

# Experimental Validation of Rudder Representation in Reduced-scale Physical Model Tests

R. de Oliveira Bezerra & J.C. de Melo Bernardino

*University of Sao Paulo, Sao Paulo, Brazil*

**ABSTRACT:** Froude-based reduced-scale modelling of port areas is widely used to assess manoeuvring safety, including passing ship effects, confined navigation, and berthing operations. For reliable results, ship models must reproduce full-scale displacement responses to rudder inputs, particularly for turning performance. Variations in rudder geometry influence flow patterns and the resulting hydrodynamic forces that govern manoeuvrability. This study experimentally investigates the impact of rudder shape and aspect ratio on manoeuvring performance by testing eighteen NACA rudder profiles with a free-running scale model. Standard manoeuvring tests, such as turning circle trials, were conducted. The results revealed that strict geometric scaling of the rudder leads to significant discrepancies in model behaviour, while modifications to rudder geometry improve dynamic similarity. This research provides practical data showing how rudder design adjustments affect manoeuvring responses and highlights that adapting rudder geometry for scale models is an effective strategy to enhance the similarity between model and prototype ship behaviour.

## 1 INTRODUCTION

The design and safe operation of port areas depend on an accurate understanding of ship manoeuvrability. As maritime traffic continues to grow [9] and port environments become more constrained, the ability to predict ship behaviour in complex navigation scenarios becomes increasingly critical. Reduced-scale physical modelling, based on Froude similitude, remains one of the most reliable and widely adopted techniques for evaluating manoeuvring performance in port planning and design [1]. These models support assessments of passing ship effects [5], confined water navigation [4], mooring line dynamics [2], and berthing or unberthing operations.

To ensure the validity of these simulations, it is essential that the displacement response of the ship model to rudder inputs closely replicates that of the

full-scale vessel. Guidelines such as those from the IMO [7] provide recommendations for the physical representation of ships in model tests. Validating the model's response typically involves conducting standardized manoeuvring trials—such as turning circle, zig-zag, and stopping tests—whose results should closely match those observed in the prototype. This validation approach is widely adopted and applied not only in physical model testing but also in computational simulations [6,8].

Although Froude scaling ensures similarity in gravitational and inertial forces between a model and its full-scale counterpart, it does not capture all hydrodynamic effects—particularly those related to viscosity. In physical modelling, rudders are typically constructed by applying a geometric scale reduction of the full-size design. However, this approach can lead to discrepancies in manoeuvring behaviour, especially

in free-running tests intended to replicate realistic ship movements. These inconsistencies arise because the scaled rudder may not generate forces in proportion to those of the prototype. One way to mitigate this issue, as demonstrated in previous computational studies, is by adjusting the rudder's shape and aspect ratio—key factors that significantly influence the hydrodynamic forces acting on the ship [6,8]

This study aims to contribute to this field by presenting a comprehensive experimental investigation into the effects of rudder shape and aspect ratio on the manoeuvrability of a free-running ship model. Eighteen different rudder configurations derived from the NACA series were tested under controlled conditions. Standard manoeuvring trials, such as turning circle tests, were used to evaluate dynamic responses.

The main objective is to assess whether adjustments to rudder geometry can improve the similarity of manoeuvring behaviour between the model and the prototype. By identifying configurations that yield more accurate displacement responses, this research seeks to provide practical guidelines for rudder design in physical models. Ultimately, enhancing the fidelity of rudder representation in scale models contributes to more reliable simulations of ship behaviour, better-informed engineering decisions, and safer port operations.

## 2 MATERIAL AND METHODS

### 2.1 Model Tank and Test Setup

The tests were conducted in a model tank located at the University of Sao Paulo (USP), Brazil. This model is 40 meters long, 18 meters wide and 1.2 meters deep (Figure 1). To simulate deep-water conditions and avoid bottom interference during manoeuvring trials, the water level was set at 1 meter.



Figure 1. Physical model at the USP used for reduced-scale manoeuvring tests.

To track the ship's position over time, a set of four overhead cameras was installed along the tank at a height of 10 meters, covering the entire testing area. The system uses bottom-mounted reference markers and correlates pixel positions to real-world coordinates. This tracking algorithm was developed by USP and has been applied in various experimental studies over the years [1,3,5]. The system provides a

spatial resolution of 0.1 meters and operates at a sampling frequency of 30 Hz.

