

Manoeuvring Study – Norwegian Double-Ended Ferry

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ABSTRACT: The Norwegian coastline has many long fjords where crossings are necessary for transportation of goods and passengers. In the last decade, the focus on reduced travel time along the main roads in coastal areas has increased the building of bridges and subsea tunnels. However, at present and in the future many fjord crossings will depend on ferries. The Norwegian government [7] requires that ferries, like all coastal ships in Norwegian waters, should be designed for zero or low greenhouse gas (GHG) emissions to meet the national goal of 50% reduction of GHG from coastal shipping by 2030. As ferry services are regulated by national or local governmental bodies, all new ferry operations should be performed using zero- or low-emission ferries. Thus, ferry companies require new and innovative ferry designs with reduced resistance, resulting in reduced installed propulsion power.

This paper describes work done by the ship designer HAV Design AS (former Havyard Design & Solutions AS (HDS)) to meet the governmental request for ferries with a low environmental footprint. Work on a double-ended ferry design is described. In the early design phase manoeuvring performance is not a priority item, partly due to lack of a simple and reliable manoeuvring performance prediction tool for unconventional ship designs. It is well known that optimization of resistance can be at the cost of manoeuvring performance. In this paper, a specific double-ended ferry design will be used as a case. Outcomes of design simulation of manoeuvring performance are compared to manoeuvring full-scale tests in deep, calm water. Full-scale test results will later be used to tune a simulation model for a future training simulator for double-ended ferry, where full-scale manoeuvring tests have been performed, will be used as a test case. This paper shows how the designer has worked with these two topics in parallel in the final design stage where both experimental and numerical tools have been used for design verification.

1 INTRODUCTION

Norway has a very long coastline with many wide and deep fjords. The increased focus on efficient, safe and environmentally friendly traffic in coastal areas has led to a debate on different ways for fjord crossing. The plan for a ferry-free main road from Kristiansand to Trondheim along the western part of Norway is shown in figure 1. The plan has been prepared by the Norwegian Road Authority. To fulfil

the objective of the plan, eight existing ferry routes must be removed and replaced by other types of fjord crossing, such as very long bridges (including floating types) and subsea tunnels. Based on new cost estimates for different fjord crossing scenarios, some of the crossings will continue to be operated with ferries. However, to fulfil the national goals for coastal shipping [7] the ferry fleet must be renewed by introducing low, preferably zero, emission vessels. For some of the long and exposed routes in the

northern part of Norway, low-emission ferries are the only solution. Previous tender documents prepared by the national road authority and regional authorities responsible for transport services ask for zero or low emissions fiord crossing ferries. In the process of evaluating service offers, the two main parameters have been operational costs and emission footprint. In these tenders, the cost is weighted 70% and environmental aspects 30% when comparing offers from ferry companies, meaning that the concept with the lowest price will not necessarily win. Lately, the new tenders from different governmental bodies require zero emission for fiord crossing ferries. Thus, the only criteria when comparing offers will be the total costs (investments and operations) for a given licence period.

In the competition for new transport contracts, all ferry companies need new vessels or retrofiting old vessels with zero/low emission engines. As a result, national ferry companies have requested new vessel designs from many Norwegian ship designers. This paper describes design challenges related to double-ended ferries, how design tools and model tests were used to verify a specific ferry design (H-936) developed by HAV Design for a 120 car capacity ferry. Sea trials were used to validate manoeuvring performance of these classes of ferries. Four H-936 ferries have been built and operating on different routes in Norwegian fjords.



Figure 1. Future ferry free main road (E 39) from Kristiansand to Trondheim (courtesy Norwegian Road Authority).

2 DESIGN CONSIDERATIONS

Many of the double-ended car ferries in Norway operate in sheltered waters, but these waters have many obstacles, such as islets or underwater reefs, combined with narrow passages and shallow water effects close to the ferry quays. Transit routes are often short, many times shorter than thirty minutes. This

means many docking operations every day, often between twenty and forty.

