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VALIDATION OF SHIPHANDLING SIMULATION MODELS

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ABSTRACT

This paper describes the need for improved methods for validating numerical models used in shiphandling simulators. Such models vary in complexity, from rather simplistic models used for initial shiphandling training at maritime training centers to high-quality models used in the study of advanced marine operations. High-quality simulation models are also used in investigations of maritime accidents such as collisions and groundings. The SIMMAN 2008 conference presented the results of benchmarking studies of simulation tools currently used by research institutes, universities and training centers around the world. Many of these tools employ models based on numerical calculations using methods based on potential or viscous fluid flow, experiments using scale ship models (free running or captive) or semi empirical expressions based on regression analysis of previous model tests. The organizers of SIMMAN 2008 made the hull characteristics of certain ship types available for a comparative study of simulation maneuvering models. The outcome of the benchmark study (using IMO standard maneuvers as case study maneuvers) showed that simulated results varied significantly. In the opinion of the authors, there is an urgent need for new validation studies. The first part of this paper discusses the concepts of simulation model fidelity, verification and validation and the present guidelines issued by ITTC for validation of maneuvering simulation models. The second part looks at the outcomes of the SIMMAN 2008 conference and describes MARINTEK's contribution to the benchmark study. The use of real-world measurements in model validation is briefly discussed. The need for registration of actual test conditions, as well as the types of tests that should be included in a test scheme, are presented. Finally, the authors discuss validation requirements with respect to the actual application of the selected simulation model as an engineering tool that can be transferred to training simulators used by maritime training centers. It is assumed that simplified simulation models may reduce the quality of simulator based training for ship officers. It is believed that increased quality of simulator model will improve the transfer of training from simulators to real life operations and remove some of the uncertainties related to investigation of maritime accidents.

Keywords: Simulation, Shiphandling, Hydrodynamic models, Verification, Validation

1. INTRODUCTION

At the 21st ITTC (International Towing Tank Conference) in Trondheim, Norway, the Maneuvering Committee selected a new ITTC benchmark ship for comparison of various methods for predicting ship maneuverability. They agreed to use the Esso Osaka as the benchmark vessel. Since the Specialist Committee on Esso Osaka delivered its recommendations to the 23rd ITTC (ITTC, 2002 [15]) there was no major study of the quality of ship maneuvering models until the SIMMAN 2008 study [28]. A number of simulation models for study of ship maneuvering in deep/shallow open calm water have been developed based on linear and non-linear differential equations with constant maneuvering coefficients (Abkowitz, M. A., 1964, [1]), (Norrbin, N. H., 1970, [22]), (Ogawa, A. & Kasai, H., 1978, [23]), (Jensen, P. S., Romeling, J. U & Chislett, M.S.,1993, [17]). Most models have been three degree of freedom (3-DOF) models including surge, sway and yaw motion. A few 4-DOF models have also been introduced to take care of roll motion, especially for high speed vessels. In the course of the past decade, a number of unified models have been developed (Fossen, T.I., 2005, [8]), (Hoff, J.R., 2007,

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[10]), (Faltinsen, O. & Skejic, R., 2008,[27]) to study shiphandling in waves.

The SIMMAN initiative included the advanced distribution of selected ship hull data to enable research institutes and universities to compare the outcomes of various simulation models. MARINTEK was one of the institutions that took part in the SIMMAN 2008 initiative. We used our semi-empirical method to develop a 3 DOF simulation model for both versions of the KVLCC vessel (Martinussen, K. & Ringen, E. 2008, [20]). In general the MARINTEK calculation of the ITTC standard maneuvers provided results in a good agreement with the "basic values" obtained from a selected set of tests with a free-sailing model as can be seen on Figures 4 and 5.

Simulation models are used for different tasks and the authors believe that the way in which published models are validated needs to be improved. Verification is usually defined as the process of assessing that a model is operating as intended while validation is the process of assessing that the conclusions reached from a simulation are the same as those obtained from the realworld system being modeled [24] "Validation is the process of determining that we have built the right model, whereas verification is designed to see if we have built the model right" ([24], pg. 129).

The level of validation depends on the actual application of the model. For initial navigation training, the simulation model should respond realistically to rudder and engine orders for sailing in open/coastal waters for vessels operating in confined waters it will be necessary to validate shallow water and bank effects. For critical operations with a specific vessel the actual ship involved and the operational parameters it will encounter during real world operations must be validated.