All tests were conducted in still water and inside a closed environment, ensuring that external factors (like wind) did not influence the results.

### 2.2 Ship Model Description

The scale model represents a VLOC (Very Large Ore Carrier) with a capacity of 400,000 DWT, built at a non-distorted geometric scale of 1:170, in accordance with Froude similitude criteria. Table 1 presents the main geometric dimensions of both the prototype and the scale model.

Table 1. Main geometric characteristics of the prototype and the scale model of the VLOC (Very Large Ore Carrier).

| VLOC    | Prototype (m) | Scale Model (m) |
|---------|---------------|-----------------|
| LOA     | 362.00        | 2.13            |
| LPP     | 350.00        | 2.06            |
| Breadth | 65.00         | 0.38            |
| Depth   | 30.40         | 0.18            |
| Draft   | 23.00         | 0.13            |

The ship model was built in fiberglass, faithfully reproducing the lines of the full-scale vessel at the corresponding scale. Figure 2 shows the body plan of the prototype alongside an image of the constructed scale model. The weight distribution was carefully adjusted to ensure that the center of mass and moments of inertia were properly calibrated. As a result, the model's behavior in water accurately corresponds to that of the full-scale ship.



Figure 2. Body plan of the full-scale ship (left) and the corresponding scale model built in fiberglass (right).

The propulsion system consists of a DC motor connected to a scaled propeller, controlled by a PWM system that regulates speed while maintaining torque. All velocity settings were based on the sea trial report of the full-scale ship, ensuring that each propulsion stage drives the model at the corresponding scaled velocity. Rudder control is provided by a servomotor connected to the rudder's rotation axis through a gear mechanism. Each rudder is mounted with the same standardized axis to allow easy interchangeability during tests. Communication between the computer and the ship is established via a radio frequency transmitter, and commands are issued using a joystick. This system is described in greater detail in [1].

### 2.3 Rudder Configurations

Two geometric variables of the rudder were tested: the thickness profile, defined by different NACA airfoil sections, and the aspect ratio, a parameter representing the ratio between the rudder's span (height) and chord (width). All rudders used in the tests were of the spade type, with a fixed height of 16.3 meters in the prototype (corresponding to 9.6 cm in the scale model). This

height was maintained to reflect the dimensions of the reference ship, as increasing it could render the rudder ineffective in shallow water conditions. Therefore, variations were applied only to the profile shape and width, ensuring compatibility with port operational constraints.

Figure 3 presents an example of a rudder design, illustrating the key variables used to define the geometric variations tested in this study. Based on these parameters, a total of 18 rudders were produced using 3D printing technology: one corresponding to the geometric scale of the prototype and 17 others representing variations in thickness profile and aspect ratio. All rudders were scaled to match the model dimensions. Table 2 summarizes the values of each geometric variable of the rudders used in the tests, presented in millimeters.

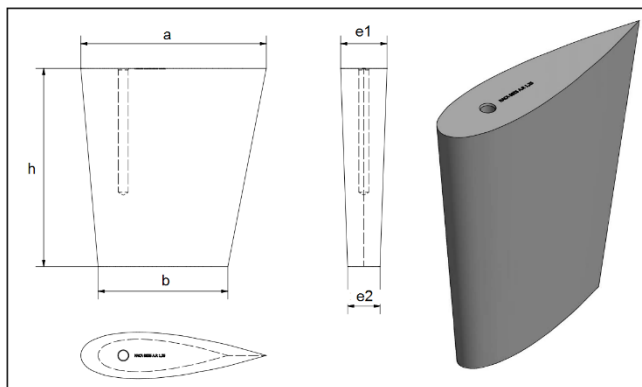


Figure 3. Illustration of the rudder geometry, highlighting the variables considered in the study: thickness profile (NACA series) and aspect ratio (span-to-chord ratio).

