Intuitive operation
and pilot training
when using marine
azimuthing
control devices

AZIPILOT

Report Title:

Deliverable 1.8:

Identify best practice for manoeuvring model test procedures

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EXECUTIVE SUMMARY

The aim of this task was to identify best practice for manoeuvring model test procedures, and assess those areas of applied hydrodynamics relevant to this. The results of reviews carried out in previous WP1 tasks were used to inform the assessment and decision making. The criteria and requirements framing the question have also been informed by work carried out in the other work packages.

The existing procedures were studied and shortcomings highlighted, creating a map of improvements required to achieve best practice. The project recognises that model testing is still the main prediction method used when designing new ships, and as such, careful consideration has to be given to the full range of inputs, from mathematical models up to performance predictions. Such versatile approaches result also from ship and environmental requirements.

The unique abilities, and challenges, of azimuthing control devices necessitate a renewed look at the analyses regularly performed, in particular with respect to steering the vessel at sea, in harbour and at very low speeds.

To achieve this, groups of results, with corresponding validations, were an extremely valuable source of information. In addition to the review carried out, advantages and drawbacks associated with azimuthing propulsion were considered, as were assigned test procedures.

Attention was particularly focussed on the two main groups of manoeuvrability tests - captive and free running model tests of azimuthing control devices.

1. INTRODUCTION

Meaning of manoeuvrability predictions

Manoeuvrability is generally considered by ship designers and ship operators to be one of the most important aspects of a ship's performance as it significantly affects its safety and economic operations. Recently, the emergence of not only huge vessels and high risk vessels (VLCC, ULCC, LNG, LPG etc.) but innovative azimuthing propulsors has led to the requirement of closer attention being paid to the manoeuvrability of a ship. Accordingly, there have been serious efforts to improve the manoeuvring design capability over the last few decades and a moderate amount of progress has been achieved in relation to commercial vessels in recent years.

Manoeuvrability of a ship should be repeatedly reviewed and considered by the designer as one of the important factors during the design. In particular, in the preliminary design stage, knowledge of the effect of a change in principal design particulars will be a key asset to the naval or merchant ship designer. A model test might be quite accurate but mathematical modelling is more appropriate for this work as it offers the necessary flexibility. The information needed, however, for numerical simulation of the manoeuvring behaviour of a merchant vessel, such as linear and non-linear hydrodynamic derivatives, control derivatives and propulsion characteristic models for versatile innovative vessels does not exist at present. Likewise a clear and practical formulation of the relationship between ship parameters and the manoeuvring characteristics of azimuthing propulsion vessels is very limited in the public domain now.

That is why, the development of models for predicting the hydrodynamic derivatives and propulsion characteristics and establishing the relationship between ship parameters and the manoeuvring qualities of azimuthing vessels will be an essential task in the development of a preliminary design capability for these vessels.

The currently available design tools range from rules of thumb to sophisticated model test series coupled with full scale trials and from simple linear prediction programs to man-in-the-loop test simulations. Directly relevant to the present research are:

- Use of Databases: This is a practical method for predicting ship manoeuvrability in a simple way, provided the hull geometry is similar to the ship range used in the data base; because of this restriction, this method lacks flexibility.
- Free Running Model Tests: Typically used to evaluate turning performance and course keeping ability. This method can be used to evaluate the manoeuvring performance during the design stage, but it is a very time-consuming, expensive and inflexible approach.
- Numerical Simulations: When assisted by accurate input data, this is the most powerful manoeuvring design tool. Trends show that analysis has progressed from linear to non-linear models and from regression to modular models. The main hurdle presently lies on developing a theoretical capability to evaluate the hydrodynamic manoeuvring derivatives accurately. Captive model tests and semi-empirical methods may produce accurate results, but the system identification and the theoretical predictions require further developments.

2. RECOGNITION OF RESPECTIVE FIELDS OF SHIP HYDRODYNAMICS IN RESPECT TO MODELING TECHNIQUES

2.1 State of the art in modelling techniques

The basic idea of model testing is to experiment with a scale-model to extract information that can be scaled to the full-scale ship. Despite continued research and standardisation effort, a certain degree of empiricism is necessary, in the model-to-ship correlation, which is a method to enhance the prediction accuracy of ship resistance by empirical means. The total resistance can be decomposed in various ways. Traditionally, model basins tend to adopt approaches that seem most appropriate to their respective organization's corporate experience and accumulated databases. Unfortunately, this makes various approaches and related aggregated empirical data incompatible.

