EXPLORING THE HYDRODYNAMIC EFFECTS AT HIGH RUDDER ANGLES ON INLAND VESSELS

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SUMMARY

Studies on inland vessel manoeuvrability remain limited, making it difficult to establish trends and regression models similar to those for seagoing ships. The influence of shallow water, restricted channels, and variable water currents further complicates manoeuvring analysis. Due to lack of dedicated data, many existing studies from maritime are adapted to inland vessels despite their limitations. In particular, wake modelling, originally developed for single-propeller, single-rudder ships, is often applied to multi-propeller, multi-rudder inland vessels. However, it assumes wake variations occur solely due to vessel kinematics, overlooking confined water effects, multi-rudder asymmetries, and direct propeller-rudder interactions. This study experimentally examines rudder deflection effects on thrust and mathematically evaluates wake characteristics using a twin-propeller, quadruple-rudder (TPQR) inland ship model under varying loading conditions, speeds, rudder deflections, and water depths, including shallow water. Results show that high rudder deflections increase propulsion system thrust, reduce aft flow, and generate asymmetries in thrust and wake at lower h/T ratios between port and starboard, offering insights for refining inland vessel manoeuvring predictions.

NOMENCLATURE

DST	Development Centre for Ship Technology and Transport Systems	
TPQR	Twin-Propeller Quadruple-Rudder	
A_{R}	Lateral projected area of single rudder	m^2
B	Breadth	m
C_{B}	Block coefficient	–
D	Propeller diameter	m
h	Water depth	m
L_{PP}	Lenght between perpendiculars	m
L_{WL}	Lenght of the waterline	m
m	Blockage parameter: maximum transverse area of model ship divided by tank cross section area	–
n	Propeller revolution rate	Hz
T	Draft	m
T_{P0}	Thrust measured under neutral rudder angle ($0°$)	N
$T_{\mathrm{P}\delta}$	Thrust measured with rudders deflected at angle δ	N
u	Surge velocity during tests	m/s
w_{P0}	Wake fraction at propeller position under neutral rudder angle ($0°$)	–
$w_{\mathrm{P}\delta}$	Wake fraction at the propeller position with rudders deflected at angle δ	–
Λ_{R}	Geometric aspect ratio of the rudder	–
δ	Rudder angle (also referred to as rudder deflection)	°
λ	Scale ratio bewteen ship in model and full scale	–

1 INTRODUCTION

Understanding the interaction between the hull, rudder, and propeller, or more generally, between the hull, steering, and propulsion systems, is important for predicting and optimizing a vessel's manoeuvrability. This interplay is highly complex: the hull alters the incoming flow to both the rudder and propeller, while the propeller accelerates the wake behind the hull. In turn, the rudder not only deflects the slipstream flow but also modifies the upstream conditions experienced by the propeller. These interdependencies create a continuous feedback loop, making it challenging to isolate individual effects with simplistic assumption and theoretical models.

Most research on vessel manoeuvrability has primarily focused on seagoing ships due to the availability of extensive data and the relative form-uniformity among them, as many seagoing vessels are mass-produced. A comprehensive collection of manoeuvrability studies is documented in Sukas, Kinaci, and Bal (2019), where the majority of references pertain to seagoing or coastal vessels. As noted by Liu et al. (2017), studies on inland vessel manoeuvrability remain limited, making it difficult to establish generalised trends and regression models similar to those developed for maritime ships. However, inland vessels operate in highly constrained environments, where additional hydrodynamic effects, such as shallow water, restricted channels, and variable water currents (not to mention navigating through dense traffic, manoeuvring in confined port areas, and passing through locks) play a significant role in shaping their manoeuvring characteristics. These factors introduce complexities not typically encountered in maritime navigation, where vessels are primarily designed with other priorities in mind, such as seakeeping and stability in waves and wind in open waters, making manoeuvrability a less critical aspect.

Due to this data gap, many of the existing theories, formulations, and assumptions used to predict inland vessel manoeuvrability are derived from maritime studies and extrapolated to inland navigation to compensate for the lack of dedicated data. An example of this approach is the work of Liu et al. (2017), in which several existing methods developed for seagoing ships were combined and compared to identify the most suitable one for application to inland vessels. While this approach provides a basis for manoeuvring predictions, its accuracy and applicability to inland vessels remain an open question, particularly when considering the hydrodynamic complexities of confined waterways.

