ENHANCED FREE-RUNNING MANOEUVRING TESTS OF INLAND VESSELS IN MODEL SCALE

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SUMMARY

The transformation of inland shipping towards an automated mode of transport with clean propulsion concepts is initiated. While the path of automation with its intermediate steps is largely defined and first solutions for partial automation and remote control are available on the market, the race for technologies to decarbonise the drivetrain is completely open. However, it is evident that the operating costs of the drives and the investment costs for the drive power will increase significantly. As a result, the expected decline in the availability of power reserves for critical situations links the topics of automation and decarbonisation. Both fields of research require an improved knowledge of the manoeuvring behaviour of existing and future inland vessels. Free-running manoeuvring tests in model scale are of great importance in this development process, offering direct insight into manoeuvring characteristics. For example, evasive manoeuvres according to the European Standard laying down Technical Requirements for Inland Navigation vessels (ES-TRIN) are mandatory for ship's approval. In order to meet this increasing demand, a novel concept for this type of test has been developed at DST. Manoeuvres with a wooden model, equipped with remote-controlled propulsion and steering systems, are performed in front of the towing carriage. An optical motion tracking system tracks the model's movement, which is converted in real-time to full-scale GPS coordinates, enabling the use of real-world navigation technology. The technology integrates a rate-of-turn controller, a track-control system, and other automated functions for precise rudder control during predefined manoeuvres. Special attention is given to improving the reliability and repeatability of these tests, achieved through partial automation of the manoeuvres. A special focus of this paper is the investigation of the manoeuvring performance of ship models in shallow water condition and different water depths. Based on ongoing and completed research projects, examples of the system application and the results obtained are presented and discussed. In addition to evaluating the results in relation to ES-TRIN requirements, the findings also serve as a valuable basis for refining mathematical manoeuvring models. By ensuring repeatable and reliable model-scale manoeuvres, the accuracy of full-scale manoeuvre predictions can be enhanced, along with a deeper understanding of potential measurement uncertainties.

NOMENCLATURE

AHRS	Attitude and Heading Reference System	
BAW	Federal Waterways Engineering and Research Institute (Germany)	
BMWK	Federal Ministry for Economic Affairs and Climate Action (Germany)	
CFD	Computational Fluid Dynamics	
DST	Development Centre for Ship Technology and Transport Systems	
EOT	Engine Order Telegraph	
ES-TRIN	European Standard laying down Technical Requirements for Inland Navigation vessels	
GPS	Global Positioning System	
NMEA	National Marine Electronics Association	
RC	Remote Control	
WLAN	Wireless Local Area Network	
λ	Scale	-
C_B	Block Coefficient	-
h	Water depth	m
L	Length	m
L_{PP}	Length between Perpendiculars	m
L_{WL}	Length of Waterline	m
r	Rate of Turn	°/min

S_{wett}	Wetted Surface	m^2
T	Draft	m
t	Time	s
V	Displacement	m^3
v_M	Model Velocity	ms/s
v_S	Ship Velocity	km/h
δ	Rudder angle	°
σ	Standard Deviation	-

1 INTRODUCTION

With decarbonisation and automation, inland waterway shipping is facing a profound transformation that has already begun in recent years. The work is currently focussing strongly on various propulsion systems using alternative forms of energy (batteries, hydrogen, methanol, ammonia, etc.). At the same time, the spread of market-ready partial automation systems (such as track guidance assistants) is increasing rapidly and extensive research is being conducted into fully automated systems.

Both aspects also relate to a large extent to the knowledge of the manoeuvring characteristics of the ship. In the field of alternative propulsion technologies, it can be assumed that overpowering – as it is often found on current ships – will no longer be present to the same extent in the future. The determination of a realistic and sufficient propulsion power for defined purposes of an inland vessel is also enabled by the use of modern computer-aided methods and the inclusion of detailed data sets of the boundary conditions (e.g. water depths and current velocities) as part of the ship development process. The reduction in available propulsion power can lead to a significant change of the manoeuvring capability. This can either result in the vessel's non-compliance with the applicable regulations or a restriction of the usual ease of manoeuvring due to a limited power reserve. In any case, early knowledge of the manoeuvring behaviour is crucial in order to initiate technical revisions and/or develop and implement suitable training concepts.

In the context of automation, determining the manoeuvring behaviour as precisely as possible is a central component for implementing the required algorithms. In addition to the simplified approaches commonly used to date (e.g. model by Nomoto et al. (1957)), increasingly complex modelling is required. Even if the use of artificial intelligence is promising for this field of research, defined reference and validation tests are an important element. Furthermore, as long as humans remain part of an automated system, training measures will play a decisive role.