The main operation can be divided in four phases: acceleration – transit – retardation and manoeuvring / berthing. Very often both retardation and final manoeuvres overlap. Before entering the quay, waters are often both narrow and shallow introducing shallow water and bank effects changing the manoeuvring performance. In addition to these effects, the captains have experienced unusual manoeuvring responses during retardation before arrival at the ferry port. This has led to development of special operational procedures on how to use the fore and aft azipulls in the retardation phase. Adding the influence of harsh weather conditions increase the challenges to be coped with by the bridge crew.

When ferry companies compete for governmental fjord crossing contracts, two factors are weighted in the selection process – operational costs and emission footprint. In addition, operational regularity is a challenging as it is required that operation should be possible under all weather conditions, except extreme cases where the weather gets a specific name. As operational costs are strongly related to energy consumption (electricity, different types of fuels or hybrid solutions), the design will focus on resistance reduction and propulsion efficiency in addition to selection of engine power sources.

To be able to fulfil governmental requests for reduced GHG emissions from new ferries, the ferry companies have requested new vessel designs from many Norwegian ship designers. Double-ended ferry designs are often selected to reduce turn-around time at the ferry quays. As most of the crossings are inside the fjords, the critical factors for an energy efficient hull design are:

- Low calm water resistance
- High propulsive efficiency
- Controllability in strong winds near quays

Additional items to be considered are green water/sea spray on the car deck and directional stability (to reduce the additional resistance from using control units).

Figure 2 is a generic illustration of a ship design process. As can be seen from the “Performance” list, manoeuvring characteristics is missing. This could result in new ship designs giving ship masters that is difficult to handle, especially in confined waters and ports.

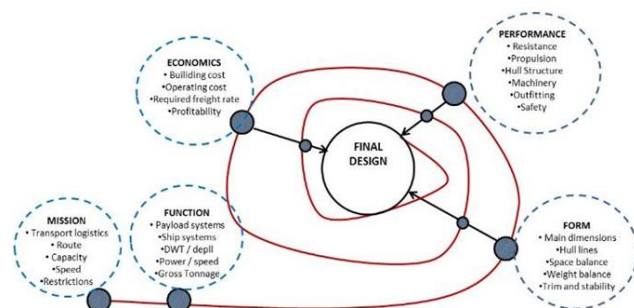


Figure 2 Design process used for a double-ended ferry.

To illustrate design tools used by HAV Design, the work related to development of their H-936 (120 car) double-ended ferry is used. The main particulars of the vessel are listed in Table 1 and a picture of the vessel in the transit phase is shown in Figure 3. A brief overview of the tools (experimental and numeric) used by HAV Design will be described. For illustrative purposes, the H-936 is used as a case. Tools applied are listed in Table 2.

Table 1. Main particulars and propulsion units of the HAV Design H-936 double-ended ferry design.

Geometric parameters	
Length overall L_{oa}	111 m
Length between perpendiculars L_{pp}	84 m
Breadth B	17,5 m
Max draught T_{max}	3,6 m
Test draught T	3,0 m
Block coefficient C_B	0,36
Main propulsion	2 x 1200 kW
2 x Rolls-Royce AZP85-EL FF 12.5 TME	



Figure 3. Double-ended ferry – HAV Design, double-ended design H-936.

Table 2. Hydrodynamic tools used for designing the H-936 double-ended ferry.