In particular, wake modelling in manoeuvring simulations, initially formulated for single-propeller single-rudder ships, as reported in Hirano (1980), has been adopted for twin-propeller, twin-rudder inland vessels (Liu et al. 2017). These models assume that wake variations occur solely due to the vessel's kinematics (e.g., drift and yaw), without accounting for asymmetries in multiple-rudder, multiple-propeller configurations, which are common in inland navigation. Moreover, direct propeller-rudder interactions are not explicitly modeled but are instead incorporated indirectly through rudder interaction coefficients, commonly referred to as steering resistance deduction factors (Yasukawa and Yoshimura 2015; *Report of Research committee on standardization of mathematical model for ship maneuvering predictions [P-29]* 2012), rather than being represented as an explicit change in wake characteristics. Additionally, these models were developed under deep-water assumptions, further limiting their applicability to inland vessels, where shallow water effects significantly alter hydrodynamic interactions.

With this in mind, this study provides a foundation for refining wake modelling in the manoeuvring of inland vessels by incorporating the influence of rudder deflection angles, with the aim of encouraging a reassessment, re-evaluation, and rethinking of the traditional approach used in maritime, fostering the exploration of new methodologies better suited to inland navigation. Specifically, it investigates how rudder deflections influence the thrust, and therefore the wake, generated by the propulsion system of an inland vessel in straight-moving conditions across various scenarios, including shallow water. To analyse these effects, an experimental campaign was conducted on a ship model equipped with two ducted propellers and four rudders (TPQR), representing a typical large inland vessel operating on the Rhine. The tests covered a wide range of conditions, including different loading conditions, water depths, speeds, and rudder deflections from $0°$ to $58°$.

2 EXPERIMENTAL CAMPAIGN

The experimental campaign aimed to gather data on propulsion system thrust under varying loading conditions, water depths, speeds, and rudder angles during steady-straight motion. Tests were conducted in the large shallow water tank at DST (Development Centre for Ship Technology and Transport Systems) in Duisburg, Germany. This facility is approximately 200 m long and 10 m wide, with a continuously adjustable water depth ranging from 0 to 1200 mm. This adjustability ensures that the water depths in the model tests are scaled appropriately, fully accounting for the effects of limited water depth.

2.1 SAMPLE INLAND MODEL

The experimental evaluation used a twin-propeller quadruple-rudder (TPQR) ship model, representing a CEMT Class Va vessel operating on the Rhine. The stern design, as depicted in Figure 1, includes a flow-separation plate at the stern, two ducted propellers positioned at the end of the propeller tunnels, and four Schilling-type (fish-tail) rudders arranged in pairs behind each propeller at the edge of the propeller disk. Each rudder is equipped with an end plate at the root and is positioned close to the flow-separation plate at the tip to minimize tip vortices. Two loading cases were considered, including full and reduced draught scenarios in an even keel configuration. In both cases, the flow-separation plate, the propulsion system and rudders remained fully submerged. Table 1 summarises the primary dimensions of the ship model, where L_{WL} is the length of the waterline, T is the draft, C_{B} is the block coefficient, L_{PP} is the length between perpendiculars, B is the breadth, A_{R} is the lateral projected area of single rudder, Λ_{R} is the geometric aspect ratio of the rudder, and D is the propeller diameter. The scale ratio λ between the model and the full-scale ship is 11.

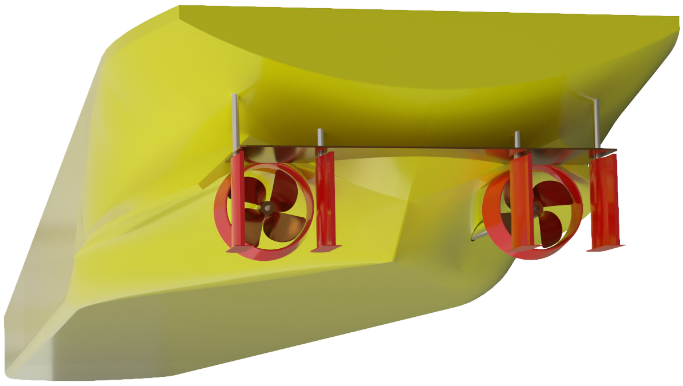

Figure 1: Rendered stern view of the studied inland vessel, featuring a flow-separation plate, two ducted propellers, and four Schilling-type rudders.

Table 1: Main data in model (MS) and full scale (FS). The scale ratio λ between the model and the full-scale ship is 11.