Table 2. Geometric parameters of the 18 rudder configurations tested, including chord length, thickness (based on NACA profiles), and aspect ratio, in millimeters.

| N° | Profile | Aspect Ratio | a     | B     | e1    | e2    |
|----|---------|--------------|-------|-------|-------|-------|
| 1  | Naca 12 | 1.00         | 93,81 | 65,60 | 11,26 | 7,87  |
| 2  |         | 1.25         | 75,05 | 52,48 | 9,01  | 6,30  |
| 3  |         | 1.5          | 62,54 | 43,73 | 7,51  | 5,26  |
| 4  |         | 1.65         | 56,85 | 39,76 | 6,82  | 4,78  |
| 5  |         | 1.75         | 53,60 | 37,49 | 6,43  | 4,51  |
| 6  |         | 2.0          | 46,90 | 32,80 | 5,63  | 3,94  |
| 7  | Naca 18 | 1.00         | 93,81 | 65,60 | 16,88 | 11,81 |
| 8  |         | 1.25         | 75,05 | 52,48 | 13,51 | 9,44  |
| 9  |         | 1.5          | 62,54 | 43,73 | 11,25 | 7,88  |
| 10 |         | 1.65         | 56,85 | 39,76 | 10,23 | 7,16  |
| 11 |         | 1.75         | 53,60 | 37,49 | 9,65  | 6,75  |
| 12 |         | 2.0          | 46,90 | 32,80 | 8,44  | 5,91  |
| 13 | Naca 25 | 1.00         | 93,81 | 65,60 | 23,46 | 16,40 |
| 14 |         | 1.25         | 75,05 | 52,48 | 18,76 | 13,12 |
| 15 |         | 1.5          | 62,54 | 43,73 | 15,64 | 10,93 |
| 16 |         | 1.65         | 56,85 | 39,76 | 14,21 | 9,94  |
| 17 |         | 1.75         | 53,60 | 37,49 | 13,40 | 9,37  |
| 18 |         | 2.0          | 46,90 | 32,80 | 11,73 | 8,20  |

The rudder that has geometric similarity with the prototype corresponds to the configuration number 4 in Table 2, with a NACA 12 profile and an aspect ratio of 1.65. Figure 4 illustrates all the rudders fabricated using 3D printing. It can be observed that as the aspect ratio increases, the rudder's chord length decreases, and as the NACA number increases, the profiles become progressively thinner.

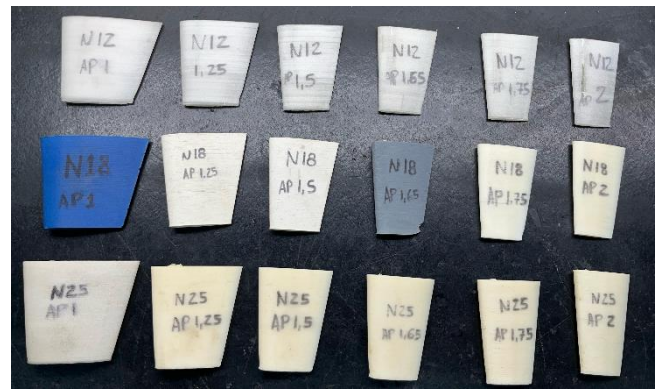


Figure 4. Set of 3D-printed rudders used in the experiments.

## 2.4 Experimental Procedures

To evaluate the performance of the rudders, turning circle trials were conducted at full-speed ahead, corresponding to approximately 15 knots in full scale, with manoeuvres executed to both port and starboard sides. A turning circle is a standard manoeuvring test in which a ship continuously turns to one side with a constant rudder angle—in this case, 35°—to assess its turning characteristics.

To allow for an objective comparison between different test repetitions and rudder profiles—beyond visual inspection—three key manoeuvring parameters defined by the IMO [7] were used. These parameters are also illustrated in Figure 5.

1. Advance – the distance the ship travels in its original heading direction from the point the rudder is applied until it reaches a 90° heading change.
2. Tactical Diameter – The perpendicular distance between the original course and the ship's position when it has turned through 180°.
3. Transfer – The lateral distance the ship moves in the direction perpendicular to its original course during the turning manoeuvre.

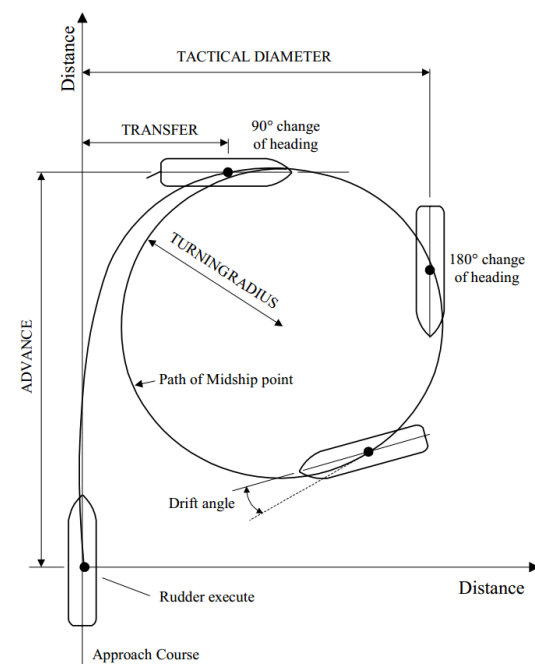


Figure 5. Illustration of turning circle geometry used to determine manoeuvring parameters.

