TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 19
Number 3
September 2025
DOI: 10.12716/1001.19.03.35

Reduction of a Push Convoy Manoeuvring Space in Inland Navigation by Drift Angle Control Using the Bow Active Rudder

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ABSTRACT: The inland vessels, barges and especially convoys are facing problems related to their manoeuvrability in restricted waters. The paper presents an auxiliary steering device significantly improving manoeuvrability and reducing the required manoeuvring space of a shallow draft inland vessels. The principle of operation of the proposed active bow rudder is based on Magnus effect - the Magnus force generated on the rotating cylinder (rotor). The presented research, based on physical model tests, confirmed the applicability of the proposed solution. The results indicate a significant improvement in the manoeuvrability of vessels and pushed convoys due to the reduction of manoeuvring space by drift angle control.

1 INTRODUCTION

Inland navigation, due to its nature, has a number of navigational limitations, including shallow water, limited width of the waterway and bridge clearance. The Classification of European Inland Waterways, applied to large European rivers that are part of the Trans-European Inland Waterway network, created by the European Conference of Ministers of Transport (ECMT) in 1992, refer to the main dimensions of maximum vessel that is able to use the waterway. The minimum air draft of bridges on the waterway, dimensions of infrastructure crossing the waterway like pipelines and locks, relate directly to the size of vessels [15]. The shallowing of inland and port waters caused by climate changes deepens the problem of operational constraints when navigating in confined waters, which in turn has a major impact on port design [7]. The power-propulsion characteristics of inland vessels should be sufficient to overcome the river current. Very good manoeuvrability is required to effectively counteract the danger of collisions with hydrotechnical structures, sandbanks or shallows, and floating objects. Due to the shallow draft and large length to breadth ratio river vessels have poor course keeping ability under lateral wind and poor turning characteristics respectively. The usual solution to this problem is a passive bow rudder or bow thruster - built into the hull or attached to the first barge in the convoy in independent floating bow. However, both solutions have their limitations.

The paper focuses on the ability of an inland unit to maintain the course, in unfavourable conditions, by drift angle control, using an active auxiliary bow steering device - the bow rotor rudder, adapted to shallow water conditions. The presented research is a continuation of the earlier numerical and experimental studies on push convoy bow steering system [1, 3].

The proposed bow rotor rudder, presented in the paper, which does not protrude beyond the ship's bottom, differs from the existing solution of “Rotor Manoeuvring System” (RMS), increasing the required under-keel clearance at the bow by 1.2 m in the operating position. Increasing course stability, RMS helps to overcome lateral wind and can partly replace

steering with a conventional rudder at speeds above 6 km/h, which results in lower ship resistance and lower fuel consumption. Originally developed in the 1980s by Van der Velden and modernised by Damen [19, 21] is now getting more popular in inland shipping on large river vessels

The analysis based on the results of the model tests, presented in the paper, have confirmed the bow rotor rudder suitability to control the drift angle. The steering force estimated from tests was lower than the determined using empirical methods. The main reasons of the loss of the lift force are flow disturbances around the rotating cylinder and vibrations at higher rotational speeds. The conclusions presented in the paper are related to the change of pivot point position during manoeuvres when using the bow rotor rudder. There is a suggestion of further experimental research in towing tank to measure the real values of forces generated on the rotor placed close to the water surface.

2 SAFE MANOEUVRING SPACE IN INLAND NAVIGATION - WATERWAY WIDTH

Several empirical methods are available to determine the safe width of inland fairways [8, 12, 13, 14]. They are tailored to the environment conditions, possible interaction effects. They are presented as a function of ship's design breadth and correction factors e.g. manoeuvring component needed to accommodate the ship's drift angle, changes of position due to the ship response to the rudder and engine settings, margins for bank suction, squat and potential errors. Additional width is required at bends related to the ship's turning radius and drift angle during the turn.

2.1 *Design width of the waterway*

The examples of the empirical methods, used in concept and preliminary design, for the determination of waterway width d, necessary for safe maneuvering, in function of the ship's breadth are the Panama Canal method [18], PIANC method [10, 12], Canadian method [6] and ASCE method [4].

Panama Canal Method [18] can be applied when using accurate navigation systems, securing the continuous positioning of the ship on the assumed trajectory [13]. The waterway width in this method is determined as follows (1):

$$d = kB + 2d_r \tag{1}$$

where:
d - waterway width [m],
k – coefficient determined experimentally,
B – ship design breadth [m],
d_r – lane width reserve [m].

