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SEA TRIALS FOR DETERMINATION OF MANOEUVRING CHARACTERISTICS IN SHALLOW WATER CONDITIONS

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SUMMARY

There is a lack of recent sea trial data to validate manoeuvring performance prediction approaches. This is especially the case for shallow water conditions. As a contribution to fill this gap a comprehensive measurement campaign was set up to precisely determine the manoeuvring performance and characteristics of a mid-size multipurpose vessel. The campaign aims to provide a manoeuvring test case for numerical and physical models of manoeuvring characteristics and performance prediction.

The sea trials were performed utilizing the MV MELLUM, a pollution control vessel patrolling along the German coast, owned and operated by the Federal Waterways and Shipping Administration Germany. The sea trials were conducted in the German Bight, where the vessel is in daily operation. To determine the manoeuvring characteristics in shallow water the sea trials have been performed at different water depths. The different water depth and hence the different under keel clearances were gained from accordingly chosen tides and locations at the German Bight. The ship's responses to different under keel clearances in terms of manoeuvring behaviour could be clearly determined by the experimental set-up and the sensors in use.

1 INTRODUCTION

Obviously, sufficient manoeuvring capability is essential for a ship to be seaworthy and for safe navigation. There are two questions connected to this: first what exactly is sufficient and second how to assure that a design will lead to a ship of sufficient manoeuvring capabilities?

The first question was apparently answered by the IMO with the definition of standards for ship manoeuvrability under resolution A.751(18), but there are reasonable objections whether the criteria are sufficiently comprehensive (Oltmann, 2011; Quadvlieg, F.H.H.A. and Coevorden, P. van, 2003). Basically it is discussed if the criteria, defined and suitable for conventional propeller rudder configurations and modern ship designs, are not sufficiently considered. Additionally the manoeuvring characteristics are only valid for deep water conditions, but become very likely relevant when sailing near the coast or even in waterways and approach channels, where shallow water conditions are predominant.

The second question is even more difficult to answer and is restricted by the validity of numerical simulation models. Anyhow, it is definitely worth the effort: provided numerical predictions of manoeuvring characteristics solely based on the hull shape and propulsion data achieve a useful degree of fidelity, preciseness and correctness. Many of the objections listed before could be addressed with this approach at the same time.

The vitality of the ongoing research on numerical simulation of manoeuvres supports this statement. Promising improvements are reported and introduced at the frequent international conferences, for instance (4th MASHCON, 2016; MARSIM 2015, 2015; SIMMAN 2014, 2014).

To validate and proof numerical models and the dedicated approaches, it is a mandatory requirement to have a good to almost perfect conformity with sea trials. This was the impetus for EXXON to perform manoeuvring trials with the VLCC "ESSO OSAKA" and publish the results as a benchmark test case for the research community. This is a profound, precise and well documented test case, which includes sailing in deep waters as well as in shallow waters, that was regarded essential to enable naval architects to develop refined and precise manoeuvring models (Gray, 1978).

Table 1. Accuracy of Positioning at Sea

Method	From	Until	Accuracy
DECCA Survey	1950	1965+	8 - 100 m
LORAN-C	1957	2010	< 500 m
DECCA HiFix	1962	1983+	< 1.5 - 10 m
Syledis	1970	1995	< 2 - 10 m
GPS SA*	1976+	2000	< 100 m
GPS without SA	2000	today	5 - 10 m
DGPS	1996	today	< 0.5 - 10 m
RTK	1993	today	0.01 m

* Selective Availability

Today, the situation improved partly but there is still a lack of sea trial data of high accuracy. Many sea trial campaigns reported were performed in the last century, when accurate positioning was not yet available. In the pre-satellite positioning era hyperbolic systems such as LORAN-C or DECCA and range-range systems such as Syledis were the primary methods for navigation and positioning at sea. As listed in Table 1 they would provide a position within 1.5-500 m accuracy depending on the system and observation constellation (Lekkerkerk 2012). When the satellite based Global Position System (GPS), initialized in 1976 for the US military, was fully operational in 1993 it progressively replaced previous positioning methods (Lekkerkerk and Theijs 2017). By today it is possible to derive horizontal positions within ± 0.01 m and vertical ± 0.02 m making use of Global Navigation Satellite Systems (GNSS) and additional real-time correction data utilizing the Real-Time Kinematic (RTK) method (Riecken and Kurtenbach 2017).