Experimental hydrodynamics (model tests)
Open water tests, stock and design propeller
Thruster fwd/aft load variations
Resistance tests, 2 waterlines
Self-propulsion tests, 2 waterlines
Trim optimization tests
Seakeeping tests, regular waves
Seakeeping tests, irregular waves - free running
Calm water stop and acceleration tests
Numerical hydrodynamics
VeSim (seakeeping, manoeuvring and dynamic positioning)
CFD (resistance, manoeuvring, hull optimization)
Stability
Internal weight analysis
Internal route, energy and fuel study
Station keeping analyses for thruster capability
Veres motion code: <ul style="list-style-type: none"> - Added resistance indication - Motion characteristics optimization
CAESES <ul style="list-style-type: none"> - Automated CAD/CFD optimization of hull - Ship speed and powering - Calm water resistance - Propeller diameter optimization - Performance in real seas
Star CCM
Calm water flow analyses optimization

3 INITIAL DESIGN VERIFICATION TESTS

Using the given design, HAV Design contracted SINTEF Ocean to conduct a series of different model tests and numerical studies (see Table 2) to investigate design characteristics and to verify the numerical models used in the early design phase. Experimental studies were performed in SINTEF Ocean's Towing Tank. At this stage studies of manoeuvring performance were not included. Model scale used for these tests was 1:12.637.

The outcomes of these tests were compared to numerical predictions from the tools described in the previous section. Figure 4 compares predicted power (on the electric motor) and measured values for sea trial with four sister vessels. The figure shows that predictions based on the model test overestimates the measured from the four sister vessels of the H-936 design for speeds above 11 knots. For the first three delivered vessels (ships 1 - 3), trial trip results have been corrected using the ISO standard [4]. This will also be done for the fourth ship (yard trials not analysed yet). The figure includes computational fluid dynamics (CFD) calculated resistance. As can be seen, these results compare well with sea trial data.

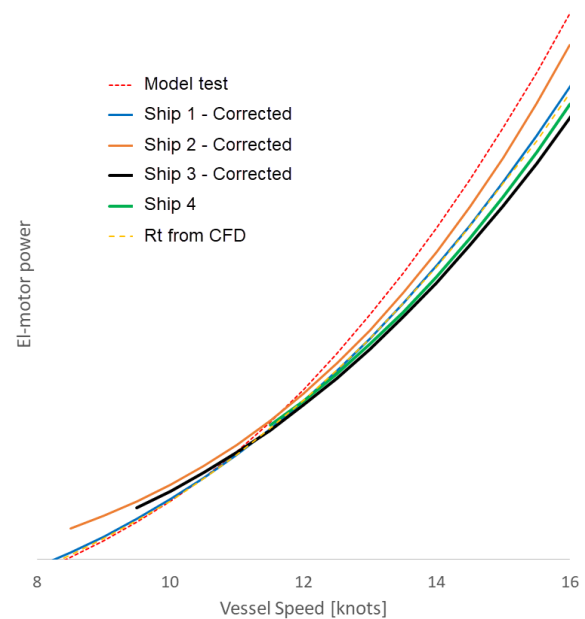


Figure 4. Comparison between sea-trial data on sister vessels and model test results.

4 DESIGN VERIFICATION OF MANOEUVRING PERFORMANCE BASED ON MODEL TESTS

For an MSc thesis [5] HAV Design and NTNU (Norwegian University of Science and Technology) collaborated to fund the building of a new hull model and to run additional model tests in SINTEF Ocean's Towing Tank. For Planar Motion Mechanism (PMM) and oblique towing tests the model scale was 1:15.33 giving an approximately 8 m long mode (somewhat smaller than the model used for resistance and propulsion tests). Figure 5 shows the model in the Hexapod system.

The focus of these tests was to investigate the quality of numerical tools for simulation of manoeuvring performance. In principle, two methods were used to generate input data to SINTEF Ocean's six degree of freedom (6 DOF) time-domain vessel simulation tool VeSim [9]. The first one is purely numerical using the HullVisc program to generate the hydrodynamic input file for VeSim [6]. It is based on linear slender body theory and a cross-flow drag formulation for non-linear damping forces. The second one is based on experimental data from model scale oblique towing and PMM tests. In the thesis, Leinebø compared outcomes from these sets of input data. A mathematical three degree of freedom (3 DOF) solver for the non-linear coupled surge, sway and yaw equations (SIMAN), was also used with only numerical input data. The simulations were performed with the aft propulsion unit working and the fore azipull turned off.

