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Validation of Manoeuvring Simulation Models.

1 PURPOSE OF PROCEDURE

This procedure proposes the necessary steps and documentation for the development of a simulation model.

This procedure is intended to help assess the validity and quality of a manoeuvring simulation model. Any validity check is a difficult task due to the lack of reliable full-scale results to compare simulations with. Nevertheless, the need for accurate simulations justifies significant attention in this area.

2 INTRODUCTION

The development of a manoeuvring simulation model can have many purposes. A distinction can be made between:

(a1) models for prediction of ship manoeuvrability;

(a2) models for use in simulators.

Prediction of standard ship manoeuvres (a1) is needed at the design stage to ensure that a ship has acceptable manoeuvring behaviour, as defined by the ship owner, IMO or local authorities.

Simulator, or time-domain, models (a2) are used in real-time, man-in-the-loop simulators, or faster simulators for training of deck officers or investigation of specific ships operating in specific harbours or channels. For these purposes, the simulation often has to model a specific ship in deep and shallow water, as well as interactions with the environment in the form of wind, current, waves, banks, ship-ship interaction, tug interaction etc. Other purposes might exist but these cover those most commonly encountered.

The requirements for validation are the same for both types of models. However, the amount of required data and, hence, the validation effort is much larger for simulator models (a2) since they typically address more parameters and operating conditions than the models used for prediction of ship manoeuvrability (a1).

The validation of a manoeuvring model covers a series of steps, which must be carried out individually:

1. Prediction of hydrodynamic forces
2. Modelling of forces in mathematical model (derivatives, coefficients, tables, direct simulation of forces)
3. Mathematical model structure
4. Integration method
5. Simulation software
6. Simulated manoeuvres

Each of the above steps is addressed in the following sections.

3 PROCEDURE FOR VALIDATION OF A MANOEUVRING SIMULATION MODEL

3.1 The Report

A simulation model should be documented in a way such that the methods and assumptions used are stated and the parameters, for which the model is valid, are clearly given. Furthermore, the documentation should include simulated standard manoeuvres and possibly address the expected accuracy of these simulations.

The purpose of the manoeuvring simulation model must be stated and a definition of the nomenclature and coordinate systems used must be given.

For a model to be used in the prediction of ship manoeuvrability (a1), at least the following ship particulars should be given:

Type of ship (container, LNG, etc.)

Hull data
- Design displacement
- Design draft
- L_{PP}
- L_{OA}
- Breadth moulded

Actual loading condition
- Draft fore/aft or mean draught/trim
- Displacement
- Wetted surface
- Longitudinal centre of buoyancy
- Moment of inertia in yaw
- *KG, BM, KB*, moment of inertia in roll
- (4-DOF model)
- Approach speed and/or service speed

Engine characteristics
- Engine type
- Shaft power

Data on propulsors
- Type
- Number of propulsors
- Position
- Diameter
- Thrust and torque characteristics
- Type dependent data (e.g. for propellers: direction of rotation, no. of blades, pitch ratio at 0.7R, area ratio A_E/A_O; for pods: lateral area, pod diameter, length)

Data on steering devices
- Type
- Number of steering devices
- Position
- Type dependent data (e.g. for rudders: type of rudder (spade, horn, flap), movable rudder area, total rudder area, height, length, aspect ratio, thickness, maximum rudder rate, maximum rudder angle**)**

Other useful information for documentation includes
- a set of hydrostatic data (at lears for the given loading condition);
- drawings of the rudder and propulsor areas, including contour and profiles;
- a body plan and stern and stem contours of the ship;
- description and drawings of appendages on the hull, including bilge keels, additional fins, etc.;
- if possible, photographs of the ship;

- if the mathematical model uses modelling of open water propeller curves, they should be included;
- for models to be used in real-time simulators, profiles exposed to wind should be included, as well as their corresponding frontal and lateral areas;
- a table giving the ship speed at various control settings in deep and shallow water;
- data on thrusters and other auxiliary manoeuvring devices, including number, position, design thrust, etc.

3.2 Prediction of Forces

A simulation model is usually based on Newton's Second Law, applied to a rigid body for six degrees of freedom:

- Translation modes:

$$\text{mass} * \text{acceleration} = \sum \text{external forces}$$

- Rotation modes:

$$\text{mass moment of inertia} * \text{acceleration} = \sum \text{external moments}$$

The mass properties of the vessel in the various degrees of freedom are generally well-known. The external forces and moments are primarily of hydrodynamic origin for marine vessels, and include effects of the hull itself, along with those of steering devices and propulsors. Additionally, forces and moments exerted by tugs, moorings, environmental forces, etc., are included as applicable in the external forces. Naturally, the accuracy of the various force and moment models greatly affects the accuracy of the simulations.