		L_{WL} [m]	T [m]	C_B [-]	L_{PP} [m]	B [m]	A_R [m^2]	Λ_R [-]	D [m]
Full draught	MS	9.935	0.255	0.901	10.000	1.036	0.0196	1.256	0.145
	FS	109.29	2.800	0.901	110.00	11.40	2.372	1.256	1.600
Reduced draught	MS	9.813	0.182	0.887	10.000	1.036	0.0196	1.256	0.145
	FS	107.94	2.000	0.887	110.00	11.40	2.372	1.256	1.600

2.2 TEST CAMPAIGN

2.2.1 Test conditions

The tests were conducted under four different combinations of two loading conditions (full and reduced draught) in even keel configurations and three water depths. This approach enabled a detailed analysis of the results, examining both the influence of changing water depth under the same loading condition and the impact of different loading conditions at the same water depth. Table 2 summarises in model scale the loading configurations, the water depths, the speeds and the rudder angles tested, where h represents the water depth, m is the blockage parameter defined as the ratio between the maximum transverse area of the ship model and the tank cross section area, u is the surge velocity and δ is the rudder deflections (to portside). The loading condition is represented here by the draught of the ship.

Table 2: Matrix of the test campaign in model scale (scale 1:11).

$\downarrow T$ [m] | h [m] $\rightarrow$	0.682	0.318	0.227
0.255 (even keel)	✓($h/T = 2.67;\ m = 0.039$) $\delta = 0, 20, 40, 58$ ° * $u = 0.670, 0.838, 1.005,$ $1.173, 1.339$ m/s	✓($h/T = 1.25;\ m = 0.083$) $\delta = 0, 20, 40, 58$ ° * $u = 0.670, 0.838$ m/s	
0.182 (even keel)		✓($h/T = 1.75;\ m = 0.059$) $\delta = 0, 20, 40, 58$ ° * $u = 0.670, 0.838, 1.005$ m/s	✓($h/T = 1.25;\ m = 0.083$) $\delta = 0, 20, 40, 58$ ° * $u = 0.670, 0.752, 0.838$ m/s

* The rudder angles provided are purely indicative of the test conditions and follow the applied control logic reported in Figure 2.

The study employed a specific rudder kinematic approach used in inland waterway vessels, where the innermost rudder, referring to the rudder that would be closest to the centre of rotation during a steady circular motion, deflect more. In a manoeuvre where the rudders turn to port, the innermost port rudder rotates the most. Conversely, in a manoeuvre where the rudders turn to starboard, the innermost starboard rudder experiences the greatest deflection, while the others follow the standard control logic. Figure 2 illustrates the rudder angles used in the tests. In this case, the extreme port rudder rotated to $22°$, $46°$, and $78°$, while the other rudders followed with deflections of $20°$, $40°$, and $58°$, respectively. These values were derived from the rudder kinematics of a European inland container vessel. Therefore, the rudder angles shown in Table 2 are representative of the test conditions rather than fixed values.

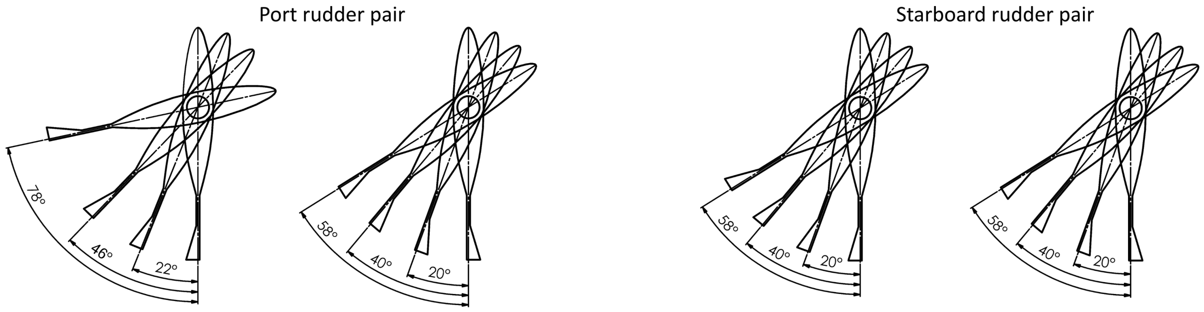

Figure 2: Schematic representation of the rudder kinematic logic used in the tests for port deflections.

2.2.2 Type of tests

The campaign included self-propulsion tests conducted with rudders and propulsion tests with deflected rudders in straight moving. All tests were conducted in accordance with ITTC procedures at varying conditions. Table 2 summarises the loading configurations, the water depth, the speeds and rudder deflections tested for each type of test. In advance of the captive model tests, propeller open water tests were carried out.

The self-propulsion tests were performed with the model in a configuration with rudders in a neutral position, defined as $0°$, where the rudders are parallel to the ship's centreline. Here the self-propulsion point of the ship at model scale was determined by applying the thrust deduction force. The propulsion tests with deflected rudders in straight moving were conducted to measure the thrust of the propulsion system at different rudder angles. During these tests, the model was positioned in the basin and towed by the carriage to have no sway. In each combination of water depth, loading conditon and speed, the same propeller rates of the ship self-propulsion points determined with neutral rudders were maintained. Rudder deflection angles of $20°$ and $40°$ and $58°$ to the port side were tested[1]. The propeller open-water characteristics were used to determine the wake fractions for each condition using the thrust identity method, which is based on the measured propeller thrust.