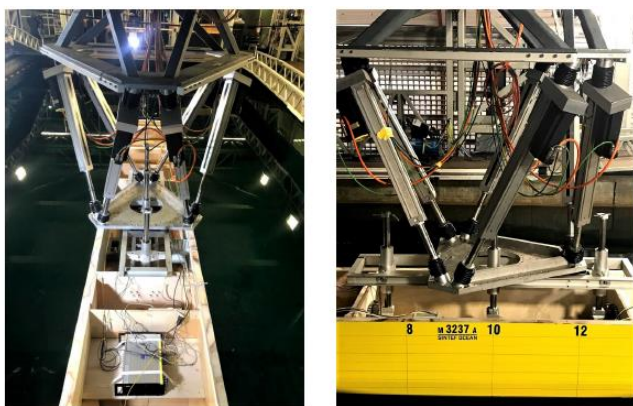


Figure 5. HAV Design H-936 connected to seakeeping carriage for PMM tests.

Challenges were experienced using an azipull propulsion model, which were solved by utilising a simplified propulsion and rudder model. They were tuned to and compared against a working model in SIMAN (previous time-domain manoeuvring simulation tool used by SINTEF Ocean). This model showed good agreement with different standard manoeuvring tests [3] with rudder/azipull angles up to 20-25 degrees (with the same numerical hull input). Figure 6 shows the results of a complete spiral simulation using both time-domain simulation tools. In figure 7 there is good agreement for the full-scale sea trial and predicted turning circle manoeuvre when VeSim used a 20- and 25-degree rudder angle and SIMAN used a 35 degree azipull angle.

Figure 6 shows some challenges when using the numerical HullVisc tool (based on slenderbody and strip theory) to create the input field for VeSim. This is mainly due to the design of double-ended ferries where the combination of main dimensions is outside the parameter range for regression formulas used when developing the present numerical tool. The numerical method experienced some unstable solutions because of this. A new numerical tool based on CFD are under development at SINTEF Ocean, and it is presently tested for a smaller HAV Design (50 car) double-ended ferry. Until CFD results are validated against model test results, the simpler and faster HullVisc tool will be applied in the early design phase.

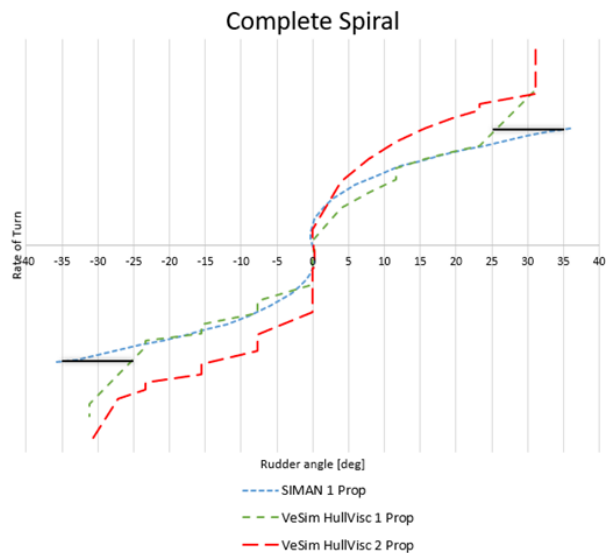


Figure 6. Complete spiral manoeuvre simulations of H-936.