To enable comparison, a real-world trial was used as a reference. Figure 6 shows the turning test results from the full-scale VLOC trials, with all values normalized by the ship's length.

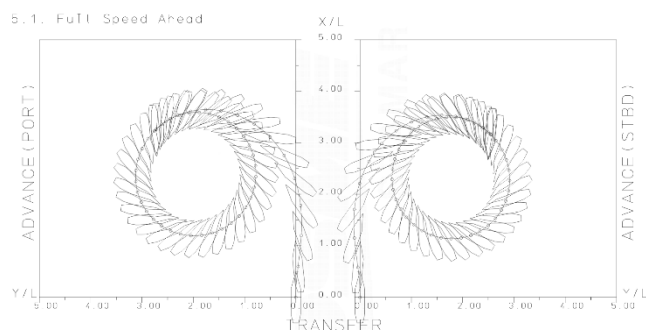


Figure 6. Turning circle results from full-scale VLOC trials, used as a reference for model-scale comparisons. All values are normalized by the ship's length.

Each rudder underwent four repeated tests on both port and starboard sides to ensure validation and improve repeatability. In total, 144 manoeuvring tests were conducted for this study. This approach improves the repeatability of the model and ensures robust and reliable data. In the end, the final values of the manoeuvring parameters were calculated as the arithmetic mean of the results from the four repetitions.

To determine the manoeuvring parameters, a custom software was developed to calculate the ship's position, velocity, and heading angle over time. Based on this data, the software automatically computes the turning circle parameters using the ship's trajectory and angular displacement. Figure 7 shows the initial position in red, the ship's path in black, and blue markers indicating the points at which the ship reaches  $\pm 90^\circ$  and  $\pm 180^\circ$  relative to its initial heading (considered as  $0^\circ$ ). The sign of the angle depends on the turning direction (port or starboard). These reference points are used to calculate the advance, tactical diameter, and turning radius.

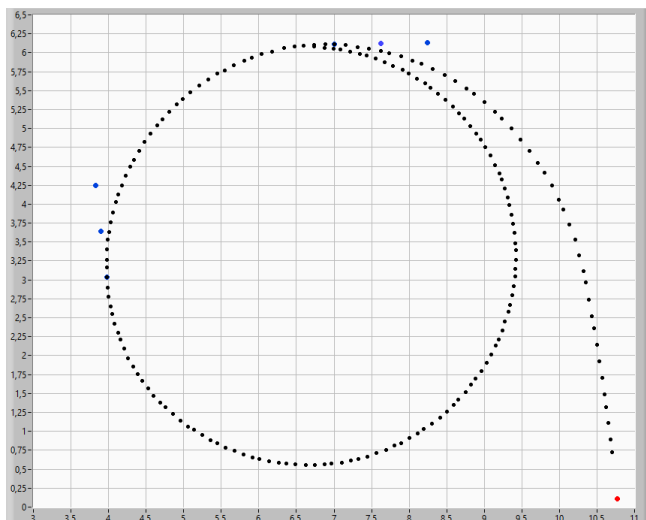


Figure 7. Ship trajectory used for manoeuvring parameter calculation. The red dot indicates the initial position, the black line represents the ship's path over time, and the blue dots show the points where the ship reaches  $\pm 90^\circ$  and  $\pm 180^\circ$  relative to the initial heading. All values are expressed in meters in real-world scale.

### 3 RESULTS AND DISCUSSION

First, the results compare the performance of the geometrically similar scaled-down rudder (Rudder number 4 from Table 2), which maintains the same configuration as the full-scale rudder in terms of height (h), length (a), thickness (b), and profile shape (NACA 12). The objective is to evaluate how a simple geometric scaling diverges from full-scale manoeuvring behaviour. Figure 8 presents a comparison between the scale model equipped with Rudder 4 and the full-scale ship trials, illustrating both starboard and port turning manoeuvres. All values shown have been converted and are presented in meters, corresponding to the dimensions of the full-scale vessel. It is worth noting that the turning plot in Figure 8 represents only one of the four repetitions performed, which may introduce slight visual discrepancies in the manoeuvring parameters compared to the averaged results.