Although there has been little change in the basic methodology of ship resistance since days of Froude (1874), various aspects of the techniques have progressed. We now understand better the flow around three dimensional, appended ship, especially the boundary layer effects. Also non-intrusive experimental techniques like laser-Doppler velocimetry (LDV) allow the measurement of the velocity field in the ship wake to improve propeller design. Another more recent experimental technique is wave pattern analysis to determine the wave making resistance.

In propulsion tests, measurements include towing speed and propeller quantities such as thrust, torque and rpm. Normally, open water tests on the propeller alone are run to aid the analysis process as certain coefficients are necessary for the propeller design. Strictly, open-water tests are not essential for the power prediction alone. The model propeller is usually a stock propeller (taken from a large selection/stock of propellers) that approximates the actual design propeller. Propulsion test determine important input parameters for the actual detailed propeller design e.g. wake fraction and thrust deduction.

The wake distribution, also needed for propeller design, is measured behind the ship model using pitot tubes or laser-Doppler velocimetry (LDV). For propeller design, measured nominal wakes (for the ship without propellers) for the model must be transformed to effective wakes (for the ship with working propellers) for the full-scale ship. While semi-empirical methods for this transformation work apparently well for the most hull forms, for those with considerable flow separation at stern i.e. typically full-hulls, there are significant scale-effects on the wake between model and full-scale. To some extent, computational fluid dynamics can help here in estimating the scale-effects.

Although the procedures for predicting full-scale resistance from model tests are well accepted, full-scale data available for validation purposes are extremely limited and difficult to obtain. The powering performance of a ship is validated by actual ship trials, ideally conducted in calm seas. The parameters actually measured are torque, rpm and speed. Thrust is measured only as a special requirement because of the difficulty and extra expense involved in obtaining accurate thrust data. Whenever possible and appropriate, corrections are made for the effects of waves, current, wind and shallow water. Since the 1990s, the Global Positioning System (GPS) and computer based data acquisition systems have considerably increased the accuracy and economy of full-scale trials. The GPS has eliminated the need for "measured miles" trials near the shore with the possible contamination of data due to shallow water effects. Today trials are usually conducted far away from the shore. Model tests for seakeeping are often used only for validation purposes. However, for open-top container ships and ro-ro ships model tests are often performed as part of the regular design process, as IMO regulations require certain investigations for ship safety, which may be documented using model tests.

Most large model test centres have a manoeuvring model basin. The favoured method to determine the coefficients for equations of motion is through a planar motion mechanism and rotating arm tests. However, scaling the model tests results to full-scale using the coefficients derived in this manner is problematic, because vortex shedding and flow separation are not similar between model and full-scale. Appendages generally make scaling more difficult. Also, manoeuvring tests have been carried out with radio-controlled models in lakes and large reservoirs. These tests introduce additional scale-effects, since the model propeller operates in a different self-propulsion point than the full-scale ship propeller. Despite these concerns, the manoeuvring characteristics of ships seem generally to be predicted with sufficient accuracy by experimental approaches.

2.2 Main similarity laws:

The model tests must be performed such way the model and full-scale ships exhibit similar behaviour i.e. the results for the model can be transferred to full scale by a proportionality factor. It can be distinguished:

- geometrical similarity;
- kinematical similarity;
- dynamical similarity.

Geometrical similarity means that the ratio of a full scale "length" (length, width, draught etc.) L_S to a model scale "length" L_m is constant, namely the model scale λ:

$$L_S = \lambda \bullet L_M$$

Correspondingly, areas and volumes are recalculated:

$$A_S = \lambda^2 \bullet A_M$$

$$\Delta_S = \lambda^3 \bullet \Delta_M$$

It means the hull model shape to be similar to full-scale ship in macro scale. It is difficult to maintain geometrical similarity in micro scale, especially in aspects of surface roughness. That is why hull models to be polished in order to be treated as "hydrodynamically smooth".

Kinematic similarity means that the ratio of full scale times t_S to model scale times t_M is constant, namely the kinematic model scale τ :

$$t_S = \tau \bullet t_M$$

Geometrical and kinematic similarity result then in the following scale factors for velocity and acceleration:

$$V_S = \frac{\lambda}{\tau} \bullet V_M$$

$$a_S = \frac{\lambda}{\tau^2} \bullet a_M$$

Dynamic similarity means that the ratio of all forces acting on the full scale ship to the corresponding forces acting on the model is constant, namely the dynamic model scale κ :

$$F_S = \kappa \bullet F_M$$

Forces acting on the ship include inertial forces, gravity forces and friction forces.
Assumption of similarity of ratios between inertial to gravity forces and inertial to friction forces, results in equal Froude and Reynolds numbers.