2. FIDELITY, VERIFICATION AND VALIDATION OF SIMULATION MODELS

Simulation systems are based on a number of models, which are conceptual representations of the real world. The evaluation of simulation systems used for engineering studies is to some degree parallel to the evaluations needed for training simulators. For both applications the major items to be investigated are:

- Simulation fidelity – level of realism that the simulation is presented to the user,
- Simulation verification – the process of ascertaining that the model is operating as intended,
- Simulation validation - the process of ensuring that conclusions reached from a simulation are similar to those reached in the real world system being modeled.

This paper discusses a list of 20 concepts related to simulation validation research. A recent paper on validation methodology for educational driving simulators [26] incorporates a list of 24 concepts such as content validity, conceptual (face) validity, external and internal validity and event validity. Various schemes for verification and validation have been prepared by simulation user organisations. A generalized process for the verification and validation of models and simulation results was proposed by Brade [2], who introduces the verification and validation triangle to illustrate the dependencies and interactions among various verification and validation concepts.

The basic concepts of modeling and simulation are described in [31]. The Wikipedia article on "Flight simulation" describes flight-training devices as well as qualification and approval requirements in international and national regulatory and/or advisory documents (Wikipedia, [30] 2011). The European Aviation Safety Agency qualifies different types of training simulator such as Flight Navigation and Procedure Trainer, Flight Training Devices and Full Flight Simulators (Joint Aviation Authorities,[18] 2008).

Recent years have seen a rise in interest in use of simulators for studies of truck driver performance and factors that can reduce the performance (such as drowsiness, alcohol and drugs) (Sancar et al, [26] 2009, Eskandarian et al, [5] 2008). Adjustments to dynamic models and user interface based on feedback from driver's test candidates have been found to be important parts of simulation system validation.

For maritime training simulators the classification society DNV has made a business of certifying maritime simulator systems on the basis of requirements in IMO's STCW (Standards for Training, Certification and Watchkeeping) Convention ([14], DNV, 2007 [4]). Maritime simulators are generally divided into three classes:

- Class A – Full mission,
- Class B – Multi-task,
- Class C – Limited task.

Section D 300 of the DnV document specifies items to be included in a simulator performance document. One item documents that the simulator can be used for all defined simulation objectives, while others refer to realistic simulation of operating capabilities and equipment, various operational conditions and different types of training tasks (emergency, procedures, maintenance, troubleshooting, decision making and teamwork etc.). For each class of simulators, DNV has prepared matrices of detailed requirements and split them into the following groups: Physical realism, Behavioural realism and Operating environments.

For MARINTEK the most interesting part is that of Behavioural realism, as we are developing and validating the mathematical models that describes the maneuvering behavior due to the external loads and control forces applied in simulation studies and training exercises.

3. CURRENT ITTC GUIDELINES FOR VALIDATION OF SHIP MANEUVERING SIMULATION MODELS

At the 23rd ITTC meeting the Maneuvering Committee approved recommended procedures for validating maneuvering simulation models (ITTC, [16]). These state that validation should include six activities:

- Prediction of hydrodynamic forces,
- Modeling of forces in a mathematical frame work (derivatives, coefficients, tables, direct simulation of forces,
- Mathematical model structure,
- Integration model,
- Simulation software,
- Simulated maneuvers.

Access to model test results from forced and free-sailing models, enables model scale evaluations to be performed. ITTC members previously used the Mariner class of vessels and the tanker Esso Osaka as benchmark cases. This leaves open the question of scale effects when predicting maneuvers for the full scale ship. There is a general lack of such data available, as Esso Osaka trials were the only ones widely used for model validation.

A number of research institutes have taken part in delivery trials for new vessels and obtained data for some of the IMO standard maneuvers. In many cases these results depend on several external factors such as weather conditions during the tests, time- and position-variable current, unknown loading conditions, changes in engine output due to engine tuning etc. As these trial data are the property of the naval architect/yard/owner, they are usually not made available to the research community. The lack of field data means that validation is often performed by comparing numerical model outcomes with results from captive model tests and tracks/responses from free-sailing models.