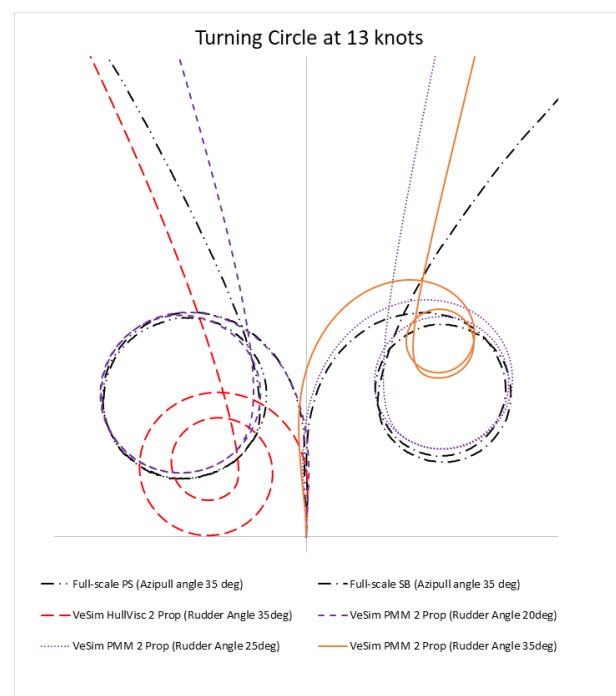


Figure 7. Turning circle manoeuvre. Simulations vs full-scale of H-936 (identical SB and PS simulations)

Two different ways of using experimental results were applied. Both are based on mapping force measurements from the experiments to common time series for surge and sway forces and yaw moment. A modified least square method was then used to estimate hull force coefficients in a 3 degree of freedom model developed by Ross [8] integrated into the six degree of freedom model used in VeSim. In the first one, only PMM test data was used and in the second the combined oblique towing and PMM tests were used. Including the oblique towing force measurements gave a large difference in some of the hydrodynamic coefficients (also for added mass coefficients). This showed how different set of coefficients in the motion equations could be developed from model tests. Even if the values of the individual coefficient in the simulation varied significantly, the outcomes from VeSim simulations were nearly the same for IMO's turning circle test [3].

But this will give challenges for manoeuvres outside the measured areas.

Table 3 compares numerical and experimental input data used in VeSim with the average overshoot angles from full-scale trials. The table presents the differences between the full-scale average overshoot angles and the predicted overshoot angles using different VeSim input. Negative values represent lower overshoot angles in the simulations compared with full-scale results, and positive values vice versa. The experimental input shows the improvement of the overestimation of the vessel's course-keeping and course-changing ability in the numerical input. The RMS values from the sea trials varied between 1-2 degrees, resulting in a high percentage deviation at low overshoot angles. The 5°/5° zig-zag manoeuvre was requested by the master during sea trials in May 2019 (see section 5).

Guidance notes from NAUT(AW) class notation states [1]: *The characteristic parameters should be within 15% of the parameters obtained from the full-scale trials. If deviation exceeds this figure, the whole full-scale trial program should be completed.*

Comparing overshoot angle predictions from VeSim with the measured sea trial data, it is seen that some results deviate more than 15%.

Table 3. Zig-Zag manoeuvre test, numerical (HullVisc) and experimental input (PMM) data in VeSim compared with full-scale results of H-936.

Zig-Zag Manoeuvre Simulations		Overshoot angles differences		
		1st (Deg)	2nd (Deg)	3rd (Deg)
Numerical input	5/5	+ 0.7	- 1.5	- 0.6
	10/10	- 1.9	- 5.0	- 4.7
	20/20	- 4.9	- 2.8	- 5.6
Experimental Input	5/5	+ 1.3	+ 0.3	+ 1.3
	10/10	- 0.1	- 1.8	- 1.7
	20/20	- 1.2	+ 0.6	+ 2.3

When applying the present simplified numerical tool HullVisc to generate input data to VeSim, the result is large discrepancies between simulated turning circle characteristics to the ones coming from experimental input data. This is an expected result as the HullVisc tool used for a double-ended ferry is outside of the validity range of correlation factors used in HullVisc as they are adapted to conventional merchant ships. The hydrodynamic coefficients in the manoeuvring equations coming from experimental PMM results give better prediction of IMO standard manoeuvres. In the early design phase, there is a need for a numerical tool for generating input, for unconventional ship designs such as the double-ended ferry, to time-domain manoeuvring simulation tools. As mentioned earlier, there is an ongoing activity to develop a specific CFD code for better estimation of hydrodynamic coefficients for the manoeuvring equations for unconventional ship designs.