Analog to the development and improvement of positioning systems, the sensors and measurement techniques for most of the additional parameters required at sea trials like motion and heading have improved in their accuracy. Observing this development in the past decade and seeing the need for full scale measurements it was tempting to launch a manoeuvre trial campaign utilising a vessel with available ship design lines to assemble a comprehensive benchmark test case.

2 SET UP OF THE MANOEUVRE TRIALS

2.1 SELECTED SHIP FOR THE TRIALS

For the sea trials a ship was required, which was of reasonable size in terms of Length of Waterline and propelled by a conventional propeller-rudder configuration. Additionally the ship should be available on demand, whenever weather conditions are forecasted beneficial for manoeuvring tests and sea trials. Further it was regarded necessary to have the opportunity to leave the measurement set-up installed on board until the trials campaign was completed.

Figure 1. Multipurpose Vessel MELLUM (Photo: WSA Wilhelmshaven)

The multipurpose vessel MV MELLUM (Figure 1) owned by the German authorities is the ship which suited the requirements best. Her particulars were considered reasonable for physical and numerical model tests with a length of 80 m, a breadth of 15 m and draught of 5.1 m. She is a twin-screw with controllable pitch propellers in ducts and conventional rudders. An additional advantage was that regular maintenance including dry docking and painting of the underwater part of the hull was scheduled just before the trails. This ensured a clean since freshly painted underwater hull and enabled to inspect and survey the hull properly.

2.2 PREPARATION

The ship hull was scanned with a laser scanner (3D-Scanner “Z+F Imager 5010”) while in dry dock (Figure 2). Based on the scans the geometry could be derived for computational fluid dynamics simulations (Figure 3).

As the aim of the project is to assemble a manoeuvring test case for computational manoeuvring models and physical model tests, all the appendages were scanned in addition to the hull with the 3D-Laser Scanner. Subsequently the data was transformed in CAD-data sets, including bow thruster tunnel, rudder profiles, head boxes, skegs, shaft brackets and profile of the ducts (Figure 3).

First use of these data was the calculation of the open water characteristics of the propellers in the duct, which is required to analyse the momentary actual thrust delivered by the propulsion system from the torque and revolution data recorded.

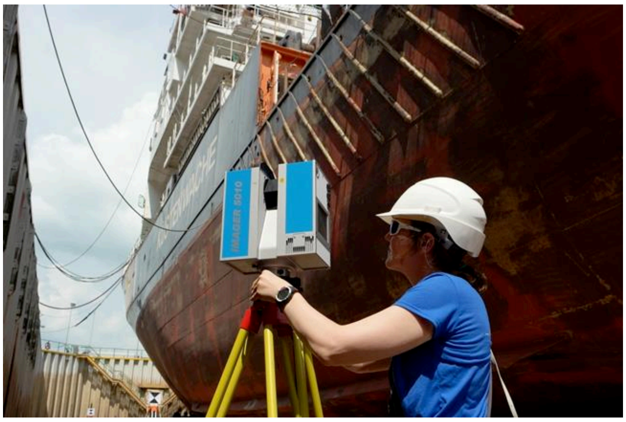


Figure 2. Multipurpose Vessel MELLUM in dry dock for regular maintenance and laser scanning (Photo: BAW)

First use of these data was the calculation of the open water characteristics of the propellers in the duct, which is required to analyse the momentary actual thrust delivered by the propulsion system from the torque and revolution data recorded.

Figure 3. 3D laser scanned data of the hull and the appendages served for CFD-Simulations (Photo/Graphic: Technical University Berlin)

During the maintenance period at the yard interfaces to the machinery automation dating back to the 80s could be adapted and installed to gain access to machinery data, like rpm, EOT etc.. There was a new sensor attached to the servo pushrod to get precise actual rudder position. The rudder commands given by the helmsman were gained together with the actual rudder position from the instrumentation on the bridge.