Free-running manoeuvring tests at model scale are one option to determine the manoeuvring behaviour of a ship. All relevant hydrodynamic effects of the ship in interaction with the environmental conditions (shallow water, banking, etc.) become directly effective. The normally moderate scale factors of the models of inland vessels (approx. 10 to 16) usually mean that scale effects are of minor importance. However, the accuracy of the manoeuvres depends crucially on the starting phase (acceleration of the ship model) and the initial state of the vessel before the manoeuvre begins. To achieve repeatable test results, the model must be kept parallel to the tank centreline at always the same distance to the tank walls with as few control commands as possible to achieve a steady approach speed with minimal rate of turn. If one of the two requirements is not fulfilled, the manoeuvre is not repeatable. Signal flows and filter algorithms have already been discussed in a first publication (see Roettig et al. (2023)).

These type of tests have been carried out for many years to determine the ship's manoeuvring behaviour and to develop mathematical manoeuvring models. However, the complexity of the ship model (especially for inland waterway vessels with multiple propellers and rudders) and the test setup (appropriate data transmission and motion capturing) has meant that this type of experiment has tended to be carried out in an academic context. A categorisation of the various options can be found, for example, in Quadvlieg (2016) and Stern et al. (2011). Examples of full-scale sea trials and free-running manoeuvring tests as well as strategies for their evaluation can be found, for example, in Oltmann (1973), Oltmann (1978), Abkowitz (1980), Rhee and K.-H. Kim (1999), Artyszuk (2003), Quadvlieg and Brouwer (2011), Im, Han, and Nguyen (2011), Araki et al. (2012), Sutulo and Guedes Soares (2014), Eloot et al. (2015), H. Xu, Hinostroza, and Guedes Soares (2018), Suzuki, Tsukada, and Ueno (2019), Hinostroza, H. T. Xu, and Guedes Soares (2019), Mei, Sun, and Shi (2020), Jin et al. (2021), I.-T. Kim et al. (2021), Yasukawa, Hasnan, and Matsuda (2021) and Kulbiej (2021). All of these publications deal with seagoing vessels. The only known work to date that uses the method of free-running manoeuvres for inland waterway vessels are the publications by Mucha et al. (2019) and Chillcce and el Moctar (2023).

This paper shows the development and implementation of a concept for free-running model tests in the large shallow water towing tank at DST. With a modern optical motion tracking system and a fibre-optic gyroscope as well as a commercial track guidance assistant (track pilot) for the control and automation of the models, the accuracy and effectiveness of these tests are significantly increased. First results show the possible applications for different research questions.

2 OBJECTIVES AND MANOEUVRING REQUIREMENTS

The presented concept for free-running model tests allows different objectives for the evaluation of obtained ship motions. A central aspect here is the assessment of compliance with the applicable minimum standard for the evasion and turning characteristics of inland waterway vessels, as published in the *European Standard Laying Down Technical Requirements For Inland Navigation Vessels (ES-TRIN)* (2025). Figure 1 shows the evasive manoeuvre with an example time series for the rate of turn (yaw rate) r and the rudder angle δ as well as the important times t_0 to t_4. The times required, depending on the water depth/draught ratio, are given in Table 1.

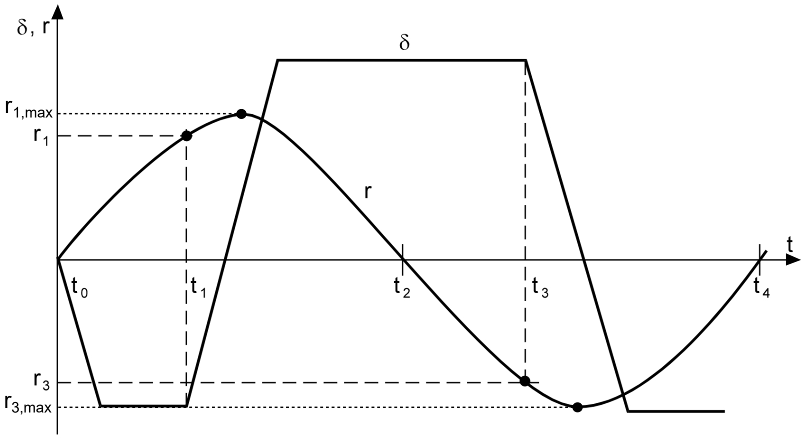


Figure 1: Diagram of the evasive action manoeuvre with extension of maximum yaw rates

Table 1: Rudder angle, rate of turn and limit values for evasive manoeuvres according to ES-TRIN

Rudder angle δ [°]	Required rate of turn $r_1 = r_3$ [°/min]	Limit values for the time t_4 $[s]$ in shallow and deep water $1.2 \leq h/T \leq 1.4$	$1.4 \leq h/T \leq 2$	$h/T > 2$
20 45	20 28	150	110	110

This manoeuvre is very similar to a zigzag-manoeuvre used in maritime navigation and considers the yaw rate instead of the course angle and can therefore be carried out on rivers and in the towing tank with limited width. The requirements for these manoeuvres are usually a deadweight of at least 70 % and a constant initial ship velocity of 13 km/h. DST has extended the official parameters to include the maximum values for rate of turn $r_{1,max}$ and $r_{3,max}$ (see Figure 1). It is expected that these – analogous to the overshoot angles in the zig-zag-manoeuvre – will allow statements to be made about the ship's ability to stop turning. In addition to the motion parameters, other parameters of the manoeuvre are also determined. This includes, for example, the sway velocity and lateral offset of the ship.