4. THE SIMMAN 2008 INITIATIVE

4.1 OUTCOMES OF THE SIMMAN 2008 INITIATIVE

The SIMMAN initiative was a result of discussions that took place between members of the ITTC Maneuvering Committee. It was decided to arrange a workshop with the "purpose to benchmark prediction capability of different ship maneuvering simulation methods including systems and CFD based methods through comparisons with results for tanker, container ship and surface combatant hull form test cases" (Stern and Agdrup, [28]). Two versions of the MOERI VLCC tanker form with bulbous bow and transom stern were included. The first version had a barge type stern with a fine stern end bulb (relatively V-shaped frame-lines) while the second had more U-shaped stern frame-lines. The stern modification results in changes in course stability characteristics and maneuvering performance. This tanker design is only a benchmark vessel as no real ship has been built with these actual hull lines. Full scale tests thus do not exist for the tanker. The different models were therefore benchmarked by comparing the calculated results of selected IMO standard maneuvers (IMO, [11]) with each model and comparing all calculations with results obtained from free-sailing models. The comparison with results from the free-sailing test was made as a blind test as these test data were not made available ahead of the workshop. The standard tests used in this study were 10º/10º and 20º/20º Zig-Zag tests and a turning circle test at full rudder, see (IMO, [13]) for description of these tests. All tests were made at nominal sea speed for the tanker. From a practical point of view IMO's current maneuverability criteria have some serious shortcomings (Dand, [3]) and should be extended with additional criteria based on operational aspects as proposed by several authors (Qaudvlieg and van Coevorden, [25]). Finally, it should be noted that the IMO recommendations for the documentation of maneuvering performances does not include vessels less than 100 m l.o.a. (with the exception of gas carriers and passenger vessels).

The study done by MARINTEK's input to the SIMMAN 2008 workshop comprised numerical simulations of all the abovementioned tests. In addition, turning circles at smaller rudder angles (5º, 10º and 20º) were included. Figures 1-3 illustrate the variation in calculated characteristic values of some selected standard maneuvers. These show that there is a significant spread in the characteristic parameters of these standard maneuvers when they are performed in deep water and under calm sea conditions. Figures 4 and 5 compare predicted ship trajectories using MARINTEK's maneuvering model and observed tracks from free sailing model tests done by MARIN [28]. As the turning circle test shows, the characteristic parameters Advance and Tactical Diameter are in good agreement. The Zig-Zag test shows that the period is somewhat smaller in MARINTEK's calculation than in the model test results. Further tuning of the numerical model should provide better agreement with model test results. This has not been done yet, as the SIMMAN 2008 workshop also showed that there were significant differences between model tests carried out in different laboratories. One outcome of the SIMMAN 2008 workshop was an understanding of the need for further validation studies for simulation models for shiphandling. Planning of the SIMMAN 2012 workshop is now under way. More information can be found at http://www.simman2008.dk/

It should be mentioned that SIMMAN 2008 only compared numerical models with model test results. Another challenge will be to collect high-quality full scale trial data that can be used for validation studies of real-world ships.