Table 2. Observed Parameters

Parameter	Unit	Device
Attitude		
Position (UTM)	[m]	Javad GNSS*
Heading	[°]	Octans Fibre Optic Gyro
Pitch	[°]	Octans MRU**
Roll	[°]	Octans MRU**
ROT	[°/s]	Octans MRU**
Heave	[m]	Octans MRU**
Surge	[m]	Octans MRU**
Sway	[m]	Octans MRU**
CoG	[°]	Javad GNSS*
SoG	[m/s]	Javad GNSS*
Draft	[m]	Vega Radar
Environment		
Water Current	[m/s]	ADCP***
STW	[m/s]	ADCP + Javad GNSS*
Water Depth	[m]	On Board Echosounder *2
Water Density	[kg/m³]	CTD-Sensor****
Water Level	[m]	Tide Gauge
Wind Speed	[m/s]	On Board System or DWD station
Wind Direction	[m°]	On Board System or DWD station
Wave Height *1	[m]	Wave Rider Buoy - BSH
Wave Direction	[°]	Wave Rider Buoy - BSH
Engine, Propulsion, Rudder		
RPM	[1/min]	Interface to automation
Pitch	[%]	Interface to automation
EOT-Command	[%]	Bridge instrumentation
Shaft Revolution	[1/s]	Shaft mounted sensor
Shaft Torque	[Nm]	Strain gauge ([µm/m])
Rudder Comnd	[°]	Bridge instrumentation
Rudder position	[°]	Bridge instrumentation

* RTK with SAPOS Corrections
** Motion Reference Unit
***Acoustic Doppler Current Profiler
**** Conductivity, Temperature, Depth
*1 Significant / (Helgoland only)
*2 + BSH (Federal Maritime and Hydrographic Agency of Germany) multibeam surveys from 2015

Next to rudder commands with actual position and engine data, there were torque meter and rotation counter mounted at each of the two shafts. A fibre optic gyro to gain orientation, GNSS antennas for positioning and speed, radar to determine momentary draught as well as tidal gauges, current profilers and wind sensors to detect the environmental conditions were included in the measurement set-up (Table 2).This configuration meets and partly even goes beyond the recommendations and demands presented by the SNAME (Society of Naval Architects and Marine Engineers Ships' Machinery Committee, 1990). Obtaining the vessels dynamic behaviour this precisely and in addition determining the relevant operational data, provides a thorough figure of the manoeuvring behaviour.

The installation was realized in a way that regular ship operation was not affected. The sensors and the equipment remained on board, ready for use whenever a sufficient calm weather window was forecasted.

After the dockyard period and before the MV MELLUM was brought back in service, the time at her berth was used to install the remaining sensors and subsequently the instrument offsets were precisely determined utilizing laser scanner, total station and tape measure (Figure 4). All offsets, hence the instrument positions relative to each other and respectively within the ships coordinate system, were determined with an accuracy of < 0.005 m for instruments on deck and with an accuracy of < 0.01 m for the position of the gyro. To derive best results for the vessels attitude it is necessary to mount the gyro as close as possible to the centre of gravity. Therefore its position was less accessible for offset determination, but the accuracy level is still more than sufficient for the task.

Figure 4. Determination of the sensors offsets on board (Photo: BAW)

2.3 SEA TRIALS

To determine the manoeuvring characteristics in shallow water the sea trials have been performed at three different water depths. At the German Bight being the navigation and service area of the MV MELLUM, two locations

could be defined as suitable. There the trials could be realized at different depth to draught ratios (h/T). Three depth to draft ratios 1.5, 2.0 and more than 5.0 have been defined as suitable. With a draught of 5.1 m the h/T results in the corresponding water depth of 7.5 m, 10 m and > 25 m.
The manoeuvres (Figure 5) were performed according the IMO standard manoeuvres in resolution A.751(18).

The sea trials have been conducted in winter 2016 to 2017 whenever there was calm weather. For the deep water conditions the area around the island of Helgoland was chosen, which provided some shelter from waves and weather. The shallow water conditions required an area of a level bathymetry and sandy bottom. This was found in the survey data of the BSH (Federal Maritime and Hydrographic Agency of Germany; multibeam surveys from 2015), north of Norderney island, close to its shore. Depending on the tide, both draught to depth ratios 1.5 and 2.0 could be realized there.

The MV MELLUM's manoeuvring behaviour was as expected. Being a twin-screw, the turning circles and Zig-Zag-Manoeuvres to port and starboard compared well. Additionally the turning circle in calm water without current was very close to a perfect circle shape (Figure 6), which was very helpful for the correction of the manoeuvres considering displacement by current and wind.

