FULL SCALE MANOEUVRING TESTS WITH A SMALL, FLEXIBLE AUTOMATED, ZERO-EMISSION (SFAZ) VESSEL

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SUMMARY

The roadmap for transitioning to zero-emission transport and logistics in Europe promotes the use of waterborne transport, specifically inland waterway transport (IWT) and coastal shipping, to shift goods from road to water. In congested, urban areas that are characterized by shallow waterways and low bridges, the use of smaller vessels for IWT may offer a more environmentally attractive option.

FOREMAST aims at facilitating the movement of goods using Small, Flexible Automated, Zero-emission (SFAZ) vessels. Solutions are developed and validated in three Living Labs (LLs) in Europe with three different types of SFAZ vessels, exploring different levels of automation and autonomy combined with innovative green propulsion.

In order to understand how the different SFAZ vessels will react to a control command, the manoeuvring characteristics of the vessels need to be known. A Living Lab in Romania considers new concepts, of which the resistance and manoeuvring characteristics can be derived based on CFD computations. For the LL in France, full scale manoeuvres have been carried out. This paper will focuses on the French LL and explains how the measured data from zig-zag, turning circle and other manoeuvres were pre-processed in order to be able to apply system identification techniques to establish a mathematical manoeuvring model of the SFAZ vessel. The same methodology will be used applied for the LL in Belgium.

1 INTRODUCTION

The “SFAZ” concept is relatively new. It stands for Small Flexible Automated Zero-Emissions vessels, which addresses several of the challenges that inland shipping faces.

Inland waterway navigation is one of the most environmentally friendly modes of transport (Barros et al., 2022). The European Commission introduced the European Green Deal as a new sustainable growth strategy, with a commitment to shift a substantial part of current inland freight transport by road to railways and inland shipping (European Commission, 2021). However, inland shipping has been struggling with a shortage of skippers (CCNR, 2024; Kriedel and Roux, 2024). From an economical point of view, it is more interesting for skippers to work on larger inland vessels. Kloch and Kristiansen (2024) studied the viability of existing inland navigation vessels and found that smaller vessels are disappearing faster than larger vessels (Kloch and Kristiansen, 2024). In terms of CEMT classes, virtually no CEMT class I inland navigation vessels have been built in Europe since 1970 (Bačkalov et al., 2024). As a consequence, some smaller waterways are underutilised to the point that some of them risk falling into disuse, only to be used by the occasional pleasure craft. This raises the question whether these underutilized waterways can be used by a new type of small vessel.

At first instance, urban waterways seem the most interesting for re-development, as changes in logistical planning are required in order to develop an optimal distribution network that integrates transport via urban waterways and last-mile delivery. The economy and liveability of cities depends to a large degree on efficient urban logistics. In many cities, this efficiency is under pressure due to factors such as increasing population and faces challenges such as congestion, emissions, noise, and safety issues. Historically, many cities were founded near a waterway because transport by water was easier than over land. Over the last couple of centuries, road transport has replaced transport by water as the main mode of transport. Over time, this gradual shift in transport habits has often overlooked the spatial correlation between waterway and urban development (Pourmohammad-Zia and van Koningsveld, 2024). Several sources have pointed out that inland waterways present untapped potential that can improve urban logistics in many cities and examples have been given of successful solutions worldwide (Wojewódzka-Król and Rolbiecki, 2019).

The World Economic Forum has projected a 32% increase in urban delivery-related traffic emissions and a 21% increase in congestion from 2020 to 2030 (World Economic Forum, 2020). The majority of these emissions originate from the ‘last mile’ delivery stage, an inherently inefficient process characterised by low product volume and a high number of destinations. Several companies have looked at waterways for last mile deliveries (CCNR, 2022). Alternative routes between ports and consignors/consignees using different models of transport can be explored using methods, such as graph theory (Paulauskas et al., 2022). Pourmohammad-Zia and van Koningsveld (2024) evaluated the benefits of transitioning from a roadway-centric to a waterway-based system for the city of Amsterdam as a case study. By formulating the problem as a location routing problem with time windows, they obtained significant cost savings (approximately 28 %), reductions in vehicle weight (approximately 43 %), and minimized travel distances (approximately 80 %) within the city centre. Traditional inland vessels are used to move cargo from a central hub to several transshipment locations and the last-mile delivery is carried out with Light Electric Vehicles or moving jacks (Pourmohammad-Zia and van Koningsveld, 2024). Jaegler et al. (2024) analysed the economic feasibility of urban distribution where inland waterway transport is used for transshipment and cargo bikes/vans are deployed for last-mile delivery (Jaegler et al., 2024). Small and flexible vessels could in that sense be an interesting proposition for many cities.

Consensus has grown that automated/autonomous inland navigation can help in reviving transport on small waterways in particular (Pauwelyn and Turf, 2023). The distinction between the terms ”automation” and "autonomy” has been discussed in detail by Rødseth et al. (2022). Both terms are used to express the same concept, but the Central Commission for the Navigation of the Rhine (CCNR), refers to “levels of automation”, so it has become (slightly more) common to use “automated” for inland navigation and “autonomous” for seagoing vessels. Essentially, it means that one or more of a ship system's processes or equipment, under certain conditions, is designed and verified to be controlled by automation, without human assistance (Rødseth et al., 2022).

Several projects have investigated the technical feasibility of automated inland navigation purposes. The feasibility was first demonstrated with ferries, which offer the advantage that they usually operate continuously between two fixed destination points. Rolls-Royce and Finnferries demonstrated automated navigation on a 1.8 km long trajectory with a 53.8 m double-ended car ferry, which was remotely controlled from a centre some 50 kilometres away. The vessel detects objects by fusing sensor data and using artificial intelligence and is able to conduct collision avoidance and automatic berthing (Rolls-Royce, 2018). In another project, NTNU put a self-propelled electric passenger ferry into trial operation along the urban waterways of Trondheim (Haugan, 2022). As part of the AUTOSHIP Horizon 2020 research project, remote-controlled automated vessel operations were demonstrated in Belgium with an inland waterway barge. The Zulu 4 completed a 16.5 km long circuit that included traversing locks and passing several bridges (Taylor, 2023).

The AEGIS research project aims to develop a transport system that can better compete with road transport by using more and smaller vessels to increase frequency, differentiate speeds, reduce terminal costs and reducing port times. They point out that the main advantage of remote-controlled vessels is the possibility to operate a fleet of vessels from a single remote control centre and therefore be more flexible and efficient. Several shallow draughted (≤ 3.3 m) concept vessels are included in the project, such as a 61m long container shuttle, and a push convoy with three different types of 33 m long barges and fully electric inland waterway RORO vessels, ranging from CEMT class II to IV+ that are able to carry trailers (Krause et al., 2022). Roboat aims to make use of the existing infrastructure with novel automated surface vessels that could eventually be used for urban transportation of passengers or freight (Wang et al., 2020).

From an environmental point of view and with an increasing amount of low-emission zones in urban areas, these small, flexible and automated vessels would only make sense if they are zero-emission. Inland navigation has long had an advantage over road transport in terms of the sustainability of transport (i.e. lower emissions per transported unit). This advantage has decreased considerably in recent years, as the road transport sector is able to adopt and install new techniques more quickly than is possible in the inland navigation sector. It Is therefore important for the inland navigation sector to realise gains in terms of emissions, in order to reinforce its image as a sustainable mode of transport (Sys et al., 2020).