A variety of possible sources are available for the estimation of hydrodynamic forces and moments; they can be distinguished as follows:

(b1) data base (type ship concept)
(b2) regression equations from data base
(b3) captive model tests (see 23rd ITTC, 2002: Captive Model Test Procedure)
(b4) free-sailing models with system identification
(b5) full scale trials with system identification
(b6) calculation of forces resulting from prescribed kinematics by [illegible]D techniques
(b7) on-line application of NFD techniques during simulation

A distinction between force predictions from generic databases (b1, b2) and ship specific data (b3, b4, b5, b6, b7) has to be made. If either database method is used, it should be clearly documented to what extent the current design is represented in the database that is being used as source. As an example, a database that consists only of full form tankers, cannot be used for prediction of forces in a container ship. The adequacy of a database for a given vessel can be assessed by comparing appropriated parameters such as T/L, B/T, C_B, approach speed, etc..

Except for the full-scale trials (b5), all the mentioned sources have problems regarding scale effects. The 22nd ITTC (1999) Manoeuvring Committee report addresses scale effects, but concludes that presently no clear trend exists. The 23rd ITTC (2002) procedure on "Captive Model Testing" discusses scale effects to some extent; hence, they will not be discussed here. With regard to documentation of the simulation model, the methods used for scale effect correction in the force predictions should be clearly stated.

For the cases (b4, b5), free-sailing model tests and full-scale trials with system identification, it is essential to demonstrate that force representation is also adequate to describe manoeuvres which are not included in the trials or tests. This extrapolation may be difficult, although models that contain only the necessary effects will usually be the most successful. Oltmann (1996) gives an example wherein free-sailing model zigzag tests were used to create an adequate mathematical model. A subsequent, independent comparison with a full-scale turning circle was successful, showing that the model created from zigzag data was applicable to steady-state turning. In fact, this same study also illustrates an effective scaling of forces.

In the case of free-sailing models (b4) and full-scale trials (b5), if independent data for a direct comparison are unavailable, one should demonstrate that the system identification method gives good results with respect to benchmark data or predictions based on other methods. Similarly, the use of NFD to calculate forces (b6) should be validated against benchmark captive force measurements. Finally, simulation making use of NFD (b7) can be validated against benchmark manoeuvres from either free sailing model tests or full scale trials. The use of system identification results to validate NFD calculations, and vice versa, is not recommended.

As a final note, the use of full-scale trials for the purpose of identifying forces (b5) often have the difficulty of uncontrolled or poorly documented environmental conditions, such as second-order wave forces, wind, currents, and non-uniform sea bottom. These effects, which degrade the quality of data significantly, can be minimized through careful selection of the trial site and conditions of weather, wave height, and tidal flow. Furthermore, the vessel should be instrumented as well as possible; it may be possible to model the effects, or at least to develop upper bounds of their impact on the overall response (see 23rd ITTC, 2002: Full Scale Trials Procedure).

3.3 Modelling of Forces in the Mathematical Model.

The hydrodynamic forces acting on the ship can be represented mathematically in many forms, from the fairly simple Abkowitz derivatives for prediction of first quadrant manoeuvres, to a full four-quadrant deep and shallow water simulator model, and beyond.

Forces are described with the following means:

1. Hydrodynamic derivatives (obtained from measured or calculated forces)
2. Look-up tables of the forces
3. Algebraic equations (empirical or theoretical)
4. Direct simulation (NFD)

For any approach, the proposed mathematical model must be able to reproduce the original force data with sufficient accuracy. Results from a PMM test for a ROPAX vessel are shown in Figure 1, as an example; the measured yaw moment is given as function of drift angle and speed. The PMM tests covered three speeds to account for the speed loss during a turning circle. The proposed mathematical model for the moment is:

$$N'_H(\beta,u') = N'_\beta \beta + N'_{\beta|\beta|}\beta|\beta| + N'_{\beta\beta\beta}\beta^3 + N'_{\beta u}\beta u'$$