$$Fn_M = Fn_S = \frac{V_M}{(g \bullet L_M)^{0.5}} = \frac{V_S}{(g \bullet L_S)^{0.5}}$$

$$Rn_M = Rn_S = \frac{L_M \bullet V_M}{\upsilon_M} = \frac{L_S \bullet V_S}{\upsilon_S}$$

where: g - gravity acceleration
ν - kinematic viscosity

It is impossible to retain during model tests these numbers equal. That is why surface model tests are carried at identical Froude numbers assuming the Reynolds numbers to be higher than the critical ones. Moreover, the following similarities are applied during tests of:

2.3 Drawbacks of modelling techniques

Both manoeuvring and seakeeping of ships concern time dependent ship motions, albeit with some differences:

- The main difficulty in both fields is to determine the fluid forces on the hull (including propeller and rudder) due to ship motions (and possibly waves).
- At least a primitive model of the manoeuvring forces and motions should be a part of any seakeeping simulations in oblique waves.
- Contrary to seakeeping, manoeuvring is often investigated in shallow (and usually calm) water and sometimes in channels.
- Linear relations between velocities and forces are reasonable approximations for many applications in seakeeping; in manoeuvring they are applicable only for rudder-angles of a few degrees. This is one reason for the following differences.
- Seakeeping is mostly investigated in the frequency-domain; manoeuvring investigations usually employ time-domain simulations.
- In seakeeping, motion equations are written in an inertial coordinate system; in manoeuvring simulations a ship fixed system is applied (This system, however, typically does not follow heel motions).
- For fluid forces, viscosity is usually assumed to be a minor importance in seakeeping computations. In manoeuvring simulations, the free-surface is often neglected. Ideally, both free-surface and viscous-effects should be considered for both seakeeping and manoeuvring.

2.4 Scale-effects in ship performance modelling

Podded vessel powering predictions are treated in the same way as ships with conventional propellers. Main difference is included only in the definition of propeller efficiency η_o as it is presented in the formulae for propulsive efficiency below:

$$\eta_D = \frac{(1-t)}{(1-w)} \eta_R \eta_0$$

$$\eta_0 = \frac{(J)}{2\pi} \frac{K_{TU}}{K_Q}$$

Pod housing resistance increase due to podded propeller work:

$$\Delta R_{POD} = \Delta R_{BODY} + \Delta R_{STRUT} + \Delta R_{INT} + \Delta R_{LIFT}$$

Scale effect is taken into account by introducing the pod housing drag correction ΔK_{TU} :

$$K_{TU} = (K_{TU})_M + \Delta K_{TP} + \Delta K_{TU}$$

$$K_Q = (K_Q)_M + \Delta K_Q$$

$$\Delta K_{TU} = \frac{\Delta R_{POD}}{\rho n^2 D^4}$$ - where: ρ - water density

n – propeller revs

D – propeller diameter

$$\Delta R_{BODY} = 0.5 \rho S_{BODY} V_{PS}^2 (1 + k_{BODY}) \{C_{FM} - C_{FS}\}$$

$$\Delta R_{STRUT} = 0.5 \rho S_{STRUT} V_{PS}^2 (1 + k_{STRUT}) \{C_{FM} - C_{FS}\}$$

where:

C_{FM} – friction coefficient for pod model acc. to ITTC-57

C_{FS} - friction coefficient for full scale pod acc. to ITTC-57

3. IDENTIFICATION OF THE BEST PRACTICE ELEMENTS IN MODEL TESTS PROCEDURES

3.1 Introduction

Recommendation for 14th ITTC (1975):

- Tests have to provide owners and builders with information on ship handling characteristics for operation purpose; for the reason, beyond tests at maximum speed, tests at medium and low speed, used in the channels and the harbour vicinity, have been recommended too.
- For operation purpose tests must concern course-keeping qualities, course changing qualities and qualities of emergency manoeuvres:
    - For course-keeping qualities the suitable test methods proposed are the spiral test, the reverse spiral test and the zig-zag manoeuvres with small rudder angles.
    - For course changing qualities, the zig-zag manoeuvre test and the 15 degrees helm turning test and change of heading test have been considered.
    - For emergency manoeuvres qualities the suitable test method proposed are the maximum helm turning test and the crash stop astern test.
- Tests have to supply with ship handling data on the field of ship design and scientific purpose.
- Only tests regarded as reliable after long enough experience have been considered; for that reason some new tests have not been included in recommendations, in spite of their possible interest.
- The total duration of manoeuvring test should be acceptable for owners and builders during sea-trials.