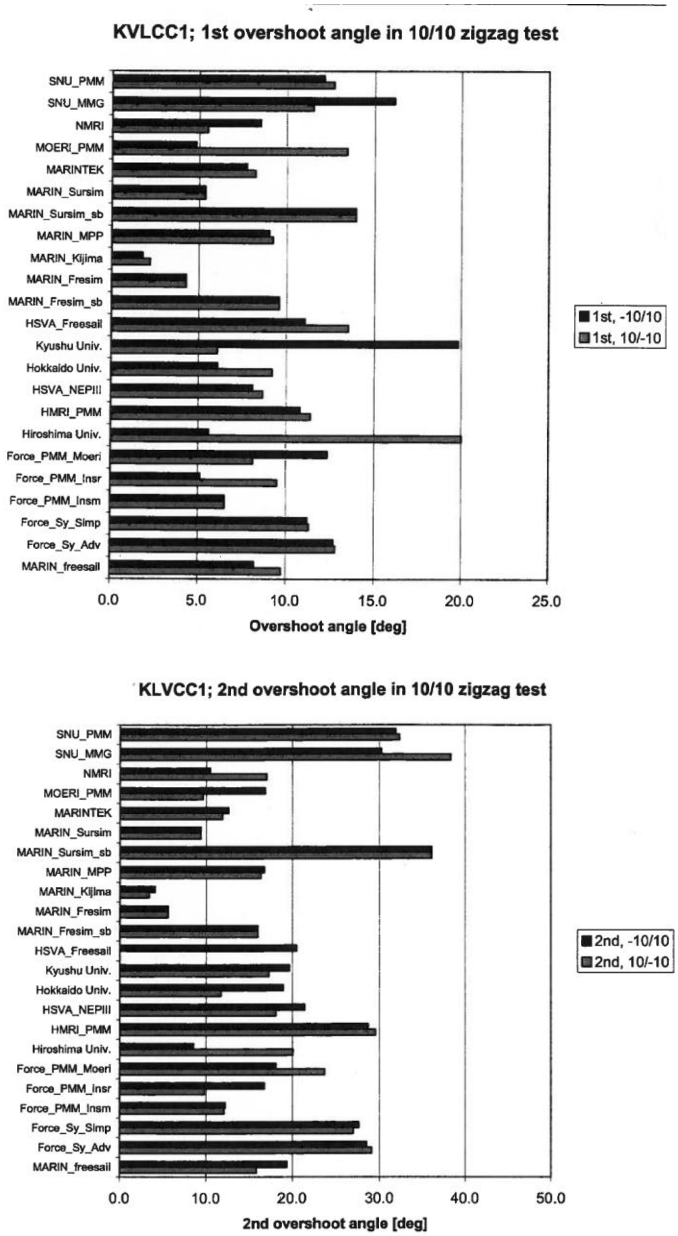

Figure 1 and 2 Comparison of 1st and 2nd overshot angle in 10º/10º Zig-Zag test (Stern and Agdrup, [28])

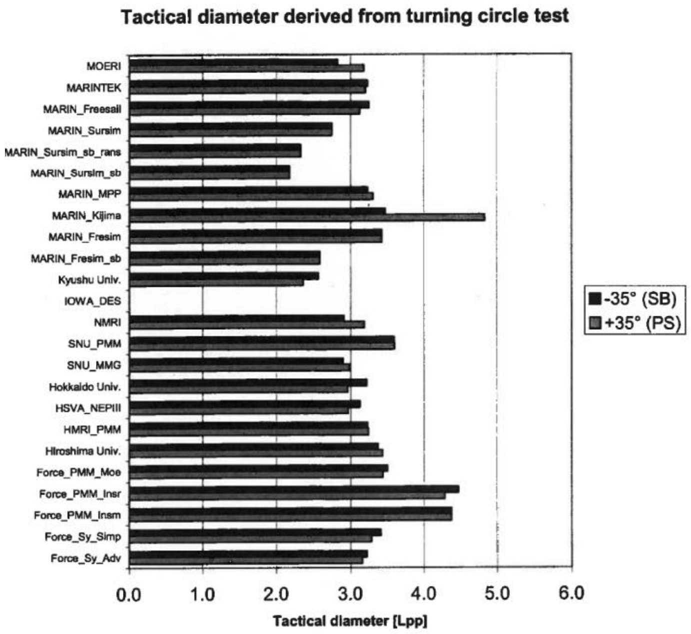

Figure 3. Comparison of tactical diameter in turning circle at 35º rudder angle

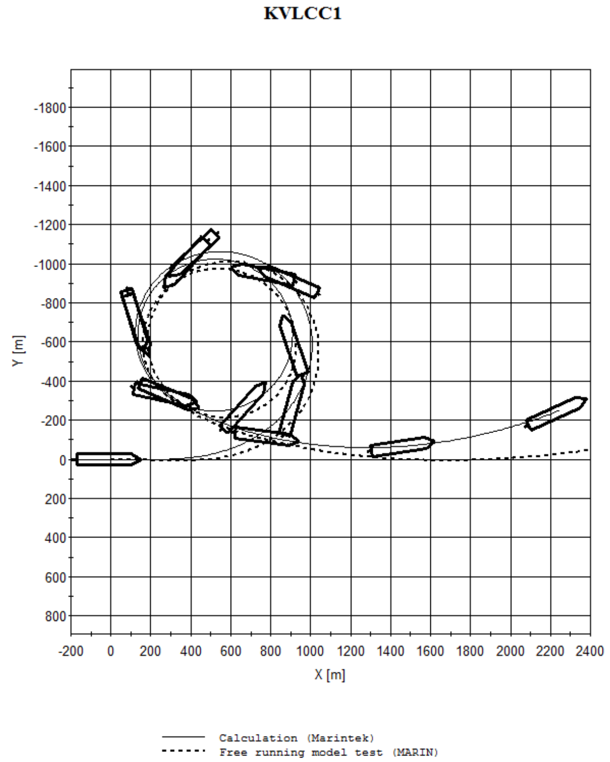

Figure 4. Comparison of turning circle track (port turn)