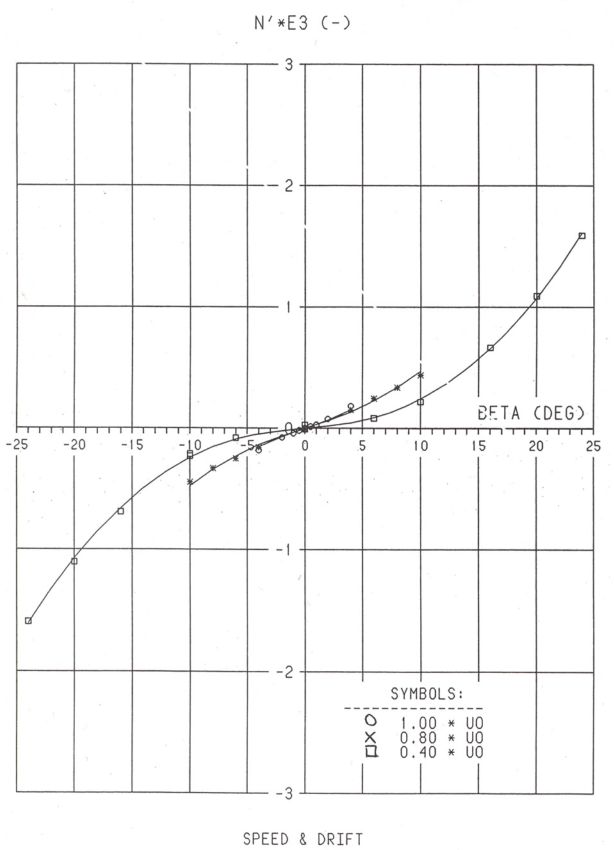

Figure 1: Comparison of measured and predicted yaw moment. Lines indicate simulation model curves; symbols show measurements.

Here non-dimensional surge and sway velocities are given as

$$u' = \frac{u - U_o}{U}, \quad \beta = -\frac{v}{U}$$

As the figure shows, the proposed mathematical model captures the measured yaw moment reasonably well, with regard to variations in both u' and β.

When databases or regression equations (b1, b2) are used, the obtained force formulation corresponds to the structure of the mathematical model. Validation of the mathematical model is therefore impossible in these cases.

Documentation of the mathematical model should include:

- Form of the model
- Nomenclature
- Non-dimensionalisation used
- All state variables
- The range of state variables for which the mathematical model is valid
- Interaction terms in modular models

All effects that are included in the mathematical model should be defined. As an example, if the model includes propeller rotational speed, the strategy for relating engine power and rpm during simulation should be explained.

3.4 Mathematical model components

With respect to the complexity of the mathematical model, the following distinctions are made:

- Whole-ship models (Abkowitz)
- Modular models of components
- Direct simulation (NFD)

Whole-ship models are typically used for prediction of ship manoeuvrability, whereas modular models may be used additionally for real-time simulator models. In the latter case, the human operator has access to a large number of sensors and interacts with a variety of vessel subsystems. While whole-ship models and modular models are typically quasi-steady, NFD models enable simulation of transient manoeuvres by increasing the resolution at the fluid level.

3.5 Integration Method

Once the governing differential equations are known, a large variety of integration methods exist to make a time-domain simulation. The implementation must be validated against a known problem with a time constant similar to what is expected for the ship manoeuvres, and which can be solved in an analytical way. For example, the step response of a first- or second-order system can be used.

The solution must also be checked for convergence, i.e. the time step and integration procedure used should be sufficient to model the frequencies included in the simulations. At the lower end, a 3-DOF model for prediction of IMO manoeuvres can be considered low frequency, for example the zigzag manoeuvre. The inclusion of roll motion immediately adds a higher frequency into the calculation, so that a smaller time step or a higher-fidelity integration scheme is required. Full 6-DOF models bring in higher resonance frequencies in heave, roll and pitch. Simulator models may introduce even more resonant components, due to interaction with moorings, fenders, and tugs, as well as waves.