Based on a systematic literature review of emissions, decarbonization, and alternative fuels in inland navigation, Raftis et al. (2023) point out that majority of the studies come from outside Europe, especially China, where considerable effort has been put into utilizing inland corridors and switching to alternative power sources for inland vessels and their propulsion systems. As the European region has extensive networks of inland waterways and the European Commission has set a goal for net zero, it seems that there is plenty of space for additional actions to stimulate environmentally friendly inland navigation. Within Europe, the focus so far is on the optimization of the inland corridors as a first step, and the focus on switching to alternative power sources for inland vessels is only a second step which merits higher research efforts (Raftis et al., 2023).

The concept of using Small, Flexible Automated, Zero-emission (SFAZ) vessels is therefore promising. FOREMAST (Freight vOlumes transfer from Road to waterborne transport, using zero-EMission, Automated, Small, and flexible vessel (SFAZ) protoTypes) builds on the findings from projects such as ReNEW (Resilience-centric Smart, Green, Networked EU Inland Waterways), which creates and tests new solutions for both climate-neutral and climate-resilient transport systems via inland waterways, and IW-NET (Innovation-Driven Collaborative European Inland Waterways Transport Network), which focuses on developing a multimodal optimisation process across the EU transport system. FOREMAST aims to explore areas which other research projects do not address. AUTOFLEX (AUTOnomous small and FLEXible vessels), for example, looks into the modernization of the design of traditional inland navigation vessels. One of the findings is that the modification of a traditional CEMT Class I reference design to a container carrier is not viable, as the vessel could not comply with the intact stability criteria for container carriers, which rendered the analysis of the further modernization steps superfluous (Bačkalov et al., 2024).

Within FOREMAST, several different SFAZ designs are studied, which are fundamentally different from traditional inland navigation vessels, in the hope that these SFAZ concepts can revive underutilized class I waterways. FOREMAST principally aims at facilitating the movement of goods using SFAZ. Solutions are developed and validated in three Living Labs (LLs) in Europe with three different types of SFAZ vessels, exploring different levels of automation and autonomy combined with innovative green propulsion.

One of the aims within FOREMAST is to develop suitable mathematical models for the different SFAZ, considering both independent operation and platooning. The mathematical model is the cornerstone of ship manoeuvring theory. Over the years, various models of different complexity and adequacy have been proposed, ranging from relatively full and complex manoeuvring models based on fundamental physical principles and much simpler models usually associated with the name Nomoto (Sutulo and Guedes Soares, 2024). In order to understand how the different SFAZ vessels will react to a control command, the manoeuvring characteristics of the vessels need to be known. A Living Lab in Romania considers new concepts, of which the resistance and manoeuvring characteristics can be derived based on CFD computations. For the LL in France, full scale manoeuvres have been carried out.

This paper will focus on the LL In France, which aims to develop and test a new vessel design and prototype of a SFAZ concept that can be used for urban and intra-urban transport of goods in Caen, France. Section 2 of the paper briefly describes why manoeuvring models are important within the development of automated inland navigation. Section 3 describes the environment in which the full scale trials were carried out, the ship characteristics and the test protocol. Section 4 describes the pre-processing of the collected data. Section 5 concludes the paper and describes the prospects for further developments.

2 DIGITAL TWIN AND AUTONOMOUS NAVIGATION

Digital twins provide a comprehensive virtual representation of the vessel and its environment. In the design phase, these virtual replicas enable early-stage optimization of hull forms, propulsion systems, and other critical components, facilitating performance analysis and risk mitigation before physical construction. This reduces development time and costs while improving overall design quality. During operation, digital twins integrate real-time sensor data from the physical ship, enabling continuous performance monitoring, predictive maintenance, and optimized route planning. By simulating various scenarios, including weather changes and potential equipment solutions, digital twins can help in making decisions, enhance crew training, and contribute to improved safety, efficiency, and sustainability throughout the ship's lifecycle. These improvements translate into significant economic benefits for ship owners and operators. Optimized energy consumption through route planning and performance monitoring directly reduces operational expenses. Furthermore, improved operational efficiency and reduced risks can enhance profitability and competitiveness of inland waterway transportation. Moreover, digital twins play a crucial role in the development and validation of autonomous navigation systems. By providing a virtual testing ground, they allow for the safe and cost-effective evaluation of autonomous algorithms and sensor integration in various simulated conditions, accelerating the development and deployment of autonomous vessels.

Both digital twins and autonomous navigation require precise prediction of ship dynamics for safe and efficient operation. Accurate ship manoeuvring models are fundamental for robust path planning and collision avoidance in dynamic environments. Moreover, model-based simulations provide a cost-effective and safe platform for testing and validating autonomous navigation algorithms.

This is even more true when vessels train need to be simulated to analyse and optimize complex interactions between autonomous vessels ensuring safe distances, synchronized movements and for effective reaction to unexpected events and emergency situations.

These models enable prediction of ship response to control inputs (e.g. rim-driven thrusters, conventional propellers) and environmental disturbances (wind, currents). Reliable motions prediction facilitates the generation of optimal trajectories, minimizing fuel consumption and transit time.

Developing accurate manoeuvring models, especially complex six degrees of freedom (6DOF) models (Delefortrie et al., 2016), is challenging and time consuming. Determining the required hydrodynamic parameters usually involves computationally expensive captive model tests or Computational Fluid Dynamics (CFD) simulations, frequently combined with system identification. This process is time consuming and not particularly suitable for the design of different types of vessels considered within the FOREMAST project, where evaluating the impact of minor hull variations, propulsion system changes, and other modifications requires rapid assessment.

Therefore, a simplified model including dominant hydrodynamics is sufficient for the present study. Such model still requires identifying several manoeuvring characteristics of the vessel. Standard manoeuvres recommended for sea trials are representative of the main manoeuvring characteristics of a ship, those tests are therefore used as a base for system identification.

The idea behind the methodology presented is to be able to have a fast and easy method to build a model which can be used for several ship versions and different purposes. Therefore, very simple pre-processing techniques are applied to investigate the quality of the data.

3 FULL SCALE TRIALS

3.1 SHIP PARTICULARS

The vessel is a trimaran of 6.5 m by 3.0 m from NEAC-INDUSTRY (shown in Figure 1) with main particulars listed in Table 1 and electronic connected architecture shown in Figure 4. The vessel is equipped with an RIM 6kW electric driven thruster of Hy.G Motors (shown in Figure 2). The energy pack has a 7,2 kWh (150 Ah) capacity, providing 1 – 3 hours of autonomy.

5

Figure 1. Development vessel for experimenting and testing, Living Lab France. Outside view (left) and ship bridge (right).