In addition to determining compliance with the regulations, parametric analyses can also be carried out with regard to the ship design or different rudder profiles. The limit of manoeuvrability can also be determined by gradually reducing the ship velocity. This is reached when the times for t_4 are exceeded or can no longer be determined because the yaw rate is no longer reached. In addition to the official 20-20 and 45-28 manoeuvres, any combination – for example for low ship velocity – can, of course, be carried out.

Furthermore, evasive manoeuvres can also be used for configuration and parametrisation of the track pilot itself. The existing implementation and performance can be compared and improved using different ship models. For example, tests can also be carried out close to the wall, which result in additional banking effects and challenging for the track guidance system to keep on the desired trajectory.

3 EXPERIMENTAL SETUP

3.1 SHIP MODEL

The wooden ship model used corresponds to a typical inland container vessel (model 1) and a tanker vessel (model 2). Both models have a scale of 1:17 and are described in detail in Tables 2 and 3.

The model propellers are driven by electric 24 V-motors that are powered by two lead-acid batteries. All propulsion parameters are determined using appropriate propeller dynamometers and duct thrust sensors. Each of the rudders is actuated

Table 2: Dimensions of ship models

Parameter	Symbol	Unit	Model 1 Model	Model 1 Ship	Model 2 Model	Model 2 Ship
Scale	λ	$[-]$	17	1	17	1
Length	L	[m]	7.94	134.98	6.471	110
Length between Perpendiculars	L_{PP}	[m]	7.919	134.63	6.368	108.25
Breadth	B	[m]	0.832	14.15	0.674	11.45
Propulsion			Twin screw		Single screw	
Rudders			Four blades		Two blades	

Table 3: Draught-dependent parameters of ship models

Parameter	Symbol	Unit	Model	Ship
			Model 1	
Draught	T	[m]	0.153	2.6
Length of Waterline	L_{WL}	[m]	7.885	134.05
Displacement	V	[m^3]	0.905	4444.6
Wetted Surface	S_{wett}	[m^2]	8.291	2396.0
Block Coefficient	C_B	$[-]$	0.897	0.897
Draught	T	[m]	0.100	1.7
Length of Waterline	L_{WL}	[m]	7.746	131.68
Displacement	V	[m^3]	0.581	2854.1
Wetted Surface	S_{wett}	[m^2]	7.318	2115.0
Block Coefficient	C_B	$[-]$	0.881	0.881
			Model 2	
Draught	T	[m]	0.165	2.8
Length of Waterline	L_{WL}	[m]	6.434	109.38
Displacement	V	[m^3]	0.627	3080.5
Wetted Surface	S_{wett}	[m^2]	5.917	1710.0
Block Coefficient	C_B	$[-]$	0.874	0.874

by a servo from RC model making. When controlling the rudders via software, the actual rudder kinematics were also taken into account, which ensures that the rudder on the inside of the curve has a larger rudder angle. On board of an inland waterway vessel this kinematic is ensured by mechanical connections between both rudder shafts.

Each model is fully remote-controlled via a real track-keeping system, as it is installed on many ships in practice. This system was slightly adapted for use in the model tests. In addition to manual control via engine order telegraph and rudder lever (track pilot off), rate-of-turn control (river pilot) and track guidance (track pilot on), there is an additional mode for automated execution of evasive manoeuvres.

3.2 MOTION CAPTURING AND MEASUREMENT

The motion of the ship model is recorded in two separate ways, which are partly redundant and can be compared to each other. On the one hand, the position and motion data is recorded by an optical motion tracking system provided by Qualisys AB, using four infrared motion capturing cameras and one video camera. All cameras are installed at the front of the towing carriage (see green circles in Figure 2). The motion capturing is performed via passive spherical markers, which are placed on the side wall of the model (see red circles in Figure 2). Placing two cameras on each front bumper of the carriages provides an effective side view for detecting ship movements close to the basin walls. With this setup, a distance of approximately 25 metres in front of the towing carriage can be covered. During the test, the carriage is manually controlled to follow the sailing ship model keeping it inside the optical range of the motion tracking system. The recorded data in the longitudinal direction of the tank is therefore initially relative to the carriage and converted to global coordinates in real time using the known position and velocity of the carriage, which are measured by a laser distance meter and an encoder wheel.