Using the PIANC method (2) [13] the waterway width d can be calculated in dependence of the basic lane width, additional lane width corrections and reserves on the right and left sides of the waterway.

$$d = d_m + \sum_{i=1}^{9} d_i + d_{rz} + d_{rc} \tag{2}$$

where:
d_m – basic lane width [m],
d_i – additional lane width correction [m],
d_{rz} – right lane width reserve [m],
d_{rc} – left lane width reserve [m].

2.2 *Widening of the waterway on the bend*

The radius of curvature and width of the river bend significantly impact safety of navigation and require careful consideration when evaluating waterway suitability. High navigation risks can be expected due to increased flow-induced drift and vessel instability. A wide river with large bend radius offer better navigation conditions. Sharp bends, with R/B values below 3, are considered to pose greater risks [14].

In the Canadian method [14] used for the determination of the waterway width on a bend, the manoeuvring component on the bend d_{mz} (4) is dependent on navigation parameters of the waterway: the traffic lane width on its linear section d_m and widening of the lane on the bend Δd:

$$d_{mz} = d_m + \Delta d \tag{4}$$

where:
d_{mz} – maneuvering component of the width of the waterway on the bend [m],
d_m – maneuvering component of the waterway width on the linear section [m],
Δd – widening of the waterway on the bend [m], without taking into account hydrometeorological conditions.

Widening of the waterway on the bend and parameters used to determine the width of the safe manoeuvring area on a bend are presented in Figure 1.

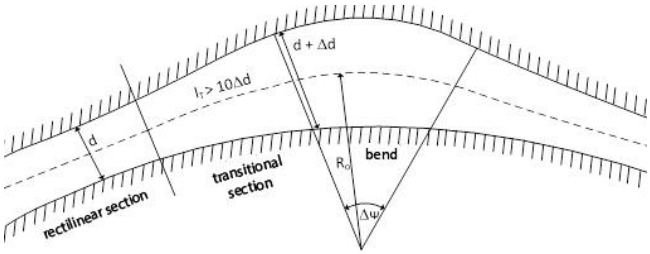

Figure 1. Determination of the width of the maneuvering area on a waterway bend.

Developed on the basis of [13].

$$\Delta d = \frac{3.4551 \cdot \Delta\psi \cdot v^2 L^2 F}{R_o K_z s} \tag{5}$$

where
$\Delta\psi$ - turning angle on a bend [°],
v - ship speed [m/s],
L - ship length [m],
F - coefficient equal to 1 - for one-way traffic, 2 - for two-way traffic,
R_o - average curvature radius on a bend [m],
K_z - ship's course keeping ability coefficient (1 - poor, 2 - good, 3 - very good),
s - minimum required visibility from the ship's bridge [m], $s \geqslant 2446$ m.

Extra width in bends, according to PIANC Report WG 141 [13], assuming quasi steady motion, when the vessel is turned by the drift angle against its course, is predicted as follows (6):

$$\Delta b_c = c_c L^2 / R_o \leq L \tag{6}$$

The parameter c_c, equal to sinβ (6), where β is the ship's drift angle, is geometrically related to the relative position of tactical turning point PP (pivot point).

$$\sin(\beta) = (c_F - 0.5) \cdot L \tag{7}$$

where:
c_F – distance between stern and PP, divided by the ship length.

c_c depends on ship draft to water depth ratio T/h, ship breadth to length ratio B/L and ship movement direction - upstream or downstream the river. It can be assumed for the single way traffic equal to 0.25 for loaded and 0.5 for empty vessels. However in practice it can be bigger or smaller e.g. in case of the use of bow thrusters [13].

For large drift angles when PP is located ahead of the bow c_F is greater than 1. The rounded values of c_c are equal to: c_c=0.5 c_F^2 for $c_F \leqslant 1$ and c_c=-0.5 for c_F>1. c_F may be reduced by about 0.1 - 0.2 in case the strong bow thruster is used [13].

The design waterway width is related to the navigation restrictions e.g. the ship's speed, mainly due to the wake wash. The propulsion-induced impacts e.g. bottom erosion from propellers at low speeds can be higher as the thrust streams are not deflected by the ship induced flow. The proposed bow rotor rudder can be used at higher speeds than bow thrusters, generating a hydrodynamic force dependent on the drift angle – with different components of drag and lift. This is very important for maintaining course and turning in the event of a strong crosswind.

2.3 *Maneuvering space of a pushed convoy in inland waterborne transport*

The essence of a push or towed barge convoys is to separate the engine room with the propulsion system from the part intended for loading. In inland waterway transport pushed convoys consisted of a pusher and a pushed barge system are much more often used than towed convoys. Compared to the towed convoy, the pushed convoy has several advantages:
- reduced water resistance in relation to the deadweight,
- fewer crew members,
- possibility of many configurations of pusher-barges sets,
- reduced building costs,
- improved maneuverability,
- reduced turning area.