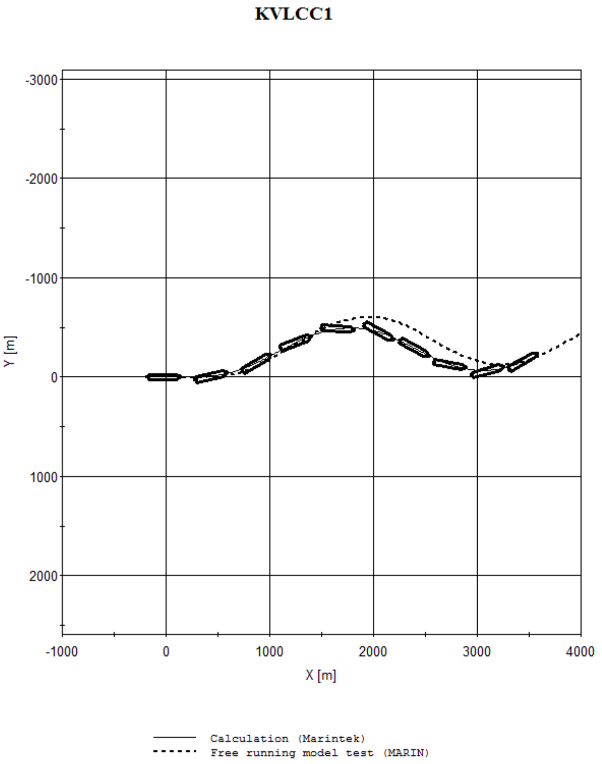

Figure 5. Comparison of ship trajectories for 20°/20° degree Zig-Zag test

4.2 DESCRIPTION OF MARINTEK’S PART IN THE SIMMAN 2008 STUDY

MARINTEK’s simulation software was tested and verified using Esso Osaka and Mariner in connection with preparing MARINTEK’s input to the SIMMAN 2008 benchmark study. The general model is shown in equation 1:

Surge

$$(m - X_{\dot{u}}) \cdot \dot{u} = (m + X_{vr}) \cdot vr + (mx_g + X_{rr}) \cdot r^2 + X_{res} + X_{vv} \cdot v^2 + X_{vvvv} \cdot v^4 + X_{pr} + X_{rud} + X_{th} + X_{wi} + X_{cu} + X_{wa} + X_t \qquad (1a)$$

Sway

$$(m - Y_{\dot{v}}) \cdot \dot{v} + (mx_g - Y_{\dot{r}}) \cdot \dot{r} = -mur + Y_v \cdot v + Y_{Uv} \cdot Uv + Y_r \cdot r + Y_{Ur} \cdot Ur - X_{\dot{u}} \cdot ur + Y_{cf} + Y_{pr} + Y_{rud} + Y_{th} + Y_{wi} + Y_{cu} + Y_{wa} + Y_t \qquad (1b)$$

Yaw

$$(I_{zz} - N_{\dot{r}}) \cdot \dot{r} + (mx_g - N_{\dot{v}}) \cdot \dot{v} = -mx_g ur + N_r \cdot r + N_{Ur} \cdot Ur + N_v \cdot v + N_{Uv} \cdot Uv + N_{cf} + N_{pr} + N_{rud} + N_{th} + N_{wi} + N_{cu} + N_{wa} + N_t \qquad (1c)$$

A brief description of the terms in (1) is:

I_{zz}	ship mass moment of inertia in yaw
m	ship mass
$X\ ,Y, N$	Surge, sway forces and yaw moment
u, v, r	Surge, sway and yaw speed
U	Total speed

Subscripts:

cf	non-linear damping according to the cross-flow principle
pr	propeller contribution
rud	rudder contribution
th	contribution from tunnel thrusters
wi	wind contribution
cu	current contribution
wa	wave drift contribution
t	contribution from tugs

When applying the equations for the SIMMAN validation study, the following activities were performed to calculate the hydrodynamic coefficients:

4.3 HYDRODYNAMIC HULL FORCES:

A pre-processing program prepares the input to the maneuvering prediction program on the basis of the shape of the underwater hull in digitized form.

Calculation of linear added mass and damping coefficients in sway and yaw is based on slender body theory. The hull cross-sections are also increased in size successively from bow to stern by adding a boundary layer. This method gives a more pronounced boundary layer correction at the stern for full hull forms than for slender ones. The longitudinal change in sectional added mass in sway is then integrated from the bow to a given section in the aft body.