Both numerical and experimental input in the turning circle simulations showed a much higher peak in rate of turn in simulations, with this a quicker established drift angle. The simulations also gave too low a period between overshoot angles, because of higher peak values in rate of turn. Further

investigation showed that the simulation did not capture the full effect of the fore azipull.

5 VALIDATION OF MANOEUVRING PERFORMANCE – IMO STANDARD MANOEUVRES

For documentation of the manoeuvring performance of the H-936 design, the ferry company Fjord1 made the double-ended ferry MF Suløy available for sea trials in May 2019. The tests were performed in Vartdalsfjorden where the water depth is 300 m, figure 8. Weather conditions were excellent, with no appreciable waves and a very low wind speed (2.8 m/s, direction 166°). Tidal current during the test period was not measured. Two sources were used for data collection. The main data source was the vessel's Integrated Automation System (IAS), where among position, heading, thruster settings, rpm and thruster angle were measured. In addition, SINTEF Ocean a dual Global Positioning System (GPS) for measuring position and heading. All signals were recorded synchronously as time series with a sampling rate of 1 Hz.

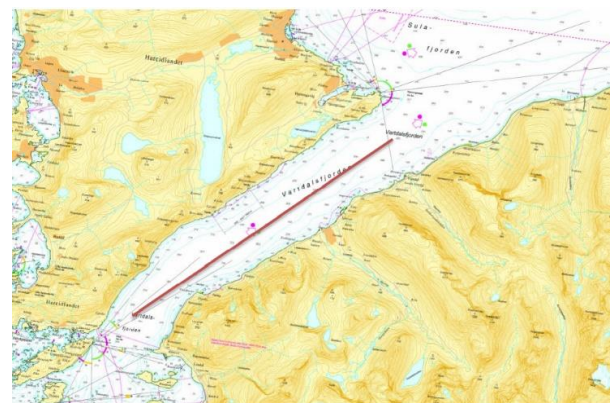


Figure 8. Test area for manoeuvring test with car ferry "MF Suløy".

An overview of the main test program is given in Table 4. The first part of the test program included IMO standard tests. Outcomes of these tests were used in the preparation of the vessel's Manoeuvring Booklet [2]. The second part was manoeuvres specified by the master on the ferry. Finally, some IMO standard tests were repeated with a small forward trim (obtained by positioning heavy trucks at the bow).

Table 4. Manoeuvring tests from MF "Suløy" test campaign May 2019. Test speed 13 knots.

Test type	Number of tests	Test parameters	Comment
Turning circles	7	Azipull angle 35°	One 720°
Zig-Zag	11	5°/5°, 10°/10°, 20°/20°	
Direct spiral	4		
Reversed spiral	9	5°/min, 10°/min, 15°/min	Investigating width of hysteresis loop
Stopping	21		Varying engine control modes, manual control

Figure 9 is a picture of the vessel performing an IMO zig-zag test. As can be seen, the sea in the test area is calm. Some initial validation studies using the full-scale tests have been described in section 4. Figure 7 (in section 4) compares turning circle paths and ways to handle the deviations between measurements and predictions by either changing the control angle of the azipull unit or replace the unit by a conventional rudder/propeller system. It was found that the applied generic azipull model gave too high control forces for high angles. Simulations were thus also run using different azipull angles – the best turning circle results were obtained using a 25° control angle to port and 20° to starboard. Also, for the overshoot angles, there are some differences between measured and predicted values. Improved outcomes from VeSim are obtained by tuning the hydrodynamic coefficients and especially control system parameters using the deviations between the initial VeSim predictions and full-scale measurements.