The disadvantages comparing to the pushed convoy include the higher risk of collisions with structures and floating objects, touching the river bed or grounding.

Maneuvering on inland waterways can be compared to maritime navigation in confined waters, with low vessel proximity to shore or seabed. The width of the waterway is determined by the breadth and drift angle of the vessel navigating under the strong lateral wind. The drift angle depends on the following factors:
- radius of the bend,
- speed of the vessel,
- powering of the vessel, auxiliary steering devices e.g. bow thruster, bow rudder
- loading condition of the vessel,
- hydrometeorological conditions: wind parameters, water currents, turbulence, high/low water level,
- direction of the vessel movement - downstream or upstream the river,
- training measures, piloting systems and decision support systems.

The size and manoeuvring characteristics of the push convoy are the most influencing factors in determination of the required waterway with in the river bend. The maneuvering space on a waterway bend is also dependent on the method of connecting barges into a push convoy [1]. Drift angle for push convoys of different sizes being towed downstream in a 3000-foot turn (914 m) was presented in [9] and [16] (Figure 2).

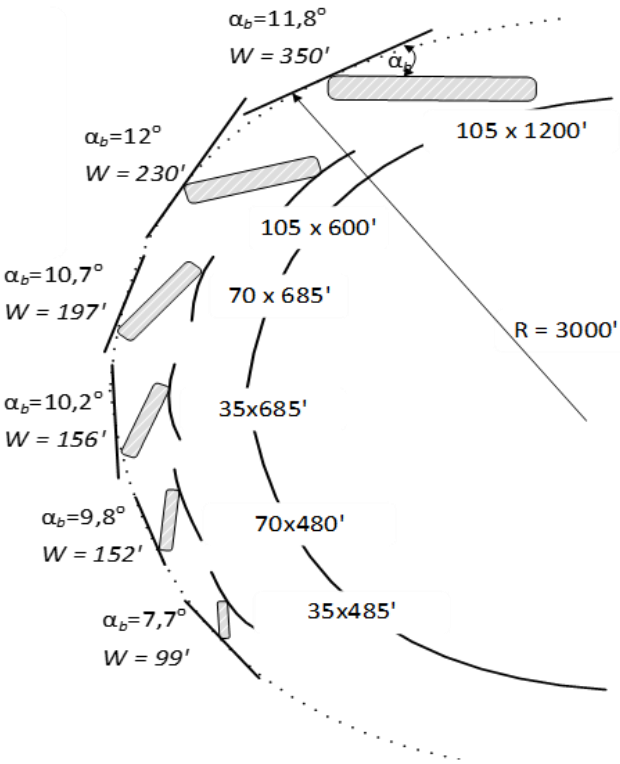

Figure 2. Drift angle for convoys of different sizes sailing downstream in a bend of 3000-foot radius R (914 m): αb - drift angle, W - channel width dependent on the convoy dimensions and drift angle. Developed based on [9] originally presented by [16].

To navigate the bends the large drift angle created by helmsman is necessary to generate the transverse component of the hydrodynamic force and yawing moment, therefore the upstream sailing convoys need smaller waterway width due to the smaller speed over ground and smaller sideways displacement, resulting with the speed multiplied by the helmsman reaction time to the drift angles.

The forces generated by a bow rudder or bow thruster installed on the barge in front of the convoy

can decrease the necessary drift angle and necessary waterway width. However, these forces are much smaller than the hydrodynamic force on the hull and they can be insufficient to decrease the required drift angle. In shallow water conditions hydrodynamic forces and necessary drift angles are larger resulting in further increase of the necessary waterway width [13]. The bow thruster force F_{BT} in dependence of sip velocity in shallow water F_{BT} and canals F_{BTC} (8) is presented in Figure 3 [13].

$$F_{BTC} = F_{BT0}\left(1 - \frac{v}{v_{0C}}\right) \tag{8}$$

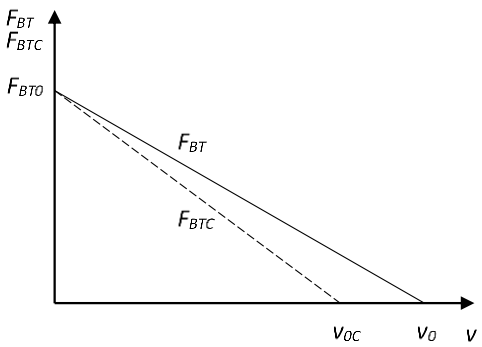

Figure 3. Bow thruster force F_{BT} in dependence of sip velocity: F_{BT0} – bow thruster force for v=0, v_0 – ship speed in shallow water where F_{BT} vanishes, v_{0C} – reduced v_0 in canals due to the return current, Developed on the basis of [13].