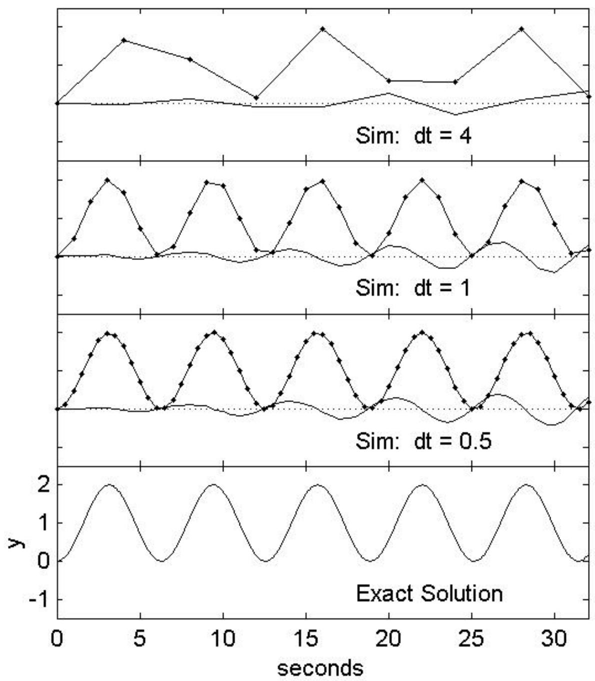

Figure 2: Simulations of an undamped second order system, showing the simulation output (points), and errors multiplied by 100 (smooth line).

As an example of simulation verification, Figure 2 shows results for the second-order differential equation

$$y'' + y = 1$$

with initial conditions y = y' = 0. The system has an undamped natural mode at 1 rad/s, equivalent to a 6.3 second period, and the simulations are made with a fourth-order Runge-Kutta technique. The time step dt = 4 leads to a simulation result that has little to do with the true solution; with dt = 1, the accuracy is much better, but insufficient detail exists at the peaks to judge the amplitude of vibration accurately. With the choice dt = 0.5, the simulation data have adequate time resolution. This example shows also that errors are not necessarily reduced by decreasing time step. In this specific case, the Runge-Kutta technique causes a gradual dissipation of energy, and hence it is considered a very stable integration scheme.

3.6 Simulation Software

The mathematical model and the integration method that is implemented must be validated through relevant test and debug cases.

3.7 Simulated Manoeuvres

The following documentation should be included for each manoeuvre performed in simulation:

- Definition of manoeuvre
- Track plot with heading indication
- Table containing time series of state variables (see below)
- For zigzag manoeuvres, time series plot of rudder and heading
- For 4-DOF models, include time series plot of roll angle
- Derived manoeuvring indices (overshoot angles, turning circle parameters etc.)

The list of state variables to be tabulated should at least include:

- Rudder/steering device angle(s)
- Horizontal position in a fixed frame of reference (x, y)
- Longitudinal speed
- Transverse speed or drift angle
- Heading
- Yaw rate
- Propeller rpm and pitch, if applicable

A 4-DOF model should also include roll angle and roll rate.

A simulator model sometimes requires the documentation of more parameters depending of the purpose of the model. Examples of additional parameters are:

- Thrusters forces and RPM
- Tug forces
- Mooring line forces
- Bank effect parameters

As noted previously, it is important that the proposed mathematical model covers the various parameter ranges encountered in the simulated manoeuvres. It should be verified that the data used by the model during the simulation are covered by the validity range of the model.

The time resolution of the output tables and the representation of the various parameters should be consistent with the application.

4 VALIDATION

4.1 Introduction

Generally, the method of prediction applied must be validated against benchmark data, and the documentation of such validation should be available in the form of a report or published paper.

Especially in situations where benchmark data is unavailable, or cannot be effectively used for validation, the accuracy of the predicted manoeuvres should be considered. Similarly, one should address the expected accuracy of derived parameters, such as overshoot angles and turning circle parameters.

We consider two main tasks which are subject to separate error analyses. The process of synthesizing a force model from measurements carries an *uncertainty analysis*, which is discussed briefly below, and in more detail in the Captive Model Test Procedure (23rd ITTC, 2002). The errors in each term may not be known precisely, but, depending on the technique, an upper bound for the error on each term can be found. Separately, the sensitivity of the simulation output to specific parameters of the mathematical model is found through *sensitivity analysis*, by nature an iterative procedure since the simulation is usually nonlinear and hence cannot be studied using analytical techniques.

These two analyses should, where possible, be extended by completing the loop, that is, verifying that the simulation recreates the experimental data within the bounds established by the uncertainty and sensitivity analyses.

For predictions based on captive model testing (b3), a discussion and some examples of uncertainty analysis are given in the Captive Model Testing Procedure (23rd ITTC, 2002); system identification is a separate task from making the force measurements, however, and is not included in the procedure. The case where both free-sailing (b4) and captive model tests (b3) exist for the same vessel in the same condition is an excellent basis for validation of the system identification process. Except for scaling effects, captive model tests, with augmentation by free-sailing tests for highly nonlinear manoeuvres, present the best prospects for control of overall modelling uncertainty. The errors will be generally limited to sensor and actuation errors, which are not difficult to quantify, and unavoidable errors induced by a finite-dimensional model.