Non-linear damping in sway and yaw is of the cross-flow principle. A cross-section is introduced in the aft body where it is assumed that flow separation is initiated. At small drift angles, this cross-section is located where the maximum curvature of the aft body hull lines occurs. It is assumed that forward of this cross-section there is no non-linear transverse force, while aft of it there is cross-flow drag. To account for the flow condition at large drift angle, the assumption is made that the section where flow separation occurs moves forward with increasing drift angle so that under transverse flow or pure yaw conditions the complete hull is subject to cross-flow force and moment. The result of this procedure is that the non-linear damping in the numerical model is not exactly quadratic but according to an exponent value of between 2 and 3.

If longitudinal resistance data for the ship or similar ships are not available the resistance is calculated by a method of Holthrop [9], modified by MARINTEK on the basis of our in-house resistance database.

The coefficients *YUv*, *YUr*, *NUv* and *NUr* take the effect of Froude number (*Fn*) on linear damping into account. Due to the difficulty of providing reliable values for these coefficients they are currently set to zero.

The coefficients *Xvv* and *Xvvvv* take the effect of drift angle on the longitudinal force into account. The introduction of these coefficients improves the calculation of speed loss in maneuvers involving large drift angles. The motivation for using *Xvv* and *Xvvvv* can be found in [21].

4.4 PROPELLER FORCES:

The propeller module is based on the work described in [29]. General analytical expressions have been developed for the performance of an arbitrary propeller as functions of blade-area ratio, blade pitch setting and any combination of propeller rate, direction of revolution, ship speed and direction of motion. The method is a four-quadrant numerical propeller model for fixed pitch and controllable pitch propellers. The propeller module takes into account the flow straightening effect and the wake of the hull as functions of local drift angle at the propeller position, as well as the sway force and yaw moment from the propeller as functions of propeller thrust and local drift angle at the propeller position.

4.5 RUDDER FORCES:

The basis for calculation of rudder lift and drag is the free-stream characteristics of conventional rudders. After calculating the free stream lift coefficient CL and drag coefficient CD for an all-movable rudder, several more calculations and modifications have to be made to arrive at the axial and transverse forces in the ships co-ordinate system.

The effective aspect ratio of the rudder is calculated as a function of the gap between the top of the rudder and hull surface. This gap changes with rudder angle. Propeller race diameter and race velocity are calculated by means of momentum theory. Flow velocity is calculated separately for those parts of rudder above, in, and below propeller race. The flow velocity over the complete rudder is then calculated as a weighted average of these velocities. The effect of the rudder on the hull may be regarded as equivalent to the effect of a flap on a wing. The lift slope calculated for the rudder alone is therefore multiplied by a factor 1+*aH* where the value of *aH* is based on information in [12].

5. A FIELD TEST CAMPAIN TO SUPPORT MANEUVERING MODEL VALIDATION

As mentioned in section 3 it is necessary to investigate normal vessel operations in addition to the IMO standard maneuvers when developing a simulation model for shiphandling operations in confined waters or in heavy weather situations. Special tests need to be performed at low speed using rudder, thrusters and main propeller. Acceleration tests from zero speed are recommended as well as specific tests taht apply kick-ahead for the main propeller and predefined rudder(s) movements . MARINTEK is collaborating with the Ship Maneuvering Simulator Centre in Trondheim, Norway to optimize a field test program for tuning MARINTEK's engineering simulation models as well as SMS training simulation models. As part of a recent project on emergency operations, the Norwegian Coast Guard allowed us to use the Coast Guard vessel KV Harstad in several field tests. These tests included both IMO standard tests (carried out in calm water and in waves) as well as specific low speed tests in which main propellers, bow and stern thrusters and high efficiency rudders were emplyed. These tests are listed in Table 1. The results were used to tune the maneuvering equations in an attempt to minimize the deviation between measured and calculated responses for a given set of test maneuvers. The tuned equations were used in a validation study in which experienced officers from the vessel were the test subjects. The test subjects had different views regarding the accuracy of the simulation model, and this face validation study confirmed the uncertainties that are introduced when the test subject group is limited. Due to the type of vessel used in this study, we are not permitted to publish details of model responses or the vessel's field-test performance.