Table 1. Ship main particulars

Symbol	Unit	Description	portside hull	central hull	starboard side hull
L_{PP}	m	Length	5.40	6.40	5.40
B	m	Breadth	0.50	0.80	0.50
B_{total}	m	Total breadth		3.00	
T	m	Draught	0.20	0.20	0.20
∇	m^3	Displacement volume	0.27	0.78	0.27
C_B	-	Block coefficient	0.50	0.76	0.50
A_L	m^2	Longitudinal windage area		6.15	
A_T	m^2	Lateral windage area		11.00	
x_G	m	Longitudinal position of the centre of gravity (measured from midship)		-0.07	
y_G	m	Transversal position of the centre of gravity (measured from centreline)		0.00	
z_G	m	Vertical position of the centre of gravity (measured from keel, z+ pointing upwards)		0.52	

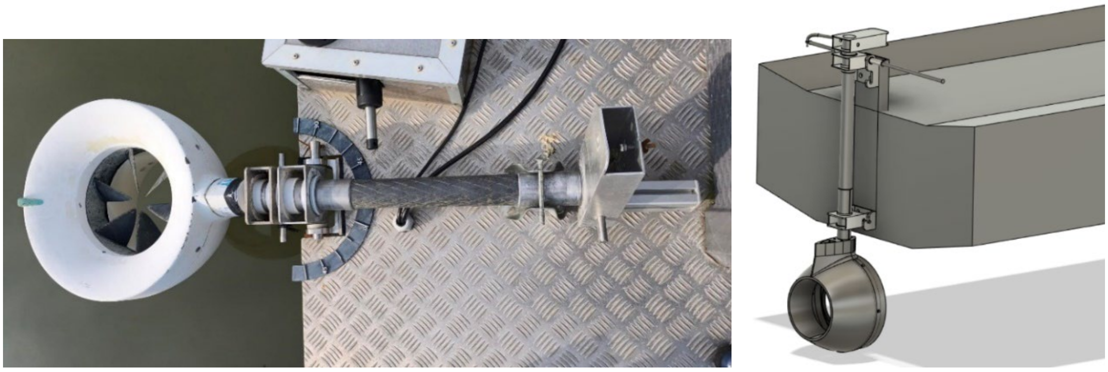

Figure 2. Hy.G Motors, RIM6kW - electric driven thruster lifted on the deck (left) and in operating position (right).

3.2 ENVIRONMENT

The Caen Canal is a 15km waterway connecting the port of Caen with the port of Ouistreham on the English Channel (La Manche). Traversing the municipalities of Hérouville-Saint-Clair, Bénouville, Blainville-sur-Orne and Ouistreham, this canal is considered a maritime zone, subject to a speed limit (RPP, 2024). Key features include three bridges (Fonderie, Colombelles, and Bénouville) and two locks in Ouistreham, each measuring 225m by 29m. The canal experiences a relatively small tidal range of 70-80 cm and low current velocities (< 0.1 m/s). With a consistent depth of 10 m and a width of 100 m. This controlled setting offers an ideal testbed for ship manoeuvring trials and autonomous vessel research.

The manoeuvres were executed in or near the Hérouville basin, as shown in Figure 3. The basin offers a free sailing area of approximately 200m by 300m, which is large enough for turning circle manoeuvres. This basin is almost unaffected by the current in the canal. However, the presence of traffic and moored vessels can introduce ship-generated waves and wind shielding effects respectively and influence the measurements. Acceleration tests and zigzag tests, requiring longer straight runs, were performed within the canal itself. This section is relatively sheltered from wind due to the presence of mature trees lining the canal banks.

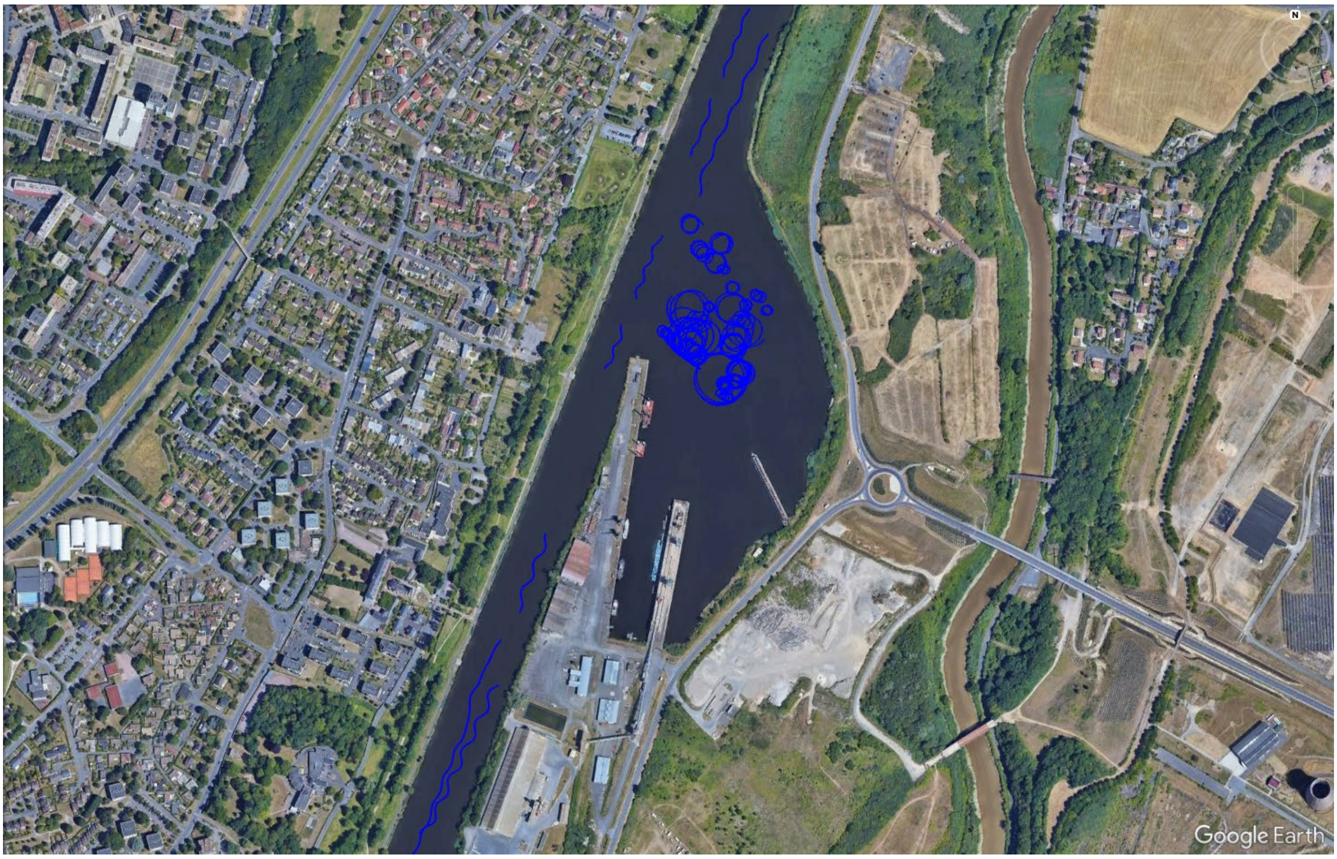

Figure 3. The Caen canal and the Hérouville Bassin in which the tests were performed. Examples of manoeuvres that were executed are shown in blue.

3.3 SHIP INSTRUMENTATION

The vessel was equipped with different sensors measuring position, heading, heave, roll, pitch and speed over ground with a compact satellite compass (Furuno SCX-20) installed on the roof of the vessel (as shown in Figure 4. This compass provides longitude, latitude at 5 Hz, heading, heave, pitch, roll, yaw at 10Hz, speed over ground at 1 Hz with 3 to 5 m accuracy for the positions, 0.1 m/s for the speed and 0.5° accuracy for heading/roll/pitch.

The relative wind direction and speed were recorded by an anemometer. The data are collected on the NMEA2000 network (Figure 7). A first pre-processing was executed by NEAC in France to select useful data and provide a user-friendly format to for further processing. The positions and speed were recalculated at the position of the centre of gravity. The data transfer was rather smooth and can be easily replicated on another vessel.

