corrected by coefficient $k_\alpha$ (see Table 9). The current drift angles can be selected from Table 10.

### Table 8. The values of wind drift angles depending on the ratio of freeboard and underwater body sail areas and the true wind heading angle $\varphi_u$ ($u$– true wind speed, $\upsilon$ – vessel speed)

| $u/\upsilon$ | $\varphi_u$ deg | $S_u/S_H$ |
|-------------|-----------------|------------|
| 1           | 0.5             | 0.5        |
| 2           | 1.0             | 1.0        |
| 3           | 1.5             | 2.0        |
| 4           | 1.0             | 2.5        |
| 5           | 1.5             | 3.0        |

| $u/\upsilon$ | $\varphi_u$ deg | $S_u/S_H$ |
|-------------|-----------------|------------|
| 1           | 0.5             | 1.0        |
| 2           | 1.0             | 2.0        |
| 3           | 1.5             | 3.0        |
| 4           | 2.0             | 4.0        |
| 5           | 2.5             | 5.0        |

| $u/\upsilon$ | $\varphi_u$ deg | $S_u/S_H$ |
|-------------|-----------------|------------|
| 1           | 0.5             | 1.0        |
| 2           | 1.0             | 2.0        |
| 3           | 1.5             | 3.0        |
| 4           | 2.0             | 4.0        |
| 5           | 2.5             | 5.0        |

| $u/\upsilon$ | $\varphi_u$ deg | $S_u/S_H$ |
|-------------|-----------------|------------|
| 1           | 0.5             | 1.0        |
| 2           | 1.0             | 2.0        |
| 3           | 1.5             | 3.0        |
| 4           | 2.0             | 4.0        |
| 5           | 2.5             | 5.0        |

### Table 9. Values $k_\alpha$ vs $H/d$ ratio

| $H/d$ | $k_\alpha$ |
|-------|------------|
| 3.0   | 0.83       |
| 2.6   | 0.71       |
| 2.2   | 0.59       |
| 1.8   | 0.48       |
| 1.4   | 0.33       |
| 1.3   | 0.29       |

### Table 10. The values of the drift angles $\beta$ depending on the ratio of current and the vessel speeds $\upsilon_T/\upsilon_M$ and relative current angle $q_T$

| $q_T$  | $\upsilon_T/\upsilon_M$ |
|--------|-------------------------|
| 0.03   | 0.05                    |
| 0.07   | 0.10                    |
| 0.13   | 0.17                    |
| 0.20   | 0.30                    |
| 0.40   | 0.50                    |
Calculation of the initial data for determining the drift and leeway angles is given in Table 11.

### Table 11. The calculated initial data for determining the numerical values of the drift and leeway angles.

| №  | $u_T = 0.5$ | $u_T = 1.0$ | $u_T = 1.5$ | $U/V = 5$ | $U/V = 10$ | $U/V = 15$ |
|----|-------------|-------------|-------------|-----------|-----------|-----------|
| 1  | 0.13        | 0.26        | 0.39        | 1.3       | 2.6       | 3.8       | 0.8       |
| 2  | 0.11        | 0.22        | 0.33        | 1.1       | 2.2       | 3.1       | 0.6       |
| 3  | 0.11        | 0.23        | 0.34        | 1.1       | 2.3       | 3.4       | 1.0       |
| 4  | 0.11        | 0.23        | 0.34        | 1.1       | 2.3       | 3.3       | 1.0       |
| 5  | 0.125       | 0.25        | 0.38        | 1.25      | 2.5       | 3.75      | 0.6       |
| 6  | 0.125       | 0.25        | 0.38        | 1.25      | 2.5       | 3.75      | 0.75      |
| 7  | 0.12        | 0.24        | 0.37        | 1.2       | 2.4       | 3.7       | 0.9       |
| 8  | 0.12        | 0.23        | 0.35        | 1.2       | 2.3       | 3.5       | 0.7       |
| 9  | 0.125       | 0.25        | 0.38        | 1.25      | 2.5       | 3.75      | 0.6       |
| 10 | 0.13        | 0.26        | 0.38        | 1.3       | 2.6       | 3.8       | 0.4       |
| 11 | 0.125       | 0.25        | 0.38        | 1.25      | 2.5       | 3.7       | 0.5       |
| 12 | 0.12        | 0.24        | 0.36        | 1.2       | 2.4       | 3.3       | 0.8       |
| 13 | 0.12        | 0.24        | 0.36        | 1.2       | 2.4       | 3.4       | 0.6       |
| 14 | 0.11        | 0.22        | 0.33        | 1.1       | 2.2       | 3.3       | 0.9       |
| 15 | 0.13        | 0.26        | 0.39        | 1.3       | 2.6       | 3.9       | 0.4       |
| 16 | 0.125       | 0.25        | 0.38        | 1.25      | 2.5       | 3.75      | 1.1       |
| 17 | 0.12        | 0.24        | 0.36        | 1.2       | 2.4       | 3.6       | 1.0       |
| 18 | 0.12        | 0.24        | 0.36        | 1.2       | 2.4       | 3.6       | 0.5       |
| 19 | 0.125       | 0.25        | 0.38        | 1.25      | 2.5       | 3.75      | 0.8       |
| 20 | 0.12        | 0.24        | 0.37        | 1.2       | 2.4       | 3.7       | 0.9       |
| 21 | 0.12        | 0.24        | 0.36        | 1.2       | 2.4       | 3.6       | 0.8       |
| 22 | 0.11        | 0.23        | 0.34        | 1.1       | 2.3       | 3.4       | 1.2       |
| 23 | 0.11        | 0.23        | 0.34        | 1.1       | 2.3       | 3.4       | 1.2       |
| 24 | 0.13        | 0.26        | 0.38        | 1.3       | 2.6       | 3.8       | 0.3       |
| 25 | 0.12        | 0.23        | 0.35        | 1.2       | 2.3       | 3.5       | 1.1       |
| 26 | 0.13        | 0.26        | 0.38        | 1.3       | 2.6       | 3.9       | 0.3       |
| 27 | 0.12        | 0.26        | 0.35        | 1.2       | 2.3       | 3.5       | 1.3       |