On the other hand an iXblue Octans Surface gyrocompass and motion sensor is installed in the model. This is an attitude and

Figure 2: Ship model 1 in front of the carriage

heading reference system (AHRS) which is used to measure the models orientation and the linear accelerations in all three dimensions of space. Especially the heading and the rate of turn are used during the automated manoeuvring of the model.

3.3 DATA HANDLING

All data between the carriage and the model is transmitted via a local WLAN. For this purpose, both the carriage and the model are equipped with appropriate antennas. The data processing and handling between the used systems, including the data acquisition system, is realised via an in-house software. The model's position relative to the carriage is gathered from the motion capture system, while heading, rate of turn and accelerations are measured by the AHRS on board of the model. Data combination, calculation, filtering and scaling to full scale is done in real time by the developed software. To use the track pilot in the same way as on a real ship, the model position is transformed into artificial GPS coordinates.

The final data is sent as NMEA 0183 data packets via Ethernet to the track pilot. The track pilot internally calculates the corresponding motions and the necessary rudder angle to keep the model on the guiding line. Using the wireless connection to the model, the desired rudder angles are transmitted using again NMEA 0183 sentence. In addition, the control commands for the drives are transmitted in the same way. It should be noted that the rotational motions of the model are by the square root of the scale factor faster, compared to full scale, what has to be considered in terms of processor performance and signal transmission.

3.4 TEST PROCEDURE

All tests are performed in DST's large shallow water basin with a total length of 200 m and a breadth of 10 m. The test procedure usually consists of four steps, after releasing the model in front of the towing carriage (see Figure 2).

1. Manual steering of the model to the guiding line used
2. Switching on the track controller (track pilot)
3. Triggering the manoeuvre start
4. Manual stopping of the ship model

The released ship model can be steered like a real ship using the engine order telegraph (EOT) and the rudder lever. Experience has shown that an activation of the track controller near the intended guiding line shows the best results for the repeatability of the tests. In this case, the controller only has to process minor position and motion deviations and the starting conditions for the subsequent manoeuvre are optimal, as the model moves straight ahead in the towing tank with only minor deviations. During the period in which the track controller is active, it is possible to fine-tune the intended ship velocity, which is displayed with good accuracy by the Kalman filter used (see Roettig et al. (2023)). The guiding line is usually defined parallel to the centreline of the tank depending on the expected space needed during the manoeuvre to reduce the distance and possible influence to the outer tank walls. Figure 3 shows the principle experimental setup and test procedure.

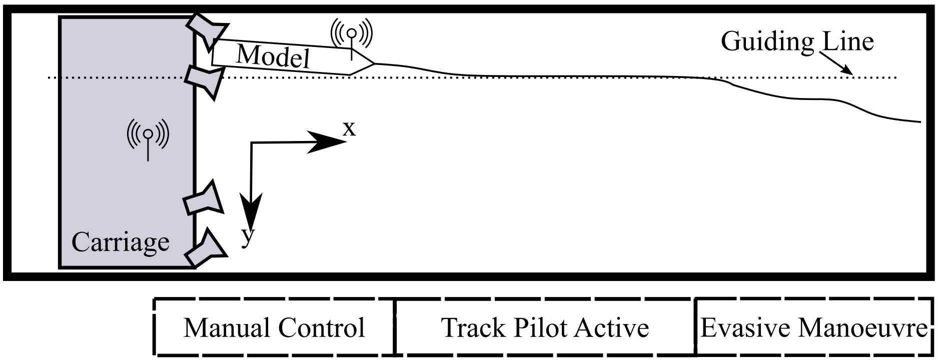


Figure 3: Experimental setup and test procedure

3.5 MANOEUVRE EXECUTION

As soon as the starting conditions are met, the manoeuvre is triggered. The rudders are then automatically set to the target value and automatically set to the opposite value when the target rate of turn is reached (see Figure 1). For example, a 45-28 evasive manoeuvre means that the rudder is set to +45 degrees. As soon as the rate of turn reaches -28 degrees per minute (turn over portside), the rudder is moved to the opposite side (-45 degrees). As soon as the rate of turn has reached +28 degrees per minute (turn over starboard), the rudder is again moved to the opposite side (+45 degrees). This sequence is executed and repeated automatically until it is stopped manually.

In this case a positive rudder angle leads to a negative yaw rate and vice versa. The coordinate system is thus defined analogue to the definitions in *European Standard Laying Down Technical Requirements For Inland Navigation Vessels (ES-TRIN)* (2025) (see Figure 1). It is expected that the overshoot of the yaw rate when the rudder is turned to the opposite side will not be very large. This means that the further acceleration of the yaw rate can be quickly stopped by moving the rudder, but the rotation of the ship itself only stops when the yaw rate has reached zero.

Finally, the automatic manoeuvre execution is stopped and the ship is manually decelerated.