Using the bow rotor rudder, generating the large steering force at higher speeds, allows to decrease the necessary drift angle and the required waterway width.

3 USING THE MAGNUS EFFECT TO REDUCE THE MANOEUVRING SPACE OF THE PUSHED CONVOY

The Magnus effect is the phenomenon of generating lift force on a rotating cylinder. The theoretical value of the lift force calculated per cylinder length unit in incompressible, steady inviscid flow can be determined by Kutta-Joukowski law (9).

$$F_L = \rho \cdot (v \times \Gamma) \tag{9}$$

where:
F_L - lift force [N],
ρ - fluid density [kg/m^3],
v - relative speed of fluid [m/s],
Γ - circulation around the cylinder [m^2/s] (10):

$$\Gamma = 2\pi a^2 r \tag{10}$$

where:
a - rotor radius [m],
r - rotational speed of the cylinder [rad/s].

The lift force calculated using formula (9) is much greater than the real rotor-generated force, which is dependent on flow characteristics i.a. interaction effects, free surface effect, flow separation and edge losses.

In real conditions the lift force for the rotor fully submerged can be calculated using formula (11) [12].

$$F_L = C_L \cdot \rho \cdot v^2 \cdot a \tag{11}$$

where:
C_L(Re, α) - lift force coefficient (12) [11],

$$\alpha = ra / v \tag{12}$$

If the rotor is installed in the bow part of the shallow draft vessel, does not protrude beyond the bottom and its upper edge is close to the free surface, the actual lift force can be about ten times smaller than for the force generated by rotor of an infinite length in open water conditions [1]. However the field experiment showed that this force is large enough to compensate yawing moment generated by the stern rudder turned by 10° [3].

3.1 *Field experiments on the drift angle control using bow rotor rudder*

The field experiment was carried out on Lake Silm at the Ilawa Ship Handling Research and Training Centre [20]. The bow rotor rudder was installed on the barge bow-shaped attachment to the ship model. The experimental test setup is presented in Figure 4.

Figure 4. The experimental setup with bow rotor rudder.

The main particulars of the ship model, barge bow-shaped attachment and rotor parameters are presented in Table 1.

Table 1. Main particulars of the ship model, bow attachment and rotor.

Main particulars of ship model	
Parameter	Value
Length (m)	12.20
Breadth (m)	2.00
Draft (m)	0.64
Model scale	1:24
Bow attachment parameters	
Parameter	Value
Length LOA [m]	2.20
Breadth B [m]	2.00
Draft T [m]	0.64
Bow scale	1:24
Rotor parameters	
Parameter	Value
Height H [m]	0.60
Cylinder diameter D [m]	0.11
Screen diameter d [m]	0.19
Rotational speed r [RPM]	0-570
RC drive power [W]	1000

The program of experiments included trials with different model speeds and different bow rotor rudder rotational speeds. The measured model course, course over ground CDG and drift angle β for model speeds from 0.52 m/s to 1.08 m/s are presented in Table 2.

Table 2. Test results

Lp.	v m/s	r RPM	Course deg	COG deg	β deg
1	0.52	300	313.92	328.33	14.40
2	0.52	300	313.52	327.63	14.12
3	0.52	300	136.71	151.32	14.61
4	0.53	300	135.54	150.77	15.24
5	0.53	300	313.14	328.08	14.94
6	0.62	300	313.90	327.61	13.71
7	0.69	300	313.02	322.74	9.72
8	0.71	300	132.68	146.12	13.44
9	0.73	300	128.82	142.87	14.05
10	0.75	300	310.68	325.34	14.66
11	0.79	300	312.84	327.53	14.69
12	0.93	550	312.76	328.17	15.41
13	0.94	500	136.42	151.92	15.49
14	0.96	400	312.66	328.72	16.06
15	0.96	400	136.16	150.50	14.33
16	1.00	300	313.40	326.02	12.62
17	1.00	300	131.32	139.10	7.78
18	1.08	300	315.60	325.45	9.86

The dependence between model velocity and drift velocity are presented in Figure 5.