All measurements were taken under steady-state conditions. After an initial transient phase, the model moved in a steady motion with the carriage before measurements were recorded.

2.3 SHIP MODEL SETUP

The experimental campaign employed a series of high-precision instruments to measure hydrodynamic forces and propellers' performance under different conditions. A load cell recorded the longitudinal force acting on the hull to get the ship self-propulsion point via the British method. Propeller performances were assessed using high-precision dynamometers mounted on each propeller shaft, measuring both thrust and torque (though torque was not used in this analysis). Additional thrust from the ducts was measured with dedicated thrust sensors. Two engines ensured that the propellers maintained the desired rotational speeds throughout the tests. Rudder deflections were controlled using high-precision rotary encoders, ensuring accurate and repeatable angles. Lastly, the towing carriage provided precise speed control, ensuring consistent velocities across all tests.

3 RESULTS AND DISCUSSION

In the experimental campaign, ship self-propulsion tests were conducted with rudders in a neutral position, as well as propulsion tests in straight moving with deflected rudders under different operating conditions. The objective of the campaign was to measure the thrust of the propulsion system across all aforementioned scenarios. For the tests with rudders in a neutral position, the ship self-propulsion point was determined, defined as the propeller rotational speed that, in full scale, would generate the required thrust for the vessel to maintain the desired speed in straight ahead motion. In tests with deflected rudders, the previously determined self-propulsion point was maintained for the same operating condition.

The thrust results are presented as the ratio of the thrust with deflected rudders to the thrust in the neutral rudder condition for the same operating scenario, illustrated in Figure 3. Each subfigure represents a different combination of water depth and loading condition. Additionally, the thrust values for the port and starboard sides are considered separately to account for potential asymmetries in the flow and rudder-propeller interactions. It should be noted that all rudder deflections occur to port side.

[1] These angles are representative of the applied control logic rather than fixed values. For further details, refer to Section 2.2.1 and Figure 2.

Subsequently, using the thrust identity method and open-water propeller characteristics, the wake fractions for each condition listed in Table 2 were determined for port and starboard sides. These are presented in Figure 4 as the ratio of the complement of the wake fraction $(1 - w)$ with deflected rudders to the complement of the wake fraction in neutral rudders for the same operating scenario. Each subfigure represents a different combination of water depth and loading condition. It is important to note that the thrust identity method allows for the determination of an effective wake factor, assuming that the characteristics of the propulsion system remain unchanged between the open-water condition with homogeneous inflow and the behind-hull condition, where the propeller is influenced by the stern, rudders, and confined waters. At this stage, this principle has been used as the basis for obtaining the parameter. More precisely, the wakes calculated in this manner implicitly account for variations in the behavior of the propulsion system under non-open-water conditions.

In this analysis, a parametric approach is considered, where surge velocity u and propeller rotation rate n vary together. However, thrust and wake exhibit different degrees of dependency on these parameters. Given this, the focus is placed on evaluating the effects of rudder angles at the self-propulsion points.

For a smoother interpretation, reference is made to the representative values of the rudder deflection logic, i.e., $20°$, $40°$, and $58°$. See Section 2.2.1 and Figure 2 for further details.