B. Test procedures:

- Turning circles;
- Pull-out test
- Turning trials from zero speed;
- Zig-zag manoeuvre;
- Direct and reverse spiral tests;
- Change of heading;
- Stopping trials:
    1). crash stop
    2). stopping trial at low speed
- Lateral thruster test

3.2 IMO recommendation in scope of manoeuvrability investigations:

3.2.1 General

IMO manoeuvrability standards, started in the twentieth, have been adopted as the **RESOLUTION MSC. 137 (76).** They were intended to create tools for uniform assessment of the manoeuvring performance of ships and to assist those responsible for the design, construction, repair and operation of ships. However, it should be noted that the Standards were developed for ships with traditional propulsion and steering systems i.e. including shaft driven ships with conventional rudders. In such circumstances, it was assumed the Standards to be periodically reviewed and updated. In order to evaluate manoeuvring performances of a new ship at the design stage, it is necessary to predict the ship manoeuvring behaviour on the basis of main dimensions, lines drawings and other relevant information available at the design stage. There is variety of methods for prediction of ship manoeuvring behaviours at the design stage, varying in the accuracy of predicted manoeuvres. In the aspects of accuracy, model tests have been considered for years as the most reliable prediction method. However, it can be said that accuracy requirement have been more lenient in this area than in other areas of ship model testing. It mainly resulted from absence of manoeuvring standards. The feedback of full-scale trial results has generally been less regular in this area than in case of speed trials. Consequently, the correlation basis for manoeuvrability is therefore of a somewhat lower standard, particularly for hull forms which can present a problem with regard to steering and manoeuvring characteristics.

3.2.2 Manoeuvrability model tests

There are two commonly used model test methods available for predicting the manoeuvring characteristics. One method employs a free-running model moving in response to specified control input (helm and propeller); the tests duplicate the full-scale trial manoeuvres and so provide direct results for the manoeuvring characteristics. The other method makes use of force measurements on a "captive" model, forced to move in a particular manner with controls fixed; the analysis of the measurements provides the coefficients of a mathematical model, which can be used for the prediction of the ship response to any control input.

Manoeuvring tests with free running models

Representative manoeuvres performed with a scale-model are the most direct method of predicting the manoeuvring behaviour of a ship. Since, it is recommended to use relatively large models, these ones, being employed for resistance and self-propulsion tests, are usually investigated. Large models are necessary to minimize scale-effects. There are limited possibilities to perform standard manoeuvres in typical towing tanks facilities. Alternatively, tests with a free-running model can be conducted on a lake. Unfortunately, it demands dedicated test stations and equipment being also dependent on weather conditions. Apart from giving direct results for due comparisons, certain effort are made now to derive respective coefficients of mathematical models with free-running models. The mathematical model is then used for predicting the manoeuvring characteristics of the ship.

Manoeuvring tests with captive models

Captive-model tests include oblique towing tests in long narrow tanks as well as "circling" tests in rotating-arm facilities. Particularly such tests are performed with use of a Planar Motion Mechanism (PMM), which can produce any kind of motion by combining static or oscillatory modes of drift and yaw. The basic principle is to conduct various simpler parts of more complex complete manoeuvres. By analysis of the forces measured on the model the manoeuvring behaviour is broken down into basic elements, the hydrodynamic coefficients. Afterwards, these hydrodynamic coefficients are entered into a computer based mathematical model and results of the standard manoeuvres are predicted by means of this model. A rotating-arm facility consists of a circular basin, spanned by an arm from the centre to the circumference. The model is mounted on this arm and moved in a circle, varying the diameter for each test. The hydrodynamic coefficients related to ship turning as well as to the combination of turning and drift can be determined by this method. Additional tests have to be conducted in a towing tank in order to determine coefficients related to the ship drift. Similarly to tests with use of the PMM, characteristics of the ship can be predicted by means of the respective mathematical model. Generally, it may be said that captive-model tests suffer from scale-effects similar to those of free-running tests, but due corrections are more easily introduced in the analysis of results.