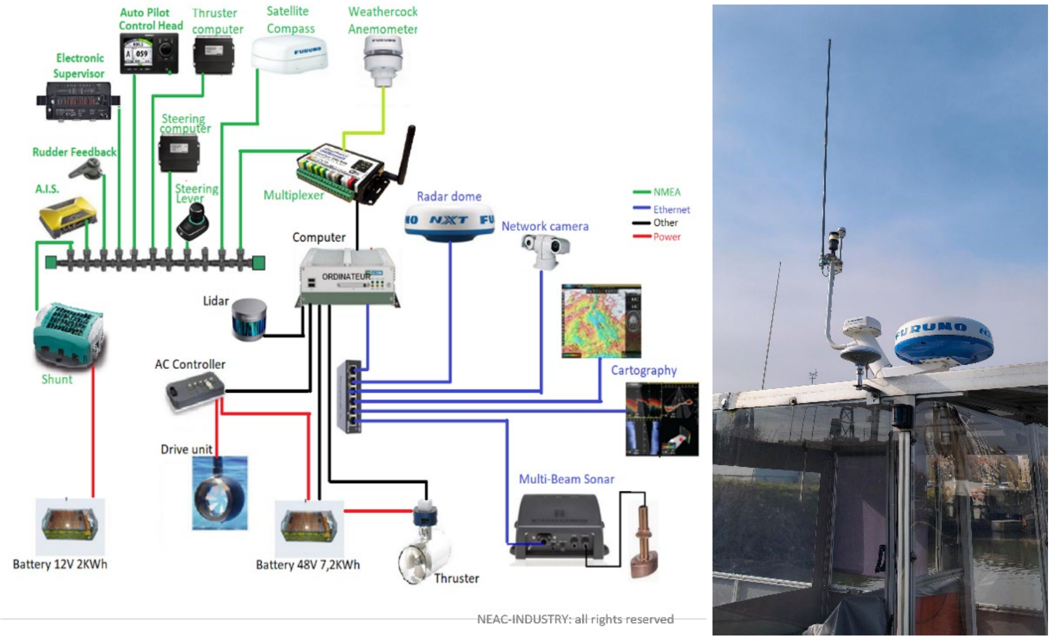

Figure 4. **Connected electronic architecture of sensors on vessel** (left) and **sensors installed on the roof of the vessel (right).**

3.4 TRIALS PROTOCOL

To identify manoeuvring characteristics, the full scale measurements have been conducted following the guidelines of relevant ITTC procedures, notably the procedure for full scale manoeuvring trials (ITTC, 2024a) and also the procedure for free running model tests (ITTC, 2024b), considering the size of the vessel. One can observe that the required accuracies were not met, which added challenges to the post-processing of the result.

A tailor-made test protocol was prepared for the manoeuvring trials in France. This test campaign was completed in three days. Prior to this campaign, several preliminary tests were conducted and analysed to check the quality of the data measured by the different sensors. This iterative process of testing, analysis, and refinement provided valuable feedback on measurement techniques and data processing, leading to significant optimization of the overall methodology and the upgrading of certain sensors.

It is worth noting that the rim-driven thruster (i.e. thrust magnitude and direction) was not controlled by an autopilot. At times, differences and delays were observed between the setting indicated by the protocol and the command given by the pilot.

Another complicating factor is that the loading condition was not always the same. Three persons were onboard during the measurements (cf. Figure 1), who did not always stay in exactly the same position. In addition, the amount and mass of the batteries onboard varied during the measurement campaign. Given the relatively small displacement of the vessel of 1.32 tons, the loading condition and particularly the trim of the vessel changed quite significantly.

One of the main challenges was to find a time window with good weather, i.e. no wind and no traffic. Moreover, the vessels relied on batteries which limited the testing time and maximum power.

3.4 (a) Acceleration tests

Acceleration tests are meant to give information on the self-propulsion points, i.e. what speed is reached with a given propeller setting and how fast this equilibrium is reached. The ship accelerates from rest (or a smaller speed) to the final speed on a straight line. The speed extends from the lowest (20% throttle) to the highest speed (100% throttle).

Speed ranges correspond to telegraph positions, 20%, 40%, 60%, 80% and 100% rpm setting. The runs were performed along and against current so that the speed through water could be determined. The acceleration tests were not corrected for wind as they were executed in the canal, which is quite sheltered from wind.

3.4 (b) Turing circle tests

Turning circle tests were performed to both port and starboard at approach speed with a maximum rim-driven thruster angle. During the turning circle tests, the ship completed a total heading angle change of 720 degrees, which corresponds to two full circles. This allows to investigate a possible drift motion due to wind or current. The tactical diameter, advance, and transfer derived from turning circle manoeuvres provide essential quantitative measures of a vessel's course changing ability (cf. Figure 5).

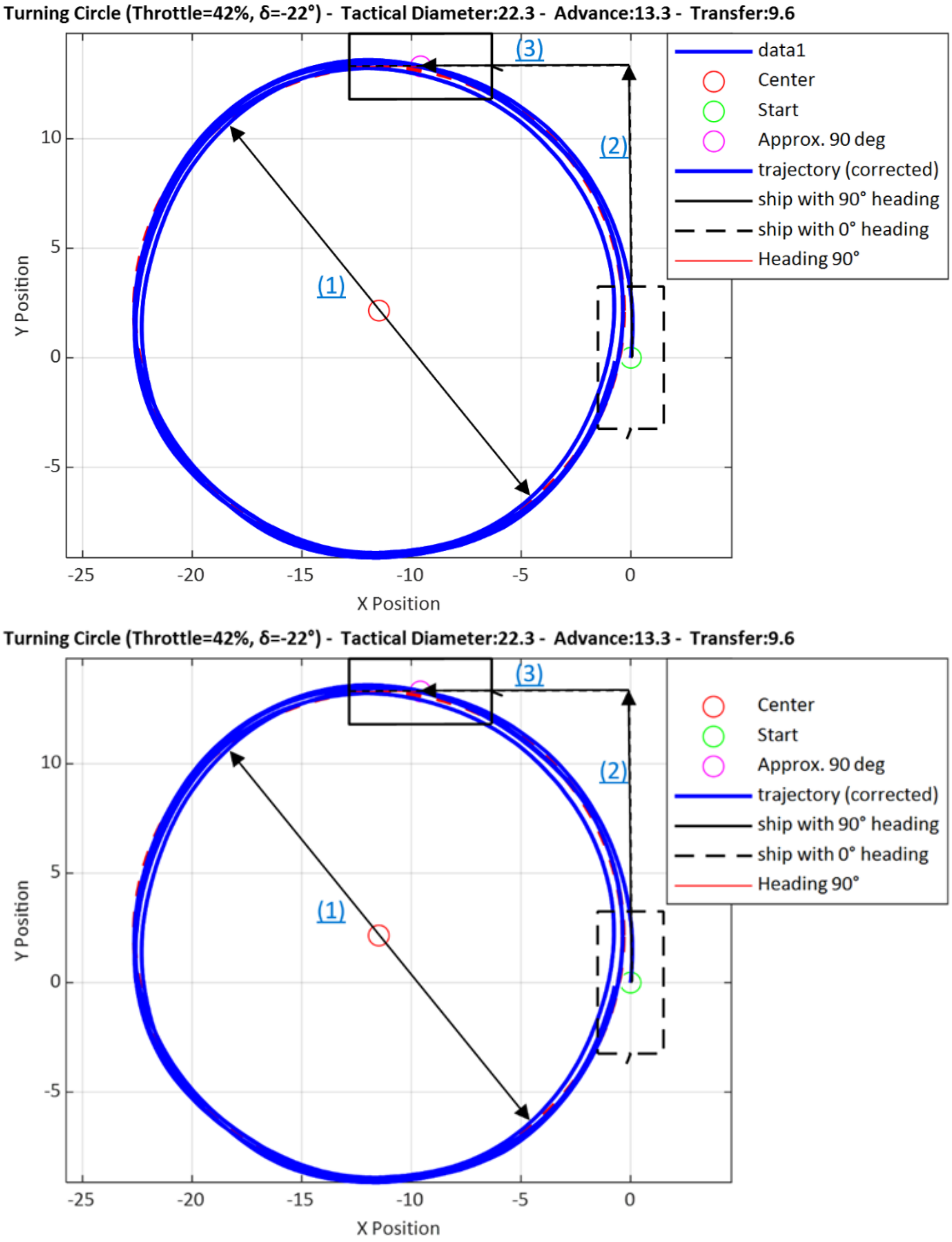

Figure 5. Example of turning circle manoeuvres with tactical diameter (1), advance (2) and transfer (3) characteristics.