3.1 THRUST ANALYSIS

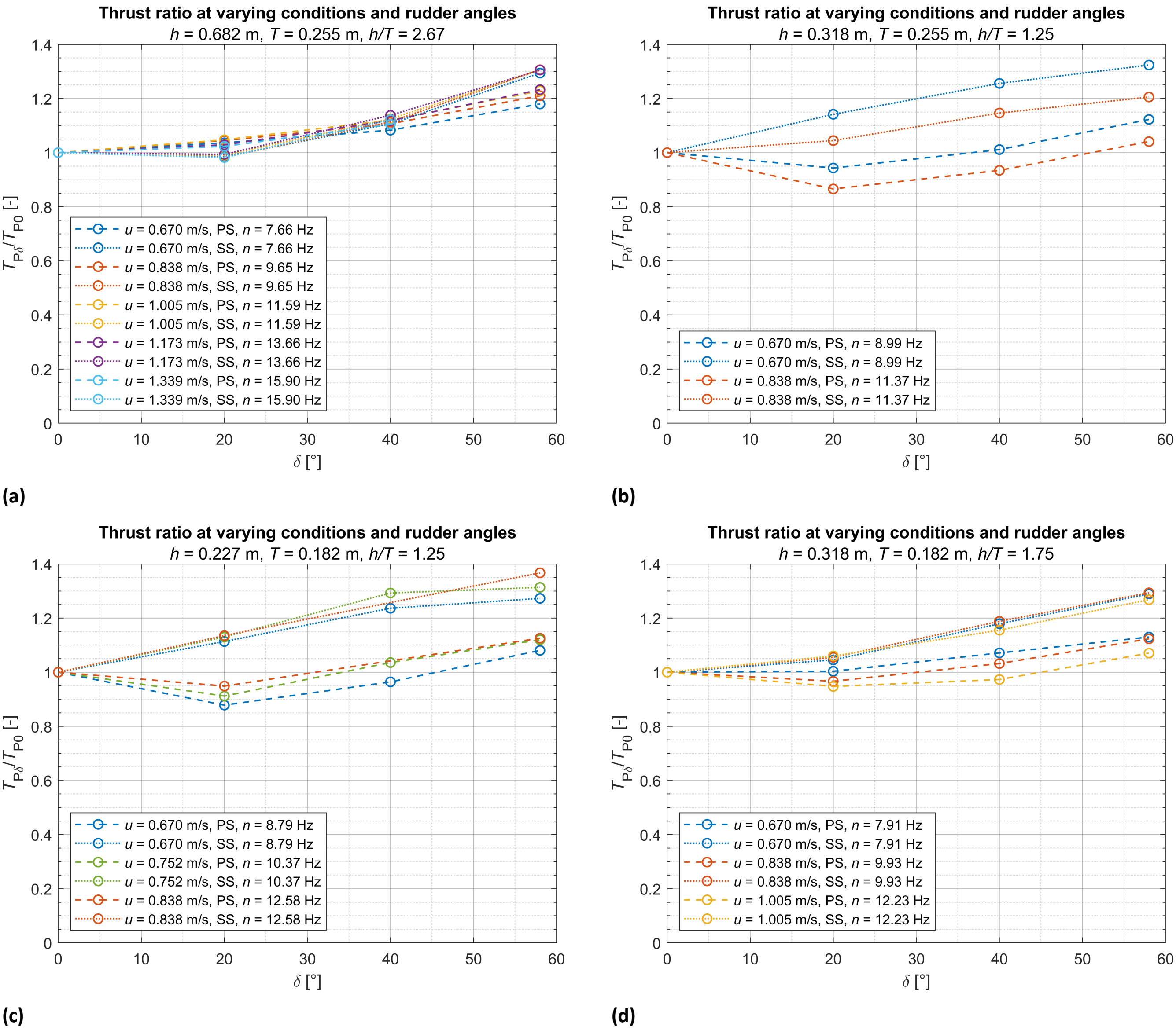

Figure 3: Ratio of thrust with deflected rudders to thrust in the neutral rudders angle across various loading conditions, water depths, and speeds. Port (PS) and starboard (SS) ratios are shown separately. Rudder deflections are toward the port side.

In Figure 3, the thrust ratio $T_{P\delta}/T_{P0}$, i.e., the thrust at deflected rudders with respect to the thrust with neutral rudders, is primarily influenced by the overall h/T ratio rather than by the individual values of h and T. This is evidenced by the fact that subfigures (b) and (c) exhibit very similar behavior, while subfigure (d) shows an intermediate trend between subfigure (a) and subfigures (b) and (c). The thrust ratio between the port and starboard sides becomes increasingly asymmetric as h/T decreases, whereas for higher ratios of h/T these asymmetries are reduced. The velocity, together with the corresponding self-propulsion point, plays a more significant role in terms of thrust variation at low h/T ratios. A more detailed analysis of these aspects is provided below.

3.1.1 Condition $h/T = 2.67$

In this condition, the asymmetries between the port and starboard sides are not very pronounced. The thrust ratio increases with higher rudder deflections on both the port and starboard sides, except for an initial plateau in the starboard propulsion system up to $\delta = 20^\circ$. Similar CFD results were found by Guo and Zou (2021), where a twin-propeller, twin-rudder vessel, with rudders positioned off-centre relative to the propeller disk, was tested in straight motion at various rudder angles up to 30° in deep water. At a rudder angle of 58°, the thrust ratio reaches a maximum of approximately 1.30 on the starboard side and around 1.25 on the port side. This difference may be also attributed to the asymmetry of the rudders deflection kinematic. The speed parameter has a minor influence on the thrust ratio, leading only to small variations up to $5\,\%$ on portside, within the tested range, at the highest rudder angles without significantly altering the overall trend.