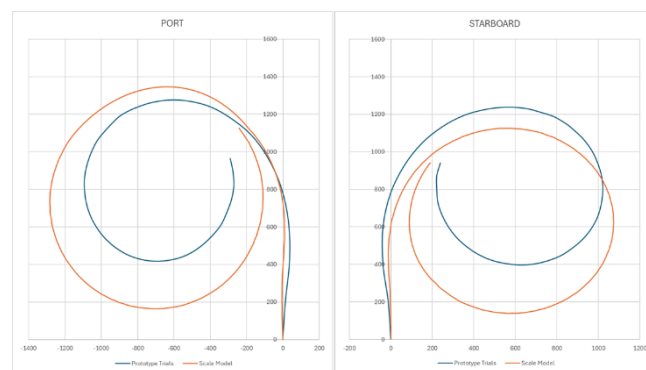


Figure 8. Comparison of turning circle trajectories between the scale model with rudder No. 4 and the full-scale ship trials for both starboard and port turns. All values are presented in real-world meters (full-scale dimensions).

For the analysis, Table 3 presents the values of the three key parameters, advance, tactical diameter, and turning radius—for each trial, providing a numerical comparison between the scale model equipped with Rudder No. 4 and the full-scale ship.

Table 3. Advance, tactical diameter, and turning radius for each trial conducted with the scale model (Rudder No. 4) and the full-scale ship. All values are presented in real-world meters for direct comparison.

| Parameters      | PORT      |             | STARBOARD |             |
|-----------------|-----------|-------------|-----------|-------------|
|                 | Prototype | Scale Model | Prototype | Scale Model |
| Advance (m)     | 1144,50   | 1162,11     | 1084,3    | 1191,93     |
| Transfer (m)    | 237,3     | 426,02      | 188,3     | 570,46      |
| T. Diameter (m) | 949,9     | 1054,88     | 875,7     | 1331,01     |

Using the manoeuvring parameters to compare the results, it becomes evident that the geometrically similar scaled-down rudder does not accurately replicate the real ship's turning behaviour. Among the parameters, advance shows the closest agreement with the full-scale values, with a percentage difference of approximately 4% for the port side. This suggests that the initial response to the rudder input occurs at a similar point in both the model and the full-scale vessel. However, the significantly larger values of tactical diameter and turning radius in the model highlight a reduced turning capability overall, indicating that the scale model turns less effectively than the real ship.

This discrepancy can be mitigated by adjusting the rudder profile configuration. Among the tested

designs, Rudder number 1 from Table 2 (NACA 12 profile with an aspect ratio of 1) provided the closest match to the full-scale manoeuvring parameters. Figure 9 and Table 4 present a comparison between the turning trajectories of the scale model equipped with Rudder 1 and the full-scale ship trials, illustrating both starboard and port turning manoeuvres.

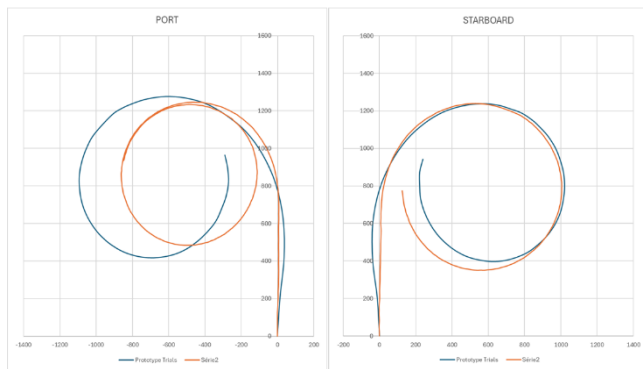


Figure 9. Comparison of turning trajectories between the scale model equipped with Rudder No.1 (NACA 12, aspect ratio 1) and the full-scale ship trials, for both starboard and port manoeuvres. All values are converted and presented in meters corresponding to the full-scale vessel.