There are two main reasons for the difference between sea trial manoeuvres and VeSim predictions. The first one is due to limitations introduced by the Hexapod system used by SINTEF Ocean for PMM tests. For highly manoeuvrable vessels, such as double-ended ferries with azipull systems, it is not possible to obtain the high drift angles and yaw rates that are measured during turning circles and other tests applying large control unit angles. The second one comes from the existing model of the hull and azipull unit interaction in VeSim. CFD is presently used to study these interactions and new models for interaction effects will be developed for double-ended ferry designs.

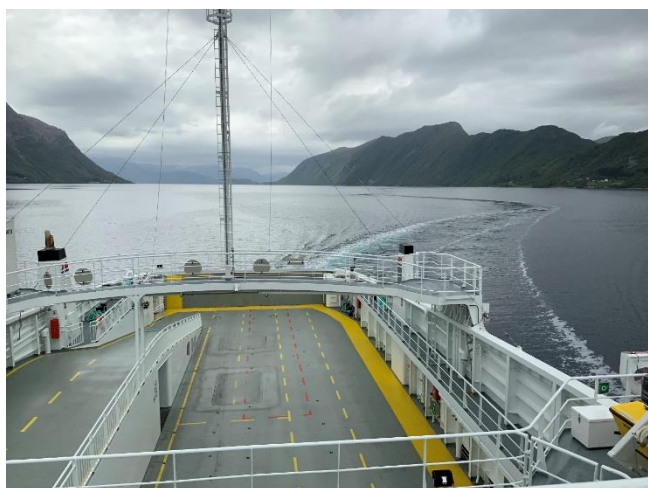


Figure 9. Zig-zag test seen stern-wise from the bridge of MF Suløy.

The results of the manoeuvring sea trials have been used by SINTEF Ocean and HAV Design to tune hull and propulsion force models for the VeSim simulation tool. The goal of this work has been to reduce the differences between sea trial measurements and VeSim predictions. The reliability of VeSim with numerical input for new hull forms needs to be improved so it can be used as one of the design tools by HAV Design in their work to develop new zero-/low-emission double-ended ferries with high manoeuvring performance. Based on tuning

experience, it is concluded that improvements are needed with respect to:

- Four quadrant azipull model
- Interaction effects between hull and azipull

Two alternative ways of improving VeSim input for early design phase studies are presently investigated. One is to extend the present HullVisc tool to unconventional ship designs by using 3D potential flow theory. The other one is to generate input data from a CFD based PMM.

6 SOME COMMENTS ON OPERATIONAL EXPERIENCE

The IMO standard tests give information for the ship designer more than for ship captains. Despite double ended ferries showing a low degree of directional instability, based on direct and reverse spiral tests, and qualifying well within IMO's criteria on zig-zag tests, there is no guarantee that the ferry is steerable in critical and typical manoeuvring situations, especially during the retardation phase. One specific effect that is purely related to the hull and propulsion units is the behaviour during retardation. Some of the ferry captains initially reported unusual effects related to control of the vessel during retardation manoeuvres. Analysing the reports, it was concluded that lack of experience with the actual control system (azipulls fore and aft) caused some of these effects. The higher the initial speed when initiating retardation, the more unstable the vessel will be in the retardation phase. Such an operational characteristic increases the stress level for the captains during the final phase of a voyage. To improve this behaviour, a set of new test manoeuvres have been suggested by the captains to identify the best operational procedure for operating both of the azipulls during retardation and docking. The outcome of such tests, and a specific operational guideline for these part of the operation under varying environmental conditions, should be documented in the vessel's Manoeuvring Booklet.