Unfortunately the research project is still underway and so only preliminary results and analyses are included in this paper. However theses do serve as a preview of the full scale manoeuvring trail data set and show some of the issues and problems involved.

3 ANALYSIS OF THE MANOEUVRE TRIALS

Figure 5. Zig-Zag Manoeuvre in shallow water with Multipurpose Vessel MELLUM (Photo: BAW)

3.1 CORRECTION OF CURRENT AND WIND

There were a couple of manoeuvres performed at very low or almost no tidal current. They served as the basis for the later corrections of manoeuvres in current and wind. As mentioned in 2.3 the current magnitude and direction was observed at the time of the trials using ADCP at a position in the vicinity of the trials, so the magnitude and direction are known. The determination of the tidal current directly at the vessels position was not possible especially in shallow water, as the manoeuvres induce too high turbulences in the water for a precise ADCP measurement.

Figure 6 shows the relative position of the course over ground (blue) overlaid with the position shifted for tidal current to get the actual track through water. In that case, the detected mean value for current speed was 0.12 m/s. Based on the almost perfect circle observed at low current speeds, the correction for higher currents was calculated according the criteria of the lowest eccentricity after occurrence of constant rate of turn. When manoeuvring in higher currents, the turning circle manoeuvres' positions over ground get deformed to ellipses with their principal axis perpendicular to the current direction. The course through water remains a circle, which radius is one of the characteristic manoeuvring behaviour criteria.

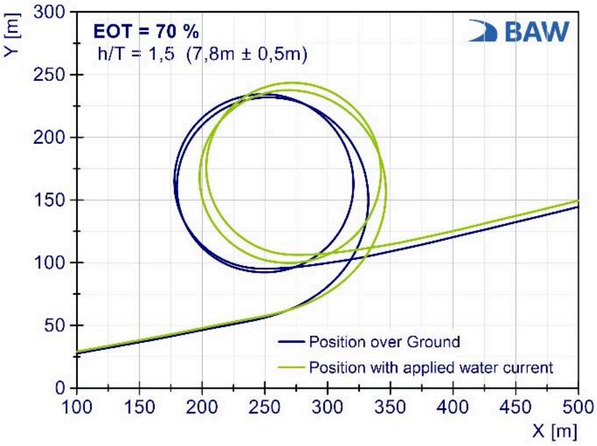


Figure 6. Relative Position of Turning Circle Manoeuvre in shallow water at very low current speed (mean value 0.12 m/s) and 70% EOT, with and without applied tidal current

3.2 EFFECT OF SHALLOW WATER

As depicted in 2.3 there were three ratios of draught to depth (h/T) chosen: 1.5, 2.0 and more than 5.0, respective 7.5 m, 10 m and > 25 m water depth. Shallow water conditions correspond to h/T = 1.5.The 2.0 case is part of the transition regime from deep to shallow water.

There is a clear correlation of the rate of turn and the under keel clearance as one of the shallow water effects. After initial turning, the ship gets into a constant movement characterized by a constant rate of turn and the course through water prescribing a circle with characteristic radius. Figure 7 illustrates the finding of direct impact of remaining under keel clearance when getting in the regime h/T < 2.0. The rate of turn (blue) shows small but significant variation in correlation with small changings in the water depth (red) and accordingly the remaining under keel clearance.

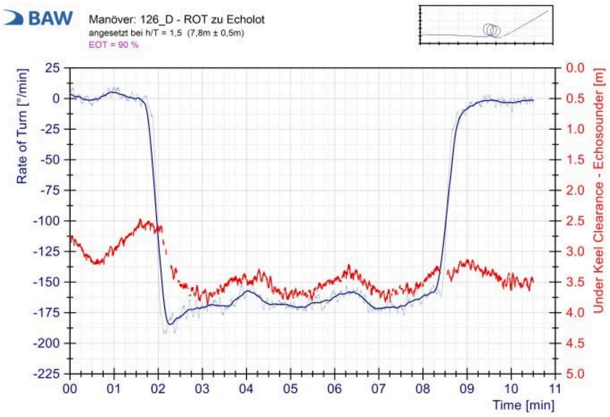


Figure 7. Turning Circle Manoeuvre in shallow water at 90% EOT, blue: Rate of Turn, red: Under Keel Clearance.