3.4 (c) Zigzag tests

Zigzag manoeuvres involve alternating the azimuth angle by δ degrees when the ship deviates ψ degrees from its initial course. The rim-driven thruster angle is reversed multiple times (typically four) during each trial, causing the ship to yaw in alternating directions. The manoeuvre is defined by the azimuth angle(δ) and heading deviation (ψ), and denoted as δ/ψ (e.g., 10/10 or 20/20).

Zigzag tests were performed to both starboard and port direction to account for environmental factors, but starboard turns are of particular interest for emergency situations. A vessel may need to alter its course quickly. Therefore, the capacity to perform a zigzag manoeuvre is a crucial aspect of a ship's handling capabilities.

The zigzag manoeuvre begins with the azimuth angle at zero (i.e. straight ahead) and the vessel maintains a constant rpm setting. Subsequently, the rim-driven thruster is turned to the desired angle δ and held until the ship's heading changes by the desired angle ψ. The rim-driven thruster is then turned to opposite angle -δ and held until the vessel's heading reaches the heading -ψ. This process is then repeated.

The analysis of the results uses characteristic steering values plotted against δ to assess the ship's response.

3.4 (d) Random manoeuvres

With the increasing use of machine learning for system identification and model validation, random manoeuvring tests have gained prominence. Consequently, random navigation data were also collected. Drifting manoeuvres were performed to estimate both the speed of the current in the canal and to estimate the drift caused by the wind. However, accurate quantification of the drift was hampered by the difficulty in obtaining precise speed through water measurements.

4 DATA PROCESSING AND ANALYSIS

4.1 Data filtering and Pre-Processing

The different sensor data were resampled to 10hz and synchronized to a common timestamp. Any blank data entries were filled in by values recorded in the previous timestamp. Filtering techniques were applied to remove outliers and to smoothen the recorded data and filter out sensor noise. Only low frequency motions are of interest for manoeuvring in inland waterways (and not high frequency wave induced motions caused by passing ships), therefore a moving average with a window of 3s was applied to filter sensor noise.

The true wind speed and direction were recomputed based on the relative wind speed and direction measured onboard and the vessel’s speed and heading.

Due to the relatively large superstructure and the small draught, the vessel is very sensitive to wind and a large drift can be observed during a steady turn, as shown in Figure 6. The velocity components are then influenced by the drift (Figure 7). Although very small current velocities are present in a canal, current also had an influence on the ship when sailing close to the entrance of the basin in the channel. If a turn takes about 1 min to be completed, a current velocity of 0.1 m/s can already produce a drift of 6 m.

Mei et al. (2020) proposed a more advanced trials correction method suitable for varying environmental disturbances (Mei et al., 2020); however, this paper employs the simpler ITTC recommended approach of comparing vessel positions at identical headings during consecutive turning circles after a steady rate of turn is reached to accurately estimate and correct for drift due to wind or current, which is deemed sufficient for estimating basic turning circle parameters. This method assumes uniform current or wind creating steady and linear drift. Future work will incorporate wind forces into the system identification to model and reproduce drift from quasi-steady winds. For example, the drift during the turning manoeuvre shown in Figure 6 was estimated at 0.06 m/s in the direction of -90° from the initial heading.

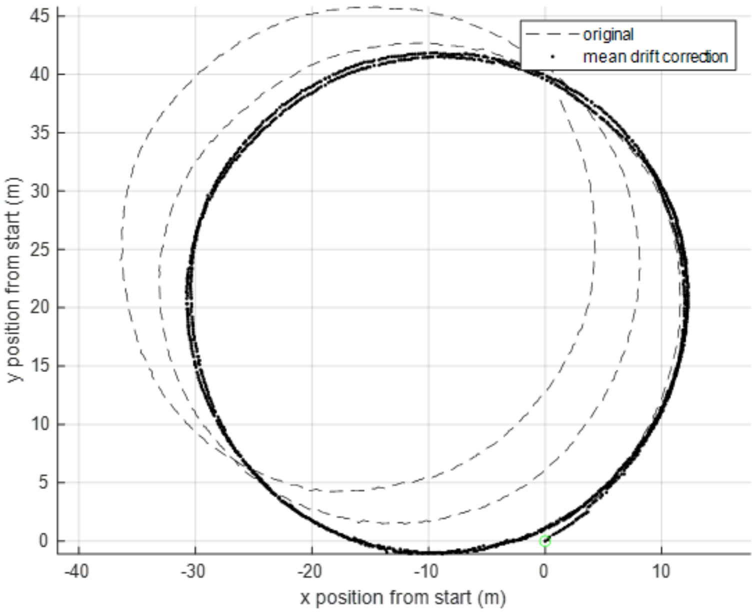

Figure 6. Correction of ship motions assuming mean drift due to wind and current.

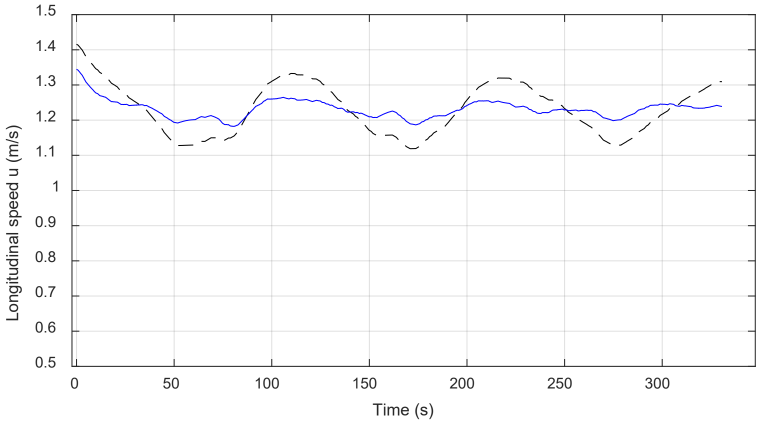

Figure 7. Comparison of measured longitudinal velocity before (dashed line) and after (blue full line) drift correction for a 10° turning circle to starboard side with 40% throttle

4.2 EXTRACTION OF THE MANOEUVRING CHARACTERISTICS

4.2 (a) Acceleration tests

Based on the different acceleration tests executed in upstream and downstream direction the maximum speed reached for different telegraph positions from 20% to 80% can be estimated, as throttle position (n) and speed (u) are proportional (as shown in Table 2 and Figure 8). The acceleration tests can also be used to estimate the reaction time to reach a steady speed related to inertial properties of the vessel.

Table 2. Results from acceleration tests.