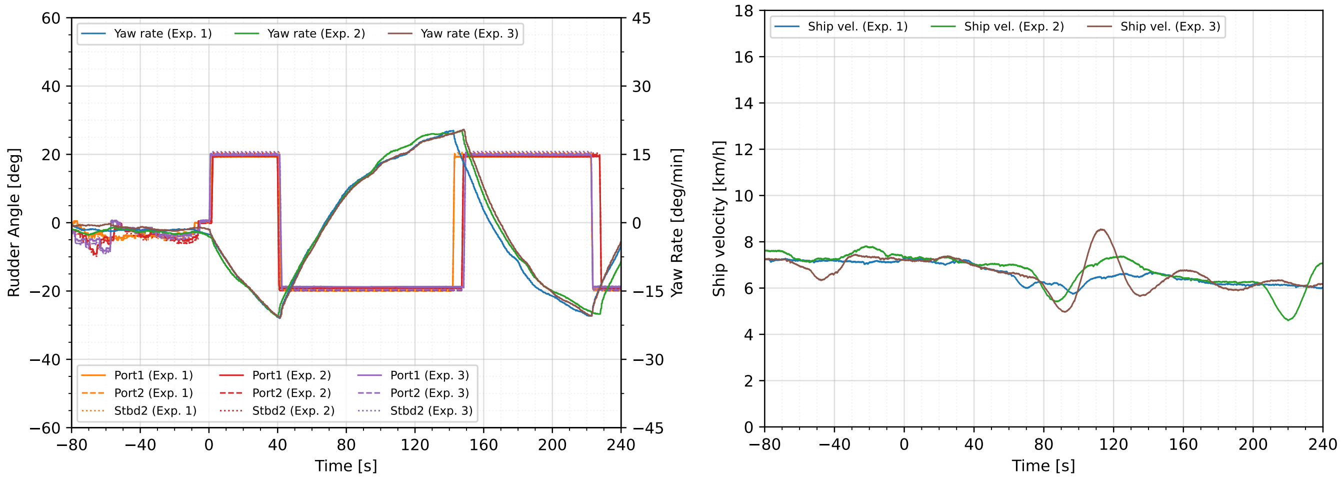
4 RESULTS

The available data is analysed with regard to the following aspects. The presentation of good repeatability is a central component of the test technique described. Determining compliance with the regulations is highly relevant when evaluating ship designs prior to construction. However, the data shown was not recorded for this purpose, but is intended to serve as a validation basis for CFD calculations and simulations with a ship handling simulator. Particularly for the scenarios in shallow water, the test execution has been modified to lower ship velocities and lower target rates of turn (20-10 instead of 20-20 and 45-18 instead of 45-28). This means that no direct statement can be made about the conformity of the manoeuvring behaviour.

However, this problem raises important questions in connection with the permissible manoeuvring behaviour of inland vessels in very shallow water and laterally restricted fairway. For ongoing efforts to make inland navigation suitable for these restricted conditions, extended procedures are needed to adequately assess manoeuvring behaviour in these situations. Indirectly, the shown results can already make a small contribution to these questions.

4.1 REPEATABILITY

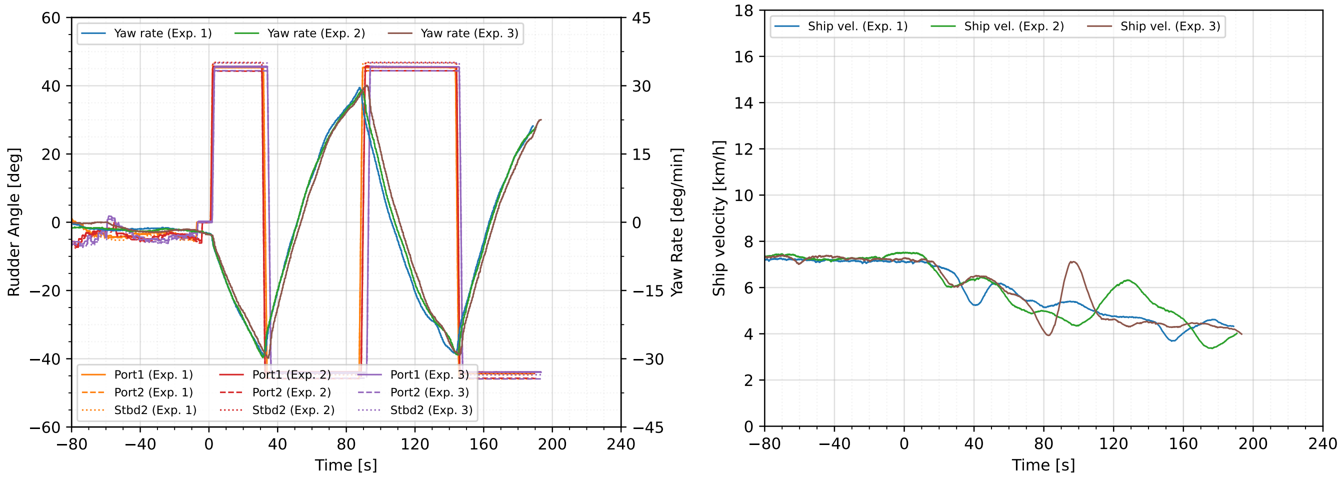
Figures 4 and 5 show examples of the repeatability of the model tests (model 1) for 20-20 and 45-28 manoeuvres with a ratio of $h/T = 1.5$ and a draught of $T = 1.7$ m. The legend labels, Port1, Port2, and Stbd2, refer to the respective rudder positions on the ship model 1, from portside to starboard. The signal for the rudder Stbd1 is missing due to a fault. The 80 seconds of negative time represent the test conditions before the start of the manoeuvre and correspond to approximately 20 seconds in model scale. It can be seen that both the rate of turn and the rudder angle differ only slightly. The still visible deviations are due to the slightly different starting conditions and residual currents in the tank. Figure 6 shows the repeatability of two 20-20 manoeuvres with model 2 and equally good agreement. The legend labels, Rudder Port and Rudder Stbd, refer to the respective rudder positions on the ship model 2, from portside to starboard.