Table 4. Advance, tactical diameter, and turning radius for each trial conducted with the scale model (Rudder No. 1) and the full-scale ship. All values are presented in real-world meters for direct comparison.

| Parameters      | PORT      |             | STARBOARD |             |
|-----------------|-----------|-------------|-----------|-------------|
|                 | Prototype | Scale Model | Prototype | Scale Model |
| Advance (m)     | 1144,50   | 1069,97     | 1084,3    | 1105,24     |
| Transfer (m)    | 237,3     | 327,86      | 188,3     | 369,17      |
| T. Diameter (m) | 949,9     | 833,83      | 875,7     | 963,01      |

This rudder maintains a similar proximity to Rudder No. 4 in terms of advance, but shows a closer match to the full-scale values for transfer and tactical diameter. Since both rudders share the same thickness profile (NACA 12), we can infer that the increased area—resulting from the higher aspect ratio—enhances the turning capability. This is physically understandable, as a larger rudder area generates greater hydrodynamic force, leading to improved manoeuvring performance.

Advance, Tactical Diameter, and Turning Radius values for each rudder configuration tested. Table 5 presents data for port turning manoeuvres, while Table 6 presents data for starboard turning manoeuvres. Each table includes the results of all four repetitions performed for every rudder configuration. All values are given in real-world meters.

Table 5. Advance, Tactical Diameter, and Turning Radius for All Rudder Trials (Port Turning)

| N°   | Profile | Aspect Ratio | Advance | Transfer | Tactical |
|------|---------|--------------|---------|----------|----------|
| PORT | Naca 12 | 1.00         | 1069,97 | 327,856  | 833,83   |
|      |         | 1.25         | 1103,12 | 406,564  | 1084,79  |
|      |         | 1.5          | 1148,44 | 531,777  | 1151,41  |
|      |         | 1.65         | 1191,93 | 570,491  | 1331,01  |
|      |         | 1.75         | 1158,2  | 523,408  | 1155,61  |
|      | Naca 18 | 2.0          | 1125,1  | 570,656  | 1293,39  |
|      |         | 1.00         | 1099,78 | 447,763  | 994,635  |
|      |         | 1.25         | 1046,3  | 462,564  | 1053,34  |
|      |         | 1.5          | 1108,46 | 499,622  | 1169,72  |
|      |         | 1.65         | 1104,63 | 526,711  | 1146,11  |
|      |         | 1.75         | 1142,28 | 544,347  | 1227,27  |
|      |         | 2.0          | 1330,52 | 585,218  | 1360,79  |
|      | Naca 25 | 1.00         | 1154,71 | 434,151  | 976,551  |
|      |         | 1.25         | 1102,73 | 451,362  | 1149,45  |
|      |         | 1.5          | 1169,41 | 507,72   | 1102,92  |
|      |         | 1.65         | 1191,84 | 544,972  | 1210,4   |
|      |         | 1.75         | 1168,91 | 650,592  | 1321,51  |
|      |         | 2.0          | 1136,98 | 645,91   | 1389,87  |

Table 6. Advance, Tactical Diameter, and Turning Radius for All Rudder Trials (Starboard Turning)

| N°        | Profile | Aspect Ratio | Advance | Transfer | Tactical |
|-----------|---------|--------------|---------|----------|----------|
| STARBOARD | Naca 12 | 1.00         | 1105,24 | 369,17   | 963,009  |
|           |         | 1.25         | 1125,63 | 419,852  | 1051,29  |
|           |         | 1.5          | 1141,93 | 468,505  | 1177,37  |
|           |         | 1.65         | 1162,11 | 426,019  | 1054,88  |
|           |         | 1.75         | 1151,94 | 476,096  | 1183,66  |
|           | Naca 18 | 2.0          | 1119,46 | 484,711  | 1164,5   |
|           |         | 1.00         | 1081,57 | 406,046  | 1130,05  |
|           |         | 1.25         | 1191,17 | 449,668  | 1085,97  |
|           |         | 1.5          | 1112,82 | 449,003  | 1035,72  |
|           |         | 1.65         | 1117,97 | 469,042  | 1171,66  |
|           |         | 1.75         | 1061,23 | 471,554  | 1120,86  |
|           |         | 2.0          | 1149,63 | 554,564  | 1385,87  |
|           | Naca 25 | 1.00         | 1202,56 | 390,489  | 1019,01  |
|           |         | 1.25         | 1086,4  | 387,065  | 978,90   |
|           |         | 1.5          | 1124,94 | 451,211  | 1104,80  |
|           |         | 1.65         | 1123,73 | 409,366  | 1061,32  |
|           |         | 1.75         | 1154,85 | 465,684  | 1128,00  |
|           |         | 2.0          | 1112,61 | 486,12   | 1185,25  |