	Speed (m/s)		
Throttle (%)	upstream	downstream	no wind
0	0.00	0.00	0.00
20	0.63	0.60	0.61
40	1.26	1.19	1.23
60	1.89	1.79	1.84
80	2.52	2.38	2.45

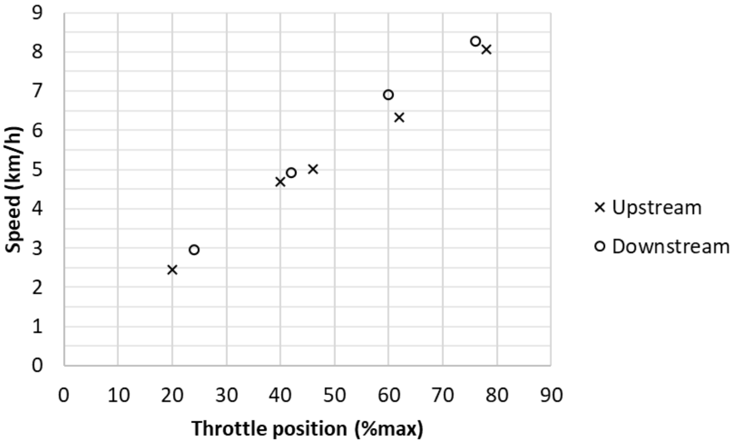

Figure 8. Speed in function of throttle position

4.2 (b) Turning circles

Figure 9 shows an example of output trajectories at 80% throttle for various rim-driven thruster orders. The manoeuvres begin immediately before rim-driven thruster application, following a period of straight, constant-speed running. Applying a thruster angle initiates sway and yaw motions until reaching a steady turn.

The final rate of turn gives an indication of the turning ability of the ship. The final speed gives an indication of the speed loss during a steady turn. The tactical diameter, representing the maximum width of the turning path (cf. Figure 5), is crucial for assessing the space required to execute a turn, particularly in confined waters or during collision avoidance manoeuvres. The advance, which is the distance the vessel travels in its original direction before reaching a 90° heading change, and the transfer, the perpendicular distance travelled during that same 90° turn, further refine the understanding of the ship's turning response. Consequently, accurate determination and analysis of these turning circle characteristics are paramount for ensuring safe and effective shipping in diverse operational scenarios.

Turning circle characteristics, corrected for drift, are presented in Figure 10. While large differences in transfer and advance characteristics are observed, the tactical diameter, final rate of turn and final longitudinal speeds shows clear trends as functions of throttle position and rim-driven thruster angle.

The influence of throttle position on tactical diameter appears limited. However, significant variations in tactical diameter were observed in repeated tests with 10° rim-driven thruster angles, suggesting sensitivity to environmental conditions. The difference between starboard turning circles at 80% throttle is attributed to substantial speed variations between the tests of November 6th and 7th, 2024. This speed difference may be due to the different test location, which spanned both the canal and the basin. Hence, current velocities are expected to differ. Furthermore, the tactical diameters obtained for 10° starboard at 80% and 60% throttle (tested on October 15th and November 7th, 2024, respectively) are relatively large compared to the 40% throttle case. This is also attributed to the test location near the basin entrance, where large moored ships create irregular wind speeds due to shielding effects. The 10° portside turning circle at 60% throttle also exhibited a larger tactical diameter than the 40% throttle case, likely due to significant wind speed variations during the turn.

These variations underscore the importance of accurate speed through water measurements given the uncertainty over environmental conditions. Unlike readily available speed over ground measured by GPS, speed through water is affected by dynamic factors (Dalheim and Steen, 2021). Traditional speed logs (e.g., impeller and doppler logs) are susceptible to these influences, leading to potential inaccuracies, especially in dynamic conditions or near other vessels and structures where wave reflections and flow interference occur. Therefore, careful consideration of environmental factors and appropriate sensor selection and placement are essential for reliable speed through water measurements.

The trials reported here were carried out in fairly good weather conditions with maximum current speeds of 0.1 m/s and mean wind speed of maximum 11 km/h with gusts of 18 km/h, but it can be seen from the analysis in Figure 10 that even then current and wind have an influence. Other factors, such as limited time windows imposed by canal and port traffic, and restricted space, may also render trials complicated. Consequently, these variations must be carefully considered when interpreting the derived manoeuvring characteristics from full scale trials. Non uniform current velocities can be corrected by simply recalculated the speed through water if the current field is known. Wind forces need to be modelled to correct drift induced by non-uniform wind.

In practice, small angles are typically used for course corrections, rarely resulting in full turning circles. The differences observed between the repeated tests is also relatively small compared to the space occupied by a full turning circle, as shown in Figure 9.

Figure 10 gives an overview of the turning circle characteristics. Small asymmetry between portside and starboard side can be observed Figure 10. The lateral speed is around 0.1 m/s (positive toward starboard side) during the turns to portside and -0.05 m/s (negative toward portside) during the turn to starboard side and is not significantly influenced by the thrusters settings.

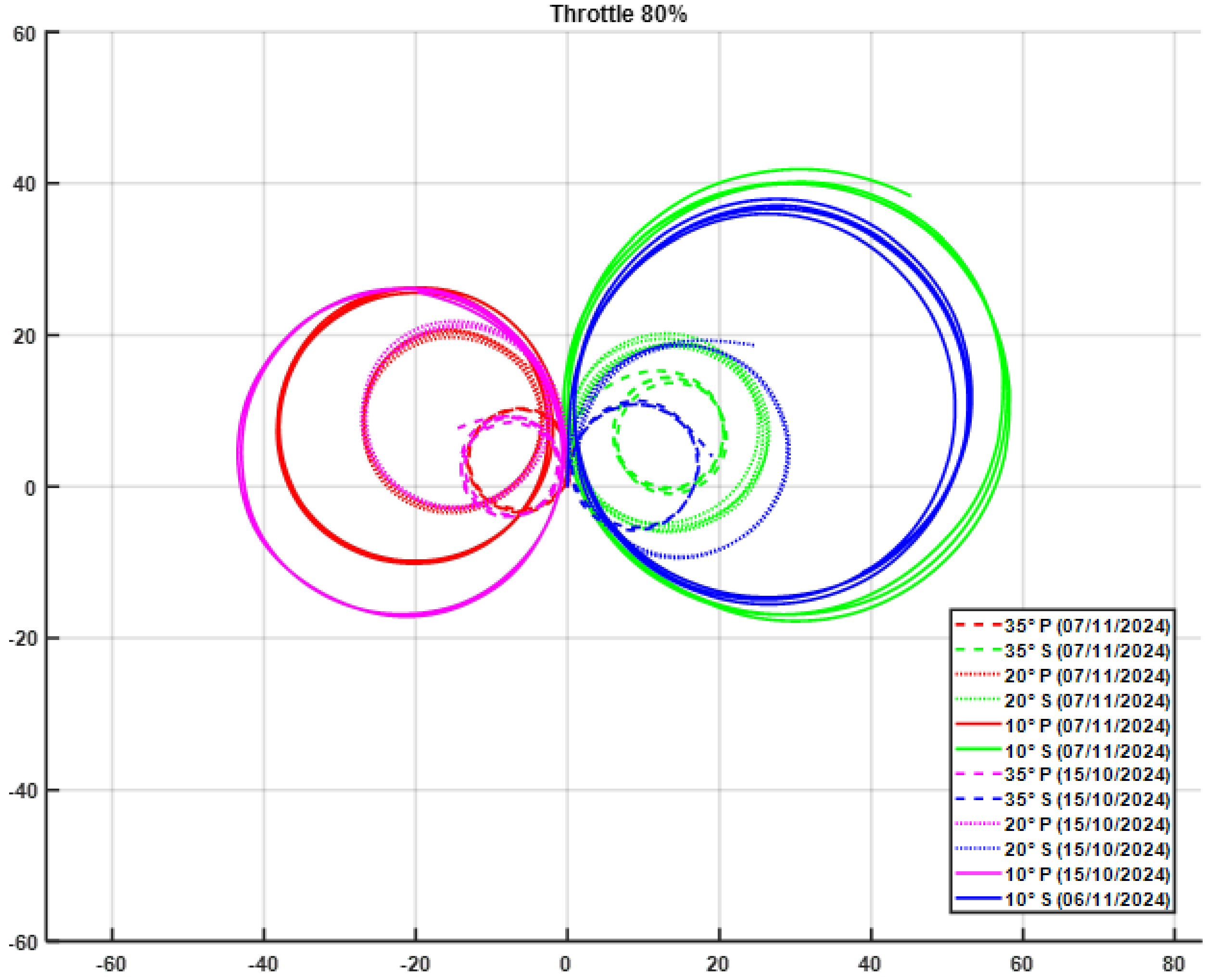

Figure 9. Trajectory of turning circles manoeuvres obtained with 80% throttle.