Table 1 Low speed field tests with KV Harstad

Test type	**Description**
Acceleration test	From zero speed, 25%MCR
	From zero speed, 50% MCR
	From zero speed, 75% MCR
	From zero speed ,100% MCR
Free drift	
Effect of tunnel thruster no. 1	Starboard , 0 kts speed
Effect of tunnel thruster no. 1	Port, 0 kts speed
Effect of azimuth thruster	Starboard, 0 kts speed
Effect of azimuth thruster	Port, 0 kts speed
Effect of both thrusters	Starboard , 0 kts speed
Effect of both thrusters	Port, 0 kts speed
Effect of both thrusters	Starboard, 0 kts speed in addition to main engines, not rudder
Effect of both thrusters	Port, 0 kts speed in addition to main engines, not rudder
Effect of both thrusters	Starboard , 0 kts speed in addition to main engines and rudder
Effect of both thrusters	Port, 0 kts speed in addition to main engines and rudder
Captain's stop	Full deflection both rudders. Rapidly reducing engine MCR to 0%MCR.

6. VALIDATION REQUIREMENTS RELATED TO APPLICATION OF SIMULATION MODELS

Engineering simulators are used for a wide range of studies, including port design, traffic management, ship maneuvering characteristics, maritime accident investigations, etc. At MARINTEK we are using our 6 degree of freedom (6DOF) VeSim tool to study various aspects of manoeuvrability and seakeeping performance (Fathi, [6]). Validation of the simulation models is then based on model tests of resistance, propulsion, seakeeping and maneuvering using free-sailing models in our Ocean Basin. Our work is performed at the design stage and at present we lack qualified field test data from these vessels for validation of the MARINTEK manoeuvring software against the real-world vessel. The standard data produced according to delivery trial procedures are generally not sufficient for validation of the mathematical models that are used for engineering studies of ship maneuvering performance. As an example, MARINTEK replied to the investigation board for the Bourbon Dolphin accident that our models at that time lacked the necessary verification and validation needed to be used for studies of the possible underlying causes of the accident.

Several studies on the relationship between training simulator fidelity and its effect on training and education can be carried out (Feinstein, and Cannon, [7]). Some of these studies showed that a higher level of fidelity did not always result in more effective training or enhanced learning. Some even found that poorer fidelity actually can assist in understanding the details of training and education. One study (Martin and Wang, [19]) pointed to overstimulation of an inexperienced learner as one cause of reduced learning in a high fidelity simulation environment. In our collaboration with the Ship Maneuvering Simulator Centre in Trondheim, we found that experienced masters on vessels performing lightering operations are satisfied with simulation models when they are performing a normal operation under calm-sea conditions (face validity). However, they request more information on the validity of simulation models for vessels performing abnormal or emergency operations and operations under limiting weather conditions. In general there will be different validity requirements for different course levels at maritime training centres. For basic shiphandling courses the models need to provide a realistic response that is typical of vessels of different types and sizes. For advanced shiphandling and emergency operations the validity requirements with respect to low speed and harsh weather operations will be more stringent. If the simulator is used for familiarization with a specific vessel or operational sites, even more validation documentation will be required.

The validation of ship-specific simulation models is also a cost/benefit challenge. Ship designs vary to a far greater extent than aircraft, trains, trucks and cars. Thus the cost of model validation will be divided among far fewer ships compared to the series of units in other parts of the transportation sector.

It is assumed that low-quality simulation models may reduce the quality of simulator based training for ships' officers. Higher-quality models will improve transfer of training from simulators to real-life operations and remove some of the uncertainties related to investigation of maritime accidents.

7. CONCLUDING REMARKS

No standard procedures are currently available for verification and validation studies of the mathematical models used in maritime simulators. DNV's certification of maritime simulator systems contains functional approach tables that specify items to be documented, but there are no formal requirements as regards model accuracy. Previous benchmark studies of ship maneuvering models have focused on comparisons of responses to the standard maneuvers defined in an IMO Regulation [11]. This is only the first step, as simulator users are more concerned with model validity for the normal maneuvering tasks encountered when a vessel is sailing at reduced speed in confined waters or maneuvering in port, when control units are frequently used. Response data for such operations are not available for R and D companies in their efforts to verify and validate their mathematical models. The call for SIMMAN2012 is a step towards obtaining data for validating the effects of shallow and confined waters in maneuvering models. However, there is also a need for open data on low-speed maneuvering characteristics for future benchmark studies of maritime simulator validity.

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