3.1.2 Condition $h/T = 1.75$

In this condition, the asymmetries between the port and starboard sides are more pronounced, than in the previous condition. The thrust ratio on the starboard side constantly increases with higher rudder deflections, whereas the thrust ratio on the port side initially decreases before increasing again at higher deflection angles. The starboard thrust ratio is consistently higher than the port thrust ratio, reaching a maximum of approximately 1.30 at $\delta = 58^\circ$, while the port thrust ratio reaches a maximum of approximately 1.15, among the considered scenarios. Velocity plays a more significant role in varying the thrust ratio on the port side, causing variations from $5\,\%$ to approximately $10\,\%$ within the tested range, while its influence remains negligible for the starboard propulsion system.

Notably, higher velocities lead to lower thrust ratio on the port side.

3.1.3 Condition $h/T = 1.25$

Considering both scenarios with $h/T = 1.25$, the thrust ratio on the starboard side constantly increases with higher rudder deflections, whereas the thrust ratio on the port side initially decreases before increasing again at higher deflection angles, more pronounced than in the previous condition. The starboard thrust ratio is consistently higher than the port thrust ratio, reaching a maximum of approximately 1.35 at $\delta = 58^\circ$, while the port thrust ratio reaches a maximum of approximately 1.10, among the considered scenarios. In this case, velocity plays a significant role for both the port and starboard thrust ratio, causing variations that can reach approximately $10\,\%$ for both within the tested range.

Notably, at higher velocities, the thrust ratio decreases on both the port and starboard sides for the condition of T = 0.255 m (subfigure b), whereas the opposite occurs in the condition T = 0.182 m (subfigure c).

3.2 WAKE ANALYSIS

From Figure 4, it can be observed that the behavior of the wake ratio $(1 - w_{P\delta})/(1 - w_{P0})$ inversely reflects the thrust ratio trends shown in Figure 3. This is also one direct consequence of the method used to derive the wake fractions. Nevertheless, the resulting ratios provide valuable insights for evaluating the propeller inflow under different operating conditions at different rudder angles.

It is noted that, in all the scenarios tested, the wake ratio reaches a minimum at the highest rudder deflections. The starboard side exhibits a more pronounced decrease in wake ratio at lower h/T ratios compared to the port side. The velocity, together with the corresponding self-propulsion point, plays a more significant role in terms of wake variation at low h/T ratios. Additionally, the rudder angle has different effects depending on the h/T ratio. A more detailed analysis of these aspects is provided below.

3.2.1 Condition $h/T = 2.67$

The wake ratio varies smoothly and almost symmetrically between the port and starboard sides. However, it decreases with higher rudder deflections on both the port and starboard sides, except for an initial plateau in the starboard propulsion system up to $\delta = 20^\circ$. This may suggest that the flow is being slowed down. In this case, the rudders might act as a barrier that