For mathematical models based on full-scale trials and system identification (b5), the main difficulty lies in the quality of the data which complicates control of experimental and system identification errors. The hydrodynamic forces themselves are simply not available.

4.2 Benchmark Data

As mentioned in the 22nd ITTC (1999) Manoeuvring Committee Report, there is little full-scale manoeuvring benchmark data available. Trials with the tanker *Esso Osaka* are the only instrumented experiments widely cited: see the 23rd ITTC (2002) Esso Osaka Specialist Committee Report, and the 22nd ITTC (1999) Manoeuvring Committee Report. This lack of high-quality data of course complicates the validation process. Consequently, free-sailing and captive model tests are commonly used as a substitute for full-scale trials. While the question of scale effects is unresolved in this case, one still has the advantage of being able to control the model geometry, the test parameters and the test environment.

4.3 Potential Causes of Prediction Error

There are a number of causes of errors affecting accuracy, related to each of the validation steps mentioned above.

- Prediction of forces is presumably the main contributor to the uncertainty of the final simulation result. Sources can include sensor noise and nonlinearities in physical tests, approximations and extrapolations inherent in the database models, and the difficulties of NFD analysis. For each of the methods (b1-b7) mentioned in this procedure, a validation procedure should be implemented. However, at the present time of writing, only the procedure "Captive Model Testing" (23rd ITTC, 2002) exists. Reference is therefore given to this procedure.

- Modelling of forces in a mathematical model: uncertainty here lies primarily in the applied method for representing the forces as functions of the state variables.

- The mathematical model structure may be inappropriate to capture the desired effects, or may not cover the range of state vectors and environments encountered in manoeuvring.

- Integration method errors are usually small compared with the other sources, provided the time step is small enough to handle frequencies in the physical problem.

- Simulation software errors are unavoidable and occur occasionally.

- Simulated manoeuvres should be made with high resolution both temporally and spatially.

4.4 Sensitivity Analysis

As noted above, to perform a formal sensitivity analysis on calculated manoeuvres from a mathematical model is a cumbersome task, due the presence of nonlinear effects in most models. However, it is still necessary to address the uncertainty of calculated manoeuvres in some quantitative way.

For direct manoeuvring predictions based on databases and regression equations (b1, b2) sensitivity analysis may be difficult because of the lack of any data specific to the vessel in question. Little advice can be given except to check the ship parameters against the population of ships represented in the database.

For situations in which a mathematical model has been created, however, the evaluation of manoeuvring sensitivity is a matter of repeated simulations, while varying the parameters in turn. The study may sweep through the parameters systematically, or randomly; the latter case is attractive if a large number of parameters exists and the effects of multiple variations need to be considered. An example case of sensitivity analysis results is illustrated in Figure **3**, from Ishiguro et al. (1996).

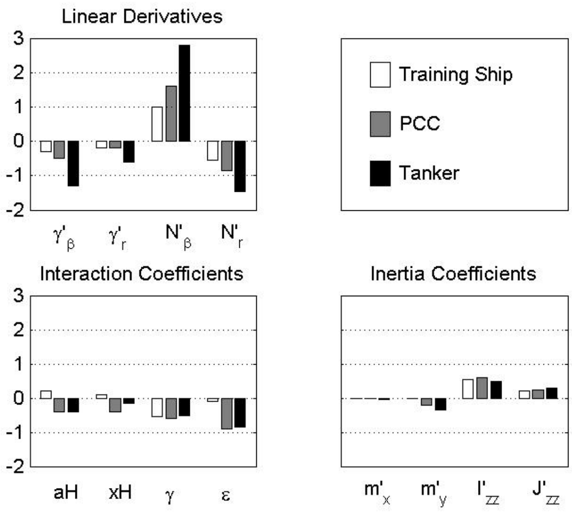

Figure 3: Relative sensitivity (ratio of change in estimated results when each parameter is individually increased 10%) of various parameters on the first overshoot angle in a 10-10 zigzag test in a simulation model. (adapted from Ishiguro et al,1996)

Sensitivity analysis has been discussed in the Manoeuvring Committee Report of the 22nd ITTC also.

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