3.6 Calculation of maneuvering lane width

The following presents a calculation of maneuvering lane of selected vessel projects under the wind and current influence for the following combinations:

- current speed 0.5 m/s; wind speed: 5 m/s, 10 m/s, 15 m/s
- current speed 1.0 m/s; wind speed: 5 m/s, 10 m/s, 15 m/s
- current speed 1.5 m/s; wind speed: 5 m/s, 10 m/s, 15 m/s

The generalized results of calculations of the drift angles values and the maneuvering lanes width of the selected ship models are presented in Fig. 3 and Fig. 4.
In Fig. 3 – 4. the curves indicated with black color correspond to the external conditions: depth of 4 m, current speed of 1 m/s, wind speed of 25 m/s; in red – depth of 6 m, current speed of 2 m/s, wind speed of 25 m/s.

For vessels of this group the limits of the values of the drift angles and the maneuvering lane width significantly depend on the water level.

Analysis of Fig. 3. – 4. as well as data on vessel projects (Table 1.) allows us to draw some important conclusions.

Figure 3. Dependence of drift angle vs true wind angle and current speeds in extreme cases.

The distribution of vessels into groups according to the criterion of the drift angle was significantly affected by the need to reduce speed in shallow water (Karetnikov et al 2019).

By comparing the data according to the criterion of the drift angle, we can conclude that the most hazardous will be the following vessels:

- the first group – project No. 613;
- the second group – project No. 15790;
- the third group – project No. 19610.

However it should be noted that with such a combination of vessels into groups, in each group the values of the maneuvering lane width vary widely (see Fig.4). This fact does not allow use the same model of the estimated vessel for simulation on the navigation simulator.

Therefore, it was decided to take the maneuvering lane width at a specific water level as a criterion for combining.

Consequently, there will be a need to regroup vessels again to reduce the gap between them. If we assume that the limiting conditions occur with the most unfavorable combinations of water level, vessel speed, current and wind speed, then two cases can be considered:

1) a) high water level; b) significant current and wind speeds;
2) a) low water level; b) low current speeds; c) significant wind speeds.
Figure 4. Dependence of maneuvering lane width vs true wind angle and current speeds in extreme cases.

The calculation results of combined drift angles and maneuvering lane width are also presented in graphical form for greater clarity. The following figures show the dependences of drift angles and maneuvering lane width for two groups of vessels that have characteristic features.

Figure 5. Dependence of drift angle vs true wind angle and current speeds in extreme cases.
In Fig. 5.–6. the curves indicated with black color correspond to the external conditions: depth of 4 m, current speed of 1 m/s, wind speed of 25 m/s; in blue – depth of 6 m, current speed of 2 m/s, wind speed of 25 m/s.

It can be seen that for vessels of this group, drift angles and maneuvering lane width are within small limits for both cases.

Generalized analysis of Fig. 3.–6. as well as data on vessel projects (Table 1.) allows us to draw some important conclusions.

4. Conclusion

The optimal criterion for combining vessels into groups is the drift angle, because it depends on external factors and on the dimensionless characteristics of the vessel (Smolentsev and Isakov 2019).

The maneuvering lane width is largely determined by the vessel dimensions and the clearances.

The criterion for assessing the vessel ability to move safely along a particular section of the waterway is the maneuvering lane width.

If the main vessel dimensions, their speeds and draughts vary significantly, it is not possible to divide all the vessels into groups for different water levels so that the error is within certain fixed limits.

If main vessel dimensions, draught and speed differ slightly, then drift angles and maneuvering lane width will be within certain limits, and hence does not matter what criterion to be used to combine groups of vessels.

Taking into account that the maneuverability lane will be affected by the vessel maneuverability, master experience of handling a specific vessel, the ability of the master to assess the vessel location and movement using the navigation marks, the maneuverability lane width can be taken as the final criterion to combine vessels into groups.
It should be noted that the estimated vessel does not have to be the largest in its dimensions, since special rules for piloting may apply to such vessels and, accordingly, special restrictions may be introduced. Along with the vessel dimensions the following criteria shall be taken into account: maneuverability, windage area, depth/draft ratio \( H/d \), breadth/draught ratio \( B/d \).

Proper approach to estimation of design vessel for navigational simulator exercises based on preliminary numerical calculations can improve performance of navigator’s qualification for work in difficult navigational conditions typical of inland waterways.

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