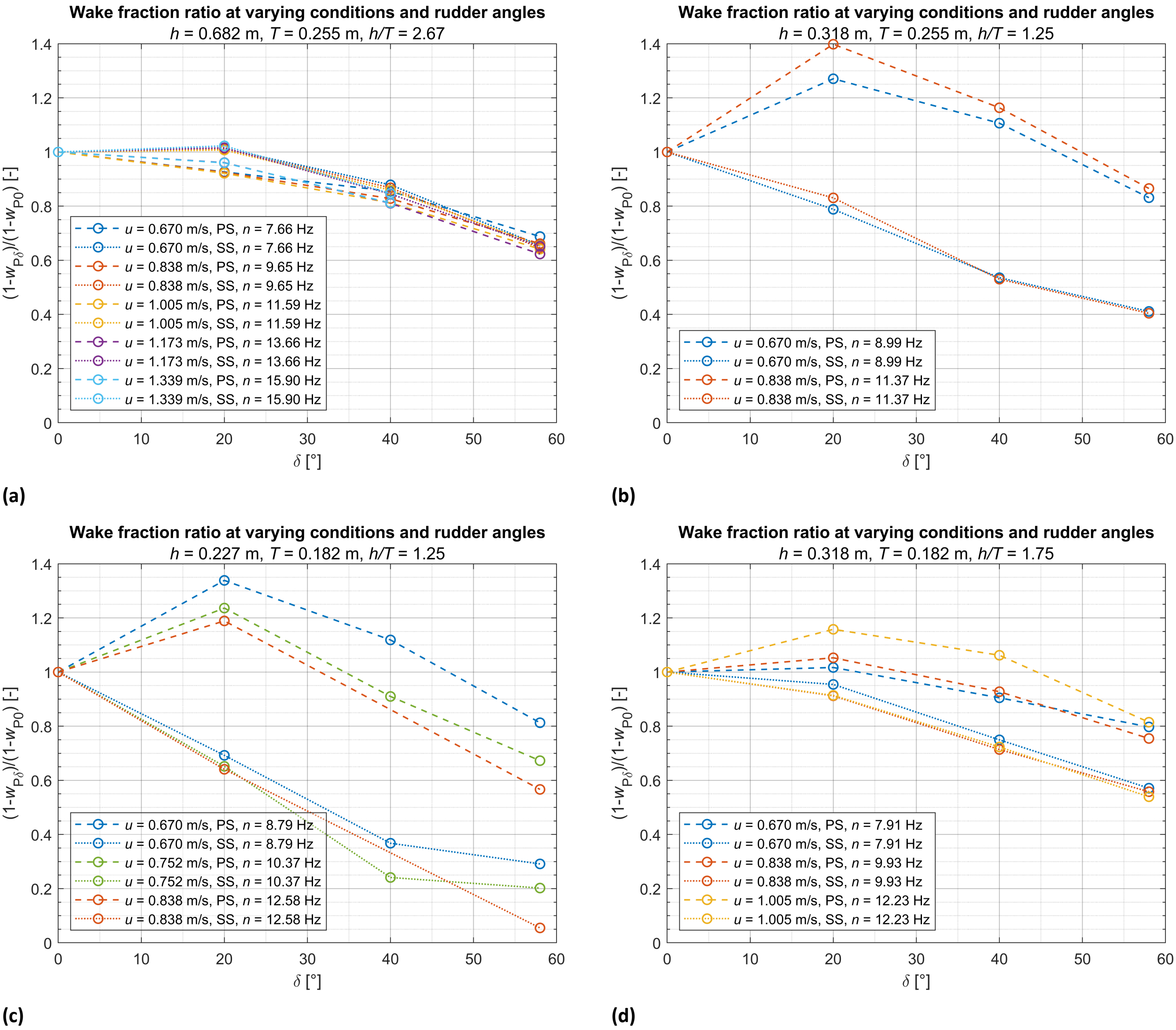

Figure 4: **Ratio of the complement of the wake fraction with deflected rudders to the complement of the wake fraction in the neutral rudders angle across various loading conditions, water depths, and speeds. Port (PS) and starboard (SS) ratios are shown separately. Rudder deflections are toward the port side.**

obstructs the passage of the flow, creating a sort of blockage effect. Nevertheless, the flow remains free to pass beneath, through and along the sides of the rudders. At a rudder angle of 58°, the wake ratio reaches a minimum of approximately 0.65 on both port and starboard side. The speed parameter has a minor influence on the thrust ratio, leading only to small variations.

3.2.2 Condition $h/T = 1.75$

In this condition, asymmetries emerge between the port and starboard ratios, falling between the cases with $h/T = 2.67$ and $h/T = 1.25$. The wake ratio on the starboard side constantly decreases with higher rudder deflections, whereas the wake ratio on the port side initially increases before decreasing again at higher deflection angles. The starboard ratio is consistently lower than the port ratio, reaching a minimum of approximately 0.55, while the port ratio reaches a minimum of approximately 0.80 at $\delta = 58^{\circ}$, among the considered scenarios. Velocity plays a more significant role in the propulsion system on the port side, causing variations of up to approximately $15\,\%$ within the tested range, while its influence remains negligible for the starboard propulsion system. Notably, higher velocities lead to higher wake ratio on the port side, suggesting a reduced blockage effect, with reference to the same scenario, but lower velocities.

The difference between the port and starboard sides indicates that shallow water effects cannot be neglected. Considering that the rudder deflections occur to the port side, it appears that the port side propulsion system benefits from the rudder deflection in that direction, experiencing less flow reduction. However, a more detailed analysis of the flow dynamics is needed to fully understand the differences in behavior between the port and starboard sides. The smaller clearence between bottom of the basin and rudders may prevent the flow from passing directly beneath the rudders, potentially forcing it to seek escape routes through and along the sides instead.

3.2.3 Condition $h/T = 1.25$

The wake ratio on the starboard side consistently decreases with higher rudder deflections, whereas on the port side, it initially increases before decreasing again at higher deflection angles, a trend more pronounced than in the previous condition. The starboard wake ratio remains consistently lower than the port ratio, reaching minimum values that vary with speed, ranging approximately between 0.30 and 0.05 for the condition with T = 0.182 m and around 0.40 for the condition with T = 0.255 m, at $\delta = 58^\circ$ among the considered scenarios. Conversely, the port wake ratio reaches minimum values ranging between approximately 0.85 and 0.55 for T = 0.182 m and around 0.85 for $T = 0.255$ m at $\delta = 58^\circ$ among the considered scenarios.