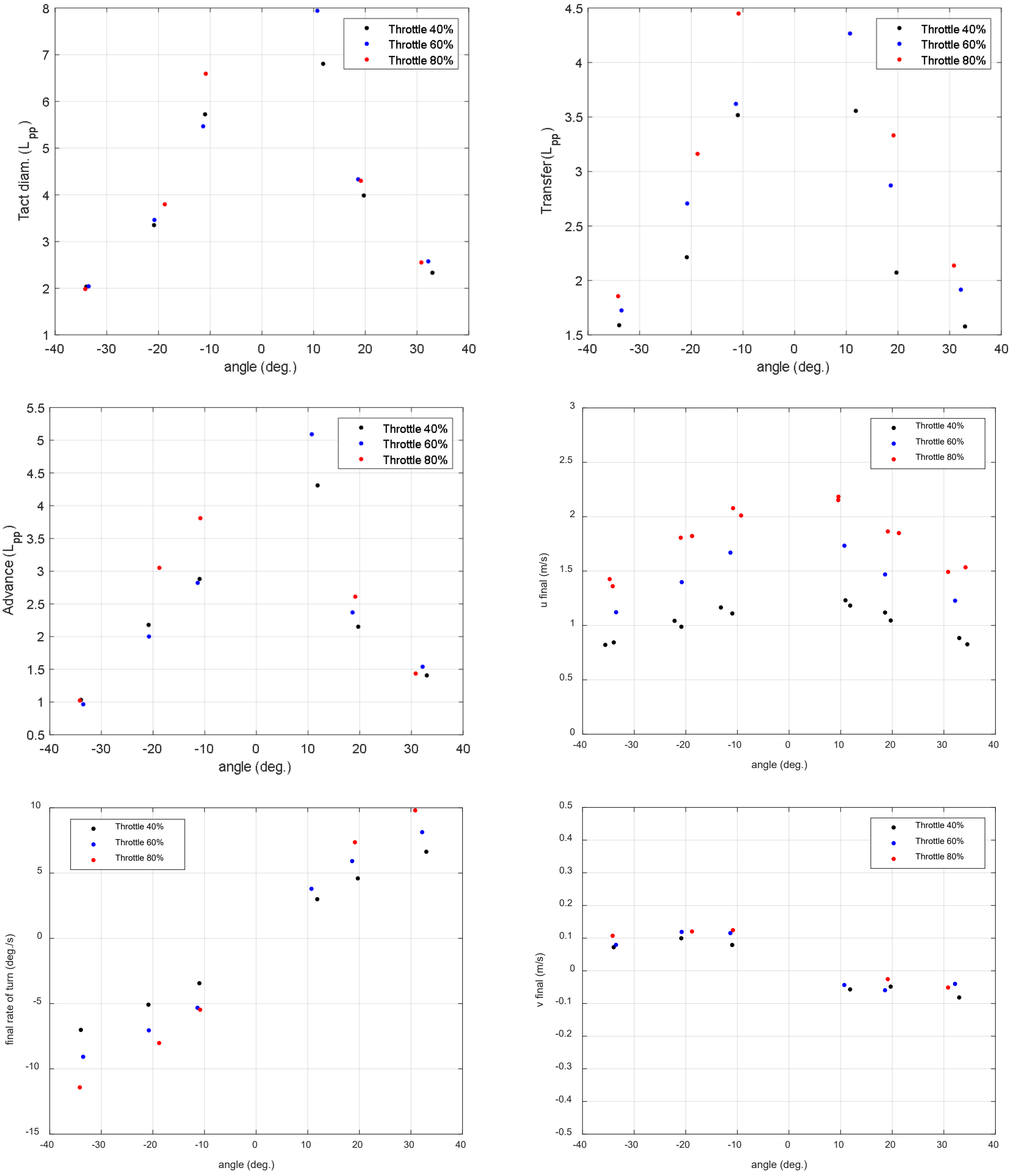

Figure 10. Turning circles characteristics.

4.2 (c) Zigzag tests

A key method for evaluating a ship's ability to maintain a desired course and control unwanted yawing motions is the zigzag test. This standard test involves applying alternating rim-driven thruster commands and provides essential information for ensuring safe navigation and preventing collisions. The test parameters, rim-driven thrust angles (δ) and heading angles (ψ), offer insight into the vessel's response to rapid steering inputs and its effectiveness in mitigating yaw oscillations. Important metrics obtained from this test include the initial and subsequent overshoot angles, the time taken to achieve a specific heading change, and the heading change rate. Lower overshoot values generally indicate better directional stability and improved yaw control, while higher values may point to an excessive response to steering inputs. These factors are particularly relevant when navigating in difficult environments, such as those with substantial wind or current effects, and are essential for performing quick avoidance actions. Zigzag tests outputs (rim-driven thruster angle, heading, rate of turn and trajectory) are also extensively used for system identification of manoeuvring models because of their ability to excite coupled motions, revealing nonlinear dynamic behaviour.

Figure 11 shows an example of 20/20 test from which the rate of turn time response and magnitude can be clearly identified in function of the rim-driven thruster angle order. The longitudinal speed loss is also clearly influenced by the lateral speed and the rate of turn.

During the first part of the manoeuvre, the longitudinal speed decreases due to non-zero thruster angle. In a second part, The speed oscillates around a mean value of about 1 m/s. The maximum speed loss is then reached when v and r reach both their maximum absolute value.