(a) Rate of turn in full scale and rudder angle

(b) Ship velocity in full scale

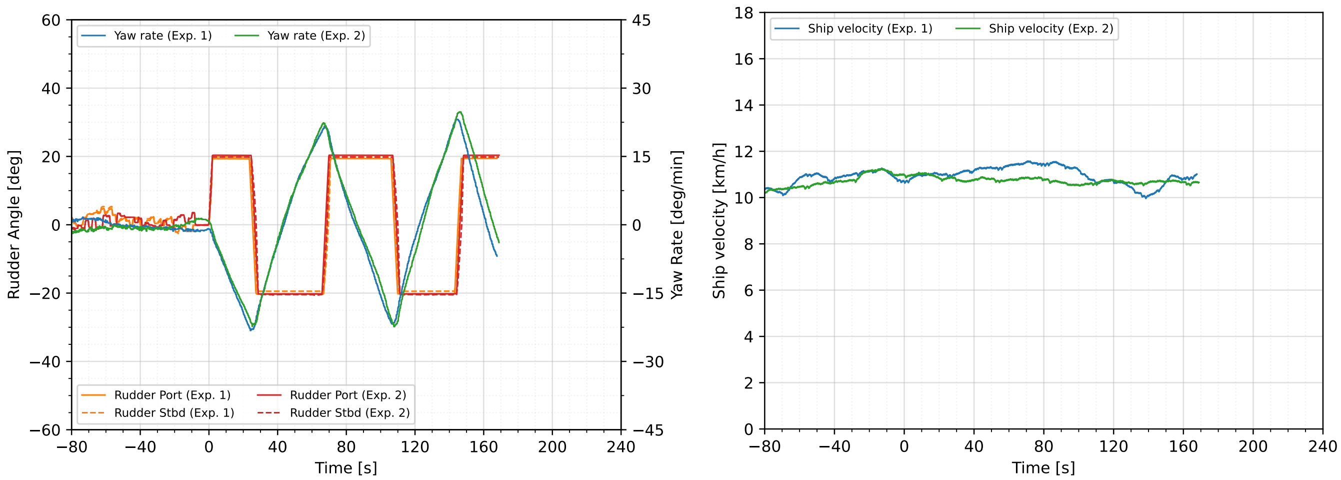
Figure 4: Repeatability of a 20-20-manoeuvre (Model 1 – $h/T = 1.5$ and $T = 1.7$ m)



(a) Rate of turn in full scale and rudder angle

(b) Ship velocity in full scale

Figure 5: Repeatability of a 45-28-manoeuvre (Model 1 – $h/T = 1.5$ and $T = 1.7$ m)



(a) Rate of turn in full scale and rudder angle

(b) Ship velocity in full scale

Figure 6: Repeatability of a 20-20-manoeuvre (Model 2 – $h/T = 1.3$ and $T = 2.8$ m)

The evaluation of the ship's velocity with the Kalman filter also shows good agreement before the test. The figures show the absolute value of the velocity vector of longitudinal and lateral velocity, which can also increase during the course of the manoeuvre, as the lateral velocity has a significant influence. Overall, however, the velocity slowly decreases due to manoeuvring. Based on the experience gained during the campaign, some tests were not repeated. As far as possible, Tables 4 and 5 show the mean values for the ship velocity at the start of the manoeuvre and the evaluated time points t_4.