For the case of T = 0.182 m (subfigure c), velocity plays a significant role for both the port and starboard propulsion systems, causing variations of up to approximately $25\,\%$ within the tested range. For the case of T = 0.255 m (subfigure b), velocity influences the port side, causing variations of up to about $15\,\%$, while its effect remains negligible on the starboard side. Despite the impact on thrust, the wake exhibits a nonlinear relationship with thrust, as described by the thrust identity method.

As explained in the previous condition, the difference between the port and starboard sides indicates that shallow water effects and speeds dependence cannot be neglected.

4 CONCLUSION

Studies of inland vessel manoeuvrability have remained limited, with many mathematical models and approaches derived from the maritime field, despite the significant differences between seagoing and inland vessels, not only in terms of design but also in terms of the environment in which they sail. In particular, wake modelling in manoeuvring simulations has been developed for single-propeller, single-rudder ships in deep water. The formulations assumes that wake variations occur solely due to the vessel's kinematics (drift and yaw). Direct propeller-rudder interactions are not explicitly modeled but are instead partly incorporated indirectly through rudder interaction coefficients rather than being represented as an explicit change in wake characteristics. Multi-rudder and multi-propeller configurations, typical of inland vessels, require a more tailored approach to account for asymmetries between port and starboard sides, especially in confined waters and at different speeds.

Starting from the evidence of this missing link, this study has investigated the effects of rudder deflection angle on thrust and wake field under different scenarios, including varying speeds, loading conditions, and water depths, particularly considering shallow water effects. By means of an experimental campaign on an inland model ship equipped with two ducted propellers and four rudders, thrust measurements were collected, and the wake fractions were identified through the thrust identity method. Results have been provided in the form of the thrust ratio between the thrust with deflected rudders and the thrust in the neutral rudder condition, and the wake ratio, defined as the ratio of the complement of the wake fraction $(1 - w)$ with deflected rudders to the complement of the wake fraction with neutral rudders, depending on the scenario.

Key findings indicate that high rudder deflections lead to increased thrust and reduced flow, with notable asymmetries between the port and starboard sides becoming more pronounced as the h/T ratio decreases and speed varies. Specifically, at a rudder deflection of 58°, the thrust ratio reaches approximately 1.30 on the starboard side and around 1.25 on the port side in deeper water conditions ($h/T = 2.67$). However, in shallower conditions ($h/T = 1.25$), the starboard thrust ratio reaches 1.35, whereas the port side remains lower at approximately 1.10. Additionally, wake ratios exhibit a significant reduction at high rudder angles of 58°, decreasing to approximately 0.65 at $h/T = 2.67$ for both port and starboard sides, and dropping as low as 0.05 at $h/T = 1.25$, while the port side follows a less pronounced decline. Speed plays a significant role in these interactions, particularly at lower h/T ratios. It can change thrust ratio up to about $10\,\%$ and the wake ratio up to about $25\,\%$, depending on the scenario.

By introducing the wake ratio parameter, it becomes possible to account for asymmetry between the port and starboard propulsion systems due to rudder deflections during manoeuvring, even in shallow water. However, to effectively integrate this parameter into current manoeuvring prediction models, a new modelling approach is required. In existing manoeuvring models, the mutual influence between the rudder and propellers is partially incorporated through rudder interaction coefficients, commonly referred to as steering resistance deduction factors. These models, however, were developed under deep-water assumptions for single-propeller, single-rudder seagoing ships, thereby neglecting the potential asymmetry between port and starboard steering and propulsion systems (Yasukawa and Yoshimura 2015; *Report of Research committee on standardization of mathematical model for ship maneuvering predictions [P-29]* 2012). Recent developments have attempted to account for asymmetry in multiple-propeller and multiple-rudder configurations. Nevertheless, the lack of sufficient data and reliable methods for estimating the behavior of port and starboard interactions often leads to the assumption of symmetry between the two sides, as done, for example, by Liu et al. (2017).

The present study highlights the need to reassess traditional maritime-derived approaches and promote the development of methodologies that better account for the differences between inland and seagoing vessels and environments. As Richard Feynman described in *The Feynman Lectures on Physics (Vol. 1, Chapter 2)*, science progresses by approximating reality, continuously refining its models to enhance understanding.

As a future development, it would be beneficial to experiment with various inland vessel configurations, ranging from single-propeller, single-rudder designs to multi-propeller, multi-rudder setups, while considering shallow water effects. This would provide a more comprehensive understanding of the variations in thrust and wake under these conditions. Additionally, the development of a new mathematical modeling framework is essential to properly integrate the updated wake modeling. Future studies should also focus on further refining the interactions between the hull, propeller, and rudder, specifically tailored to inland vessels and the unique environmental constraints in which they operate.

5 ACKNOWLEDGEMENTS

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7 AUTHORS BIOGRAPHY

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