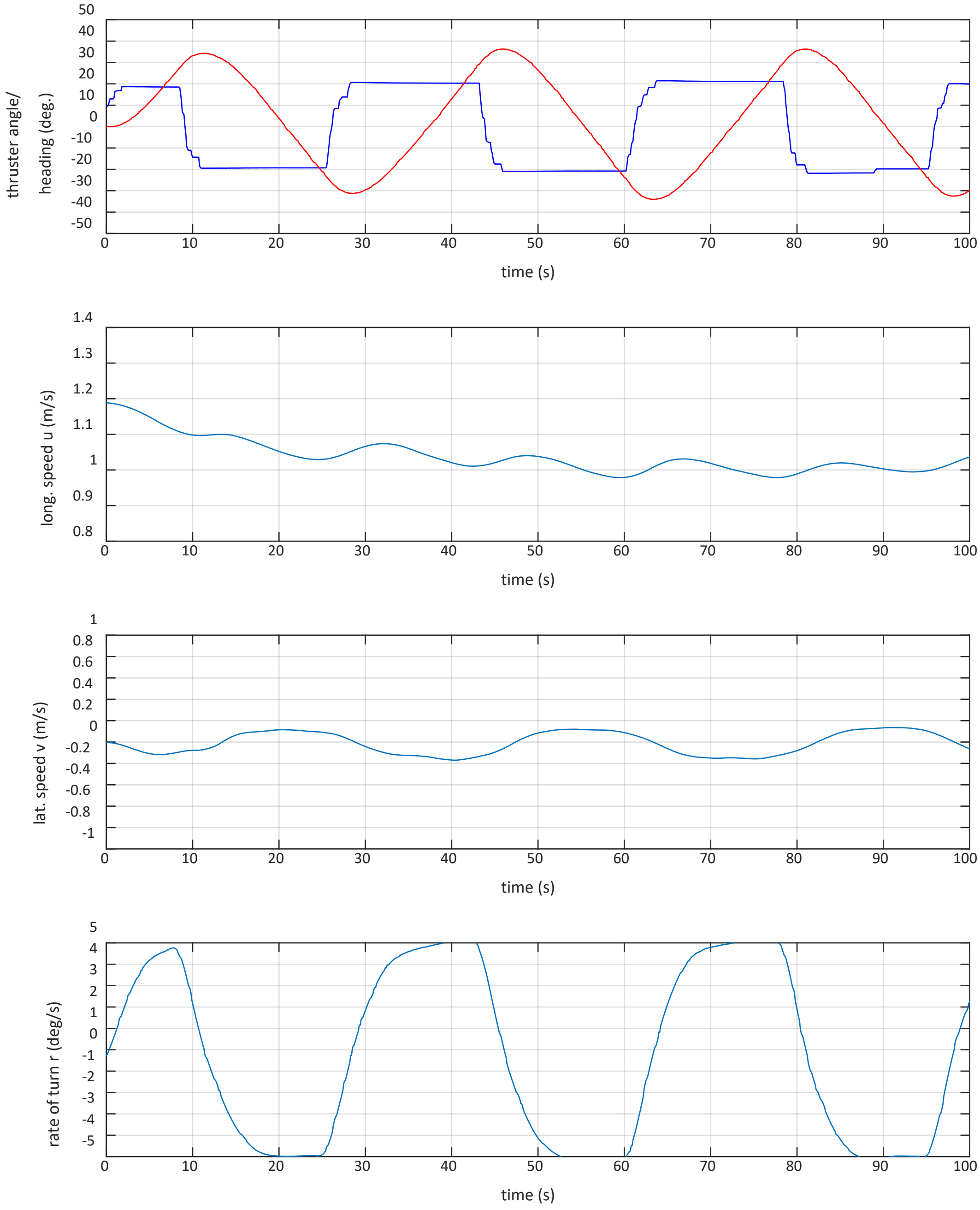

Figure 11. Example 20/20 zigzag test to starboard side - throttle 40%

10/10 and 20/20 zigzag tests starting to portside and to starboard side have been executed at 40%, 60% and 80% throttle. Figure 12 reveals substantial overshoots, with no discernible correlation between these overshoots and either rim-driven thruster angles or throttle positions. This lack of a clear trend likely stems from human operation of the rim-driven thruster, which may introduce inaccuracies in timing and execution of the intended course alterations, as illustrated in Figure 11. Hence standard parameters such as overshoot angles and overshoot times may not be accurate. Additional tests with 10/05, 15/15, 20/10 and 30/30 have also been executed in order to refine the ship's initial steering response and its behaviour during more aggressive manoeuvres which can be used as input for system identification.

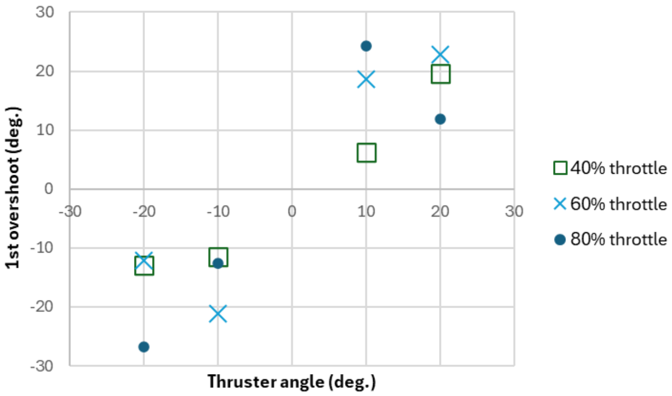

Figure 12. Zigzag test characteristics

5 FURTHER OUTLOOK

Future research will build upon these findings by focusing on several key areas. This includes refining the system identification process through simplified parameter estimation techniques to develop a simplified 3DOF manoeuvring model and exploring the influence of environmental factors such as wind, on the SFAZ's manoeuvring characteristics. The same methodology will be applied to a second LL in Belgium replicating the measurement setup on a different vessel. Furthermore, the derived manoeuvring models will be integrated into the vessel's autonomous control system to enhance its performance and robustness in challenging operational scenarios such as vessels train configuration. Investigations into an adaptive model that can be adjusted to varying design solutions are also planned. The use of such a model at a scale which is suitable for logistical and economic planning will also be investigated. This would allow making data-driven decisions to optimize vessel operations, reduce costs, improve safety, and minimize environmental impact.

6 CONCLUSIONS

The EU Horizon project FOREMAST aims at facilitating the movement of goods using Small, Flexible Automated, Zero-emission vessels (SFAZ). SFAZ is a concept that answers to the challenges facing inland shipping, aiming to revitalize small (urban) waterways offering environmentally friendly solutions.

This paper details the results of a comprehensive series of full-scale manoeuvring trials conducted using a SFAZ prototype. The trials were designed to assess the vessel's dynamic behaviour. The test program included turning circle manoeuvres, zig-zag tests, and acceleration/deceleration tests. These standard tests provide a framework for characterizing a vessel's manoeuvring characteristics. The data collected during these trials provided useful information for quantifying the SFAZ's manoeuvring performance.

The subsequent analysis of the collected data and simple sampling and filtering techniques as well as correction for drift due to environmental disturbances enabled the precise derivation of several key manoeuvring characteristics. These included essential parameters such as advance (i.e. the distance gained in the original direction when turning 90 degrees), the tactical diameter (i.e. the diameter of the turning circle), the overshoot angle (I.e. the angle the vessel deviates from the intended course after a rim-driven thruster input), the speed loss and the turning rate (i.e. the rate at which the vessel changes heading). These metrics are crucial for understanding and predicting the vessel's response to control inputs and external disturbances. Moreover, ship motions in the horizontal were accurately measured and show clear correlation with rim-driven thruster and propeller. The obtained results establish a robust baseline for the future development and validation of a comprehensive manoeuvring model of the SFAZ.

Beyond the specific results for the SFAZ, this work also demonstrates the practical feasibility and significant cost-effectiveness of utilizing small inland vessels for conducting full-scale manoeuvring studies. Compared to traditional methods involving extensive model tests programs and/or CFD or even large crewed vessels, the use of small platforms offers substantial advantages in terms of reduced operational costs, increased flexibility in testing locations and conditions. This approach opens up new possibilities for efficient and frequent testing, accelerating the development and validation of advanced autonomous navigation and control strategies.

Building upon the findings presented in this paper, future research efforts will focus on several key areas. Firstly, the influence of various environmental factors, such as wind on the vessel's manoeuvring behaviour will be systematically investigated. Finally, a simplified, yet comprehensive, 3 degrees-of-freedom (3DOF) manoeuvring model will be developed. This model will balance computational efficiency with sufficient accuracy for practical applications, enabling prediction of the SFAZ's motion in diverse operational environment and configurations.

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