Table 4: Results of evasive manoeuvres 20-20 (20-10) for model 1 in full scale

h/T	T [m]	$\overline{v_S}$ [km/h]	$\sigma(v_S)$ [%]	Manoeuvre	$\overline{t_4}$ [s]	$\sigma(t_4)$ [%]	Test runs	$\overline{\Delta r}$ [°/min]
7.34	1.7	11.0	0.26	20-20	63.1	-	1	0.3
		6.9	2.71	20-20	173.7	-	1	0.1
2.0	2.6	10.8	0.32	20-20	76.1	-	1	0.4
		7.2	0.56	20-20	192.2	1.66	2	0.1
	1.7	10.7	0.50	20-20	67.6	-	1	0.4
		7.0	0.77	20-20	149.0	3.56	2	0.2
1.5	2.6	10.6	0.72	20-20	87.4	-	1	0.5
		7.1	2.91	20-20	208.7	4.02	4	0.1
	1.7	11.4	2.81	20-20	72.5	-	1	0.7
		7.3	3.10	20-20	166.9	1.39	3	0.1
		4.3	4.83	20-20	230.5	-	1	0.0
1.2	2.6	6.9	1.75	20-10	115.8	3.91	2	0.1
		5.5	1.11	20-10	231.9	-	1	0.0
	1.7	6.1	1.52	20-10	103.5	3.41	2	0.1

Table 5: Results of evasive manoeuvres 45-28 (45-18) for model 1 in full scale

h/T	T [m]	$\overline{v_S}$ [km/h]	$\sigma(v_S)$ [%]	Manoeuvre	$\overline{t_4}$ [s]	$\sigma(t_4)$ [%]	Test runs	$\overline{\Delta r}$ [°/min]
7.34	1.7	11.0	0.26	45-28	48.8	-	1	1.3
		6.9	2.71	45-28	114.3	-	1	0.2
2.0	2.6	10.8	0.32	45-28	60.4	-	1	0.8
		7.2	0.56	45-28	129.8	1.47	3	0.3
	1.7	10.7	0.50	45-28	51.8	-	1	1.4
		7.0	0.77	45-28	106.0	0.59	2	0.2
1.5	2.6	10.6	0.72	45-28	63.5	-	1	0.8
		7.1	2.91	45-28	129.7	1.41	2	0.3
	1.7	11.4	2.81	45-28	55.5	-	1	0.9
		7.3	3.10	45-28	108.5	1.74	3	0.3
		4.3	4.83	45-28	244.0	-	1	0.0
1.2	2.6	6.9	1.75	45-18	90.6	1.09	3	0.4
		5.5	1.11	45-18	161.0	-	1	0.1
	1.7	6.1	1.52	45-18	92.2	1.56	3	0.2

4.2 COMPLIANCE WITH REGULATIONS IN SHALLOW WATER

As the data was not explicitly recorded for the purpose of analysing compliance with the regulations, only some values can be evaluated in this respect. Initially, only the data for draught $T = 2.6$ m (load greater than 70%) and ship speed $V_S \approx 11$ km$/h$ for the two ratios $h/T = 2.0$ and $h/T = 1.5$ are suitable for this purpose. Although the ship velocity is less than 13 km$/h$, these requirements are fully met. Unfortunately, the evaluation of the influence of shallow water is only possible to a very limited extent with the available data.

Unsurprisingly, the data show that the draught and thus the displacement volume have a strong influence on manoeuvrability and the important time t_4 is reached much faster. By analogy with zig-zag manoeuvres for seagoing vessels with corresponding overshooting angles, the further increase in the rate of turn (from r_1 to $r_{1,max}$ and from r_3 to $r_{3,max}$) in an evasive manoeuvre is comparable. The following average of the "overshooting rate of turn" Δr was used to analyse the results. Normally, the values are well below one degree per minute, which means that the increase in the ship's rotation can be stopped almost instantly by applying counter rudder.

$$\Delta r = \frac{|r_{1,max}| + |r_{3,max}|}{2} - \frac{|r_1| + |r_3|}{2} \quad (1)$$

Table 6 shows some results for the single screw model 2. Although the ship velocity is again a little too low, all manoeuvring requirements are already met. In this case, all tests were carried out at 80% engine order telegraph (set in shallow water $h/T = 1.3$), which explains the higher ship velocities in deeper water. It is also clearly recognisable that the overshooting rate of turn Δr is higher for the single screw vessel.

Table 6: Results of evasive manouvres 45-28 for model 2 in full scale

h/T	Rudder	$\overline{v_S}$ [km/h]	Evasive side first	t_4 [s]	Test runs	$\overline{\Delta r}$ [°/min]
1.3	1	11.2	Port	63.8	1	3.7
			Stbd	69.5	1	3.0
	2	11.1	Port	84.5	1	1.5
			Stbd	84.2	1	1.7
	3	11.1	Port	90.0	1	1.3
			Stbd	89.2	1	1.1
1.79	3	11.6	Port	85.9	1	2.8
			Stbd	96.3	1	2.9
4.46	3	12.3	Port	83.9	1	3.3
			Stbd	92.4	1	2.9