Analyzing Tables 5 and 6, we can conclude that advance is not significantly affected by changes in rudder profile or aspect ratio, as all values remain within the same order of magnitude across different configurations. However, for tactical diameter and turning radius, a consistent pattern is observed: when maintaining the same profile, an increase in aspect ratio—which implies a reduction in rudder area—leads to higher values for these parameters. This indicates a decrease in turning capability, as smaller rudder areas generate less hydrodynamic force, reducing the model's ability to execute tighter turns.

When comparing the NACA profiles with the same aspect ratio, no consistent pattern is observed, which suggests that in this test scenario, rudder thickness plays a minor role in manoeuvring performance.

## 4 CONCLUSION

This study evaluated the influence of rudder shape and aspect ratio on the turning manoeuvrability of a ship using scale model tests. The results clearly indicate that a geometrically similar scaled-down rudder of the full-scale rudder does not accurately replicate the

manoeuvring behaviour of the real ship. Among the tested rudders, a configuration with increased area—achieved by raising the aspect ratio while maintaining the same NACA 12 profile—proved to be more effective, offering better alignment with the full-scale turning parameters.

The analysis showed that advance is the parameter least affected by rudder geometry, while tactical diameter and turning radius were significantly improved with larger rudder areas. In contrast, variations in the NACA profile had minimal impact, suggesting that rudder area plays a more decisive role in manoeuvring effectiveness than profile shape in this scenario.

For future studies, it is recommended to test rudders with intermediate aspect ratios between 1.0 and 1.25, as these may offer a better compromise. By slightly increasing the turning effectiveness on port side and slightly reducing it on starboard, this configuration could bring the results of both turning directions closer to the full-scale behaviour, potentially leading to an even more accurate representation in physical modelling.

These findings are important for physical modelling practices, especially in manoeuvring studies, as they highlight the need to optimize rudder configurations rather than rely solely on geometric scaling. By adjusting the rudder dimensions appropriately, it is possible to improve the dynamic similarity between the model and the full-scale ship, leading to more accurate and reliable experimental outcomes.

## REFERENCES

- [1] Bernardino, J. C. M., Alfredini, P., Esferra, R., & Amaral, J. H. (2015). O Simulador Analógico de Manobras (SIAMA). *Revista Brasileira de Recursos Hídricos*. DOI
- [2] Bernardino, J. C. M., Pion, L. M., Esferra, R., & Bezerra, R. O. (2019). Definition of mooring plans for vessels at port terminals using physical models. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, 13(1), 107-114. DOI
- [3] Bezerra R.O., Bernardino J.C.M., Esferra R.: Displacement Measurement System for Small-Scale Vessels Berthed in Physical Models of Port Terminals. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, Vol. 18, No. 1, pp. 169-175, DOI
- [4] Eloit, K., & Vantorre, M. (2011). Ship behaviour in shallow and confined water: an overview of hydrodynamic effects through EFD. Assessment of stability and control prediction methods for NATO air and sea vehicles, 20. Link.
- [5] Esferra R., Bernardino J.C.M., Bezerra, R.O., Pion L.M. (2021). Simulation in Reduced Scale Hydraulic Models of the Mooring System of Ships Docked Under the Effect of the Passage of Other Vessels (Passing Ship). *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, Vol. 15, No. 4, pp. 845-852. DOI
- [6] Hasanvand, A., Hajivand, A., & Ale Ali, N. (2019). Investigating the effect of rudder profile on 6DOF ship turning performance. *Applied Ocean Research*, 92, 101918. DOI
- [7] International Maritime Organization. (2002). Explanatory notes to the standards for ship manoeuvrability (IMO Doc. MSC/Circ.1053). London: IMO. Link
- [8] Liu, J., Quadvlieg, F., & Hekkenberg, R. (2016). Impacts of the rudder profile on manoeuvring performance of ships. *Ocean Engineering*, 124, 226-240. DOI
- [9] United Nations Conference on Trade and Development [UNCTAD]. (2024). Review of maritime transport 2024: Navigating maritime chokepoints. Link