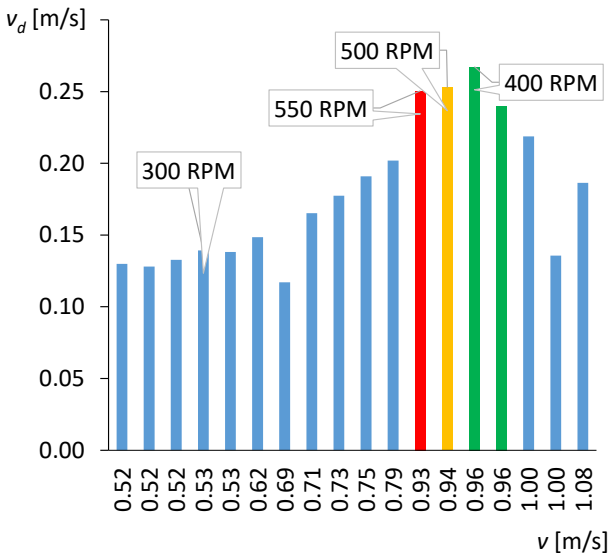

Figure 5. Drift velocity dependent on model velocity and bow rotor rudder rotational speed.

During the field experiments at 300 RPM a linear increase in the drift angle was observed from 0.52 m/s to 0.79 m/s. At higher model speeds the flow separation occurring on the rotor was the reason of drift velocity decrease. At higher rotational speeds of 400 rpm, 500 rpm, 550 rpm, an increase in drift speed of about 20% was observed, however, with this combination of rotor speed and model speed, strong rotor vibrations interrupted the experiment.

3.2 *Reduction of drift angle*

Using a bow rotor rudder when navigating inland waterways can significantly improve the maneuverability of a push-barge convoy [5]. The maneuvering space (lane width) can be reduced thanks to the ability of the convoy to move sideways in parallel, allowing to maintain a constant course. The test of maintaining a constant heading, navigating in leading lights, was conducted with the bow rotor rudder rotating clockwise at 300 rpm. The stern rudder was turned 8°–10° to portside to compensate for the bow rotor-generated yawing moment. The trajectory of the model (point at amidships) plotted during the trial is presented in Figure 6.

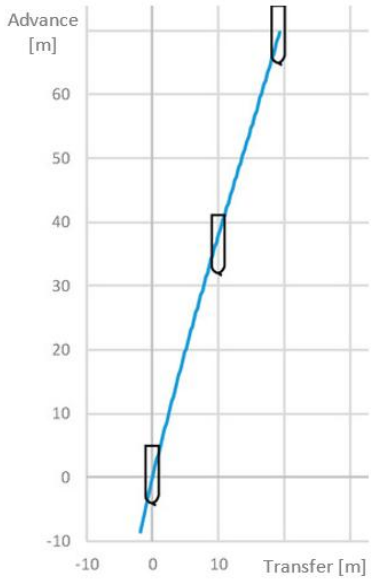

Figure 6. Model trajectory during steady course trial.

Developed on the basis of [3].

The examples of possible reduction of a push convoy manoeuvring space in inland navigation by drift angle control using the bow rotor rudder are presented in Figure 7.

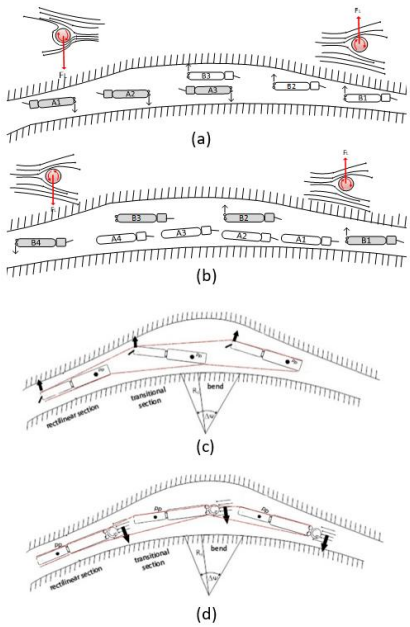

Figure 7. Examples of possible reduction of a push convoy manoeuvring space in inland navigation by drift angle control using the bow rotor rudder - manoeuvring in a river bend: (a) meeting, (b) overtaking, (c) turning with ruder only - pivot point moved ahead in the river bend, (d) turning with rotor only - pivot point moved astern.

4 CONCLUSIONS

The main factor that allows for reducing the space requirement in river navigation is the reduction of the vessel's drift angle during turning, overtaking, meeting

and passing maneuvers, because the vessel does not have to turn, but can move sideways only.

Other factors, like high or low water levels, poor visibility, poor fairway conditions, strong currents, irregular banks, ecological demands and helmsman experience - skills and stress levels, directly influence the necessary dimensions of the waterway. The direct and indirect impacts are related to the safety and ease of navigation.

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