4.3 INFLUENCE OF DIFFERENT RUDDER PROFILES

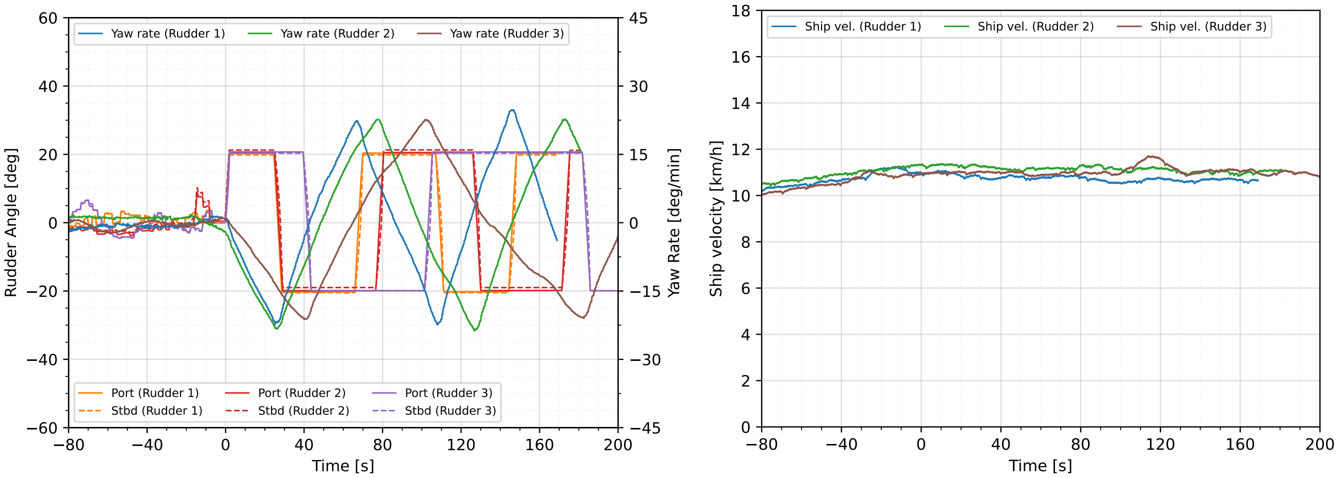
Figure 7 shows the result of an approach to determine the effect of different rudder profiles on the manoeuvring characteristics. Three different rudder profiles were tested for model 2, which differed significantly in size and shape (see Table 7). The exact profile definitions cannot be published for reasons of confidentiality. Rudder 1 describes a realistic rudder of an inland vessel with a wedge on the trailing edge. Rudder 2 has a similar profile but is more slender and has a shorter chord length. Rudder 3 was created on the basis of modified NACA profile definitions with curved centrelines, having the same main dimensions as rudder 2. The results show a clear influence of the rudder size and profile. The good characteristics of rudder 1 are certainly due to the low ratio of height to chord length. The difference between rudder 2 and rudder 3 lies in the modified profile shape. This difference can also be clearly determined from the tests.

Table 7: Rudder parameters

Rudder	Profile	Rudder height $[mm]$	Chord length $[mm]$	Profile thickness $[mm]$	Height-length-ratio $[-]$
1	Schilling type (modified)	105.9	112.4	16.4	0.94
2	Schilling type	105.9	84.1	11.1	1.26
3	Curved Centreline	105.9	84.1	11.1	1.26

5 SUMMARY AND CONCLUSION

Free-running manoeuvring tests in model scale offer the possibility of a wide range of detailed investigations of the manoeuvring behaviour of ships. With the presented test setup and the model equipment, this type of investigation can now



(a) Rate of turn in full scale and rudder angle

(b) Ship velocity in full scale

Figure 7: Influence of rudder profile in a 20-20-manoeuvre ($h/T = 1.3$ and $T = 2.8$ m)

be carried out for inland waterway vessels in DST's shallow water towing tank. The inclusion of a real track guidance system simplifies the control of the ship model and provides the prerequisites for repeatable model tests. The illustrations of repeatability shown are very promising, but with the experience gained so far, some optimisation is still possible and necessary. In particular, the implementation of a speed controller, would increase the repeatability of the approach speed, which is now given by a known propeller revolution.

In addition, only limited systematic analyses are possible for the results presented in this publication, due to the test restrictions in shallow water with regard to the achievable ship velocity and the feasibility of the defined standard manoeuvres 20-20 and 45-28. The lower ship velocity means that the target values for the rate of turn can no longer be achieved in the given tank space. For future applications of this technology, parameters and manoeuvres will be defined in advance that can be implemented in the same way at all water depths. These can be, for example, the shown manoeuvres 20-10 and 45-18 at a ship velocity of 6 km/h.

The investigation of manoeuvring behaviour in general and at low velocities in particular will continue to gain in importance in the future. Areas of application include the development of automated shipping and manoeuvring in designated low water periods with restricted fairways. The parameters of the evaluation will then also include the specific space requirements of the manoeuvring ship.

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