Based on discussions with double-ended ferry masters, they are asking for better documentation of low-speed manoeuvring performance, especially for harsh weather conditions. This should also be part of the vessel specific Manoeuvring Booklet. In addition to these tests, which will reveal behaviour during sea trials, it is even more important to detect manoeuvring challenges during the design process and hence modify design to overcome this. Hence, a methodology for developing a reliable simulation model that capture the behaviour during retardation should be specified. The essence is to conduct systematic CFD studies/ model tests to generate hydrodynamic coefficient input to the time domain simulation model so it can be used as an early design tool. This tool (for instance a simplified version of VeSim) could then be used by designers to investigate manoeuvring performance, both IMO standard manoeuvres and ship specific low speed manoeuvres requested by captains.

7 VESSEL SPECIFIC MANOEUVRING HANDBOOK

As described prior, the results from service speed turning circles, zig-zags and stopping tests were used to produce the Wheelhouse Poster and the Pilot Card. Additional IMO manoeuvres such as spiral tests and manoeuvres specified by the master (especially low-speed tests) were used by HAV Design in the development of the ship specific Manoeuvring Booklet, see figure 10. As mentioned in the previous section, vessel characteristics during the retardation phase should be found here.

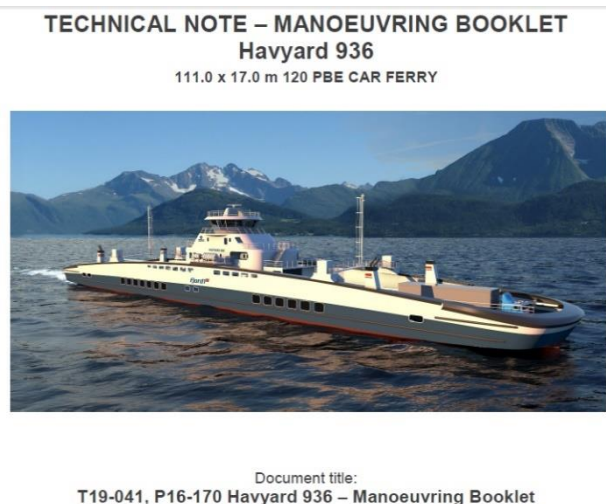


Figure 10. Front page of Manoeuvring Booklet for double-ended ferry MF Suløy.

8 CONCLUSIONS

From the MSc study, it has been shown that present numerical models to predict coefficients in manoeuvring equations need to be improved. The position of the separation point, used in the calculation of hydrodynamic derivatives, deviates significantly from values used for traditional displacement vessels. The use of regression type coefficients is not recommended for double-ended ferries, partly due to the fore and aft symmetry of the hull. Based on the comparison of simulated standard manoeuvres and full-scale measurements, it is concluded that more work is needed to understand the influence of the forward azipull in all phases of the vessel operation. Modifications of VeSim to include this influence are presently investigated.

Application of least square methods to identify linear and non-linear force coefficients from captive model test must be used carefully. Motion parameters in low-speed manoeuvres may be outside the speed and acceleration domains used in the tests. More sea trial data should be obtained for further validation studies of the manoeuvring models for double-ended ferries.

An early design phase tool for investigating manoeuvring performance of double-ended ferries is under development. Using sea trial data from a set of double-ended ferries (50, 80 and 120 cars) developed

by HAV Design, SINTEF Ocean works to improve methods (3D slender-body theory with empirical corrections and CFD PMM) for creating the hydrodynamic input files to the time domain VeSim simulation tool.

IMO standard manoeuvring tests are of little value for ship captains on double-ended ferries. They are requesting more information on low-speed manoeuvring performance which should be documented in the vessel's Manoeuvring Booklet.

Addition to these tests, which will reveal behaviour during sea trials, it is even more important to detect manoeuvring challenges during the design process and hence modify design to overcome this. Hence, a methodology for developing a reliable simulation model that capture the behaviour during retardation should be specified. The essence is to conduct systematic CFD studies/ model tests to build a time domain simulation model to be used as an early design tool. Such a tool would be used to predict outcomes of IMO standard manoeuvres, low speed manoeuvres requested by ferry captains, and special off design performance characteristics of a specific ship.

ACKNOWLEDGEMENT

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