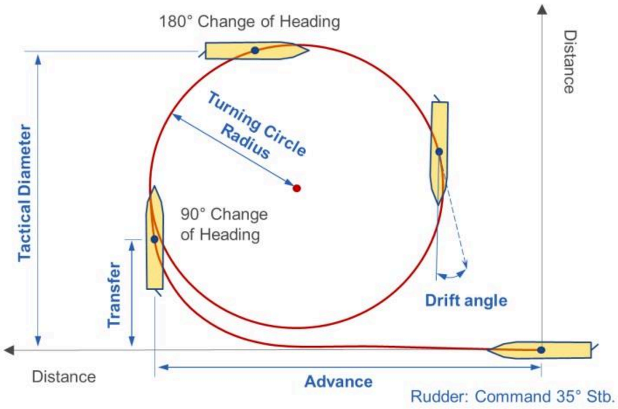
Generally it is observed, that the radius increases with decreasing water depth. The analyzed turning circle radii of this campaign given in Table 3 follow and support this empiric rule. The mean radius is larger by 1% for h/T = 2 and 14% h/T = 1.5 compared to deep water conditions of h/T = 5. While the tactical diameter shows a similar behavior as the radius, with an increase of 4% (h/T = 2) and 14% (h/T =1.5), the decrease in advance in shallow waters is less obvious with 5% (h/T = 2) and 6-7% (h/T =1.5) compared to deep water condition.

3.3 INFLUENCE OF PROPULSIVE POWER

All standard manoeuvres have been performed at least 4 times to check repeatability and for average determination. The variance of the initial conditions was next to the water depth the initial speed. For comparability and ease of numerical modelling, not the actual speed was prescribed, but the proportion of engine power delivered. In shallow water the speed reduces compared to deep water at the same power delivered. Since in the campaign the delivered power and thrust were determined, it was regarded beneficial to follow this approach.

Table 3 offers a comparison of the characteristics of the turning circle manoeuvre in terms of shallow water effect as well as of propulsive power delivered over the entire manoeuvre. It can be observed that the initial speed varies with the power delivered by an average of 15% between EOT 70% and EOT 90%. However the mean speed in the uniform phase of the turning shows smaller speed drop at less propulsive power. There is an average decrease of 47% for 70% EOT and 52% for 90% EOT. Hence the speed decrease between deep water and shallow water for the uniform phase coincides for both the propulsion powers, with having the same speed for h/T = 5 and h/T = 2 and a 10% higher speed for h/T = 1.5 compared to the deep water uniform phase. This is in good agreement with the turning radius' determined, which are of comparable sizes.

Table 3. Turning circle characteristics



h/T	Propulsion Power EOT 70%	 EOT 90%
	advance / tactical diam. / radius [m]	
>5.0	161.3 / 151.3 / 65.0	168.5 / 156.7 / 65.5
2.0	153.2 / 157.3 / 65.7	159.7 / 163.5 / 66.1
1.5	151.7 / 172.9 / 74.3	156.1 / 179.5 / 74.5
	Mean speed through water: initial / manoeuvre [kn]	
>5.0	12.2 / 6.1	14.0 / 6.4
2.0	11.8 / 6.1	13.9 / 6.4
1.5	11.5 / 6.7	13.0 / 7.0
	Mean UKC: initial / manoeuvre [m]	
>5.0	46.2 / 45.1	43.6 / 43.9
2.0*	5.0 / 5.8	5.1 / 6.3
1.5*	2.5 / 3.4	2.8 / 3.8

* Seafloor is slightly sloped and manoeuvres were generally performed towards deeper water.

4 CONCLUSIONS

An elaborate sea trails campaign was successfully finished providing the full set of data for tuning and validation of manoeuvring models, numerical as well as scaled physical model tests. The data set consists of the planned hull shape, the actual hull shape in the moment of the sea trails, the shape of the appendages and the profiles of all lifting surfaces, the ducts and the propeller blades, the thrust delivered, the environmental conditions like water depth and current speed and all of them linked with attitude determination of very high precision.

In the first step, the turning circle manoeuvre characteristics were analysed and evaluated as presented here. The other manoeuvres still to be analysed will complete the figure. After finishing the analysis, the full set of manoeuvring data shall serve as a public test case and will be published as a thorough benchmark test.

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