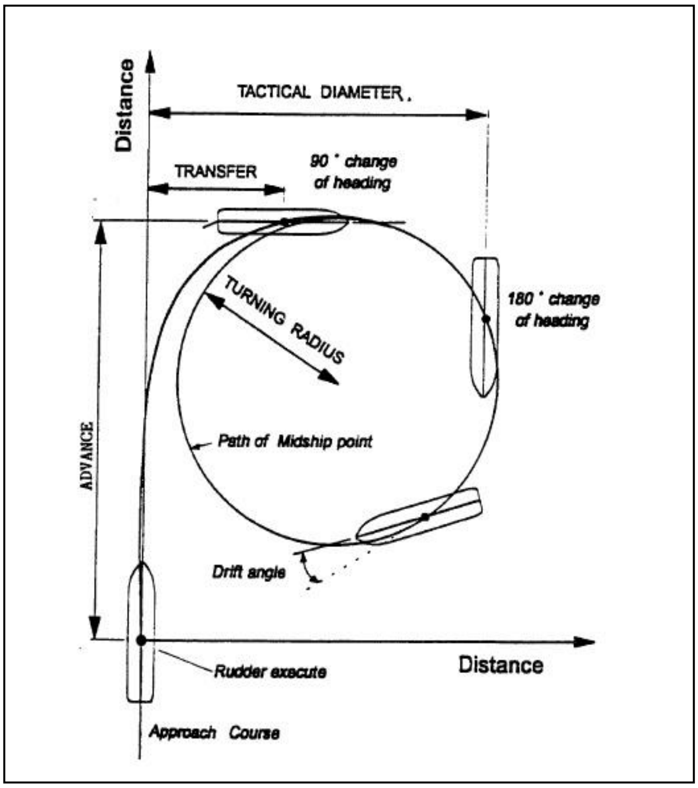
3.2.3 Standard manoeuvres and associated terminology

Conditions in which the standards apply:

- Deep, unrestricted water;
- Calm environment;
- Full load, even keel condition;
- Steady approach at the test speed.

Turning tests

Turning circle manoeuvre is the manoeuvre to be performed to both starboard and port with 35^o rudder angle or the maximum rudder angle permissible at the test speed, following a steady approach with zero yaw rate. The test speed used in Standards is a speed of at least 90% of the ship's speed corresponding to 85% of the maximum engine output.



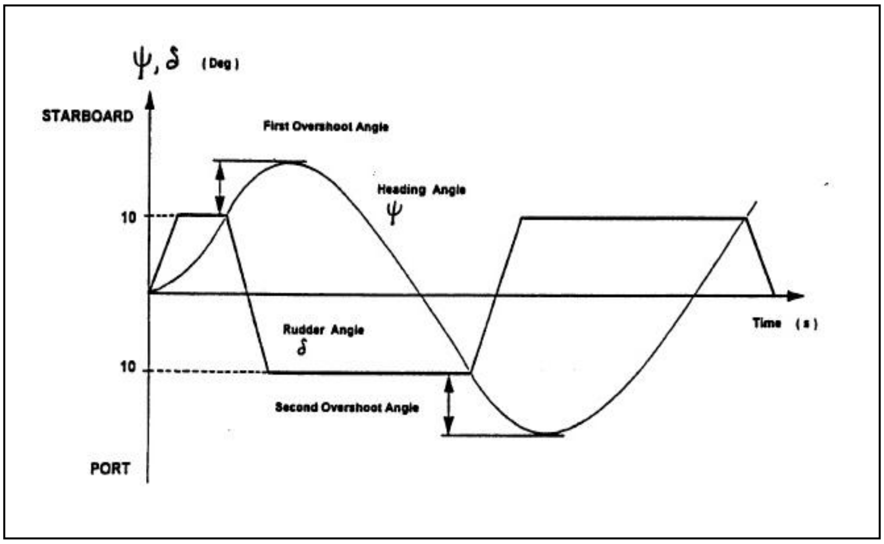
Zig-zag tests

Zig-zag test is the manoeuvre where a known amount of helm is applied alternately to either side when a heading deviation from the original heading is reached.

The 10^o/10^o zig-zag test is performed by turning alternately by 10^o to either side following a heading deviation of 10^o from the original heading according to the following procedure:

- After a steady approach with zero yaw rate, the rudder is put over to 10^o to starboard or port (first execute);
- When the heading has changed to 10^o off the original heading, the rudder is reversed to 10^o to port or starboard (second execute);
- After the rudder has been turned to port/starboard, the ship continue turning in the original direction with decreasing turning rate. In response to the rudder, the ship turns then to port/starboard. When the ship reaches a heading of 10^o to port/starboard of the original course the rudder is again reversed to 10^o to starboard/port (third execute).

The first overshoot angle is the additional heading deviation experienced in the zig-zag test following the second execute. The second overshoot angle is the additional heading deviation experienced in the zig-zag test following the third execute. The $20^o/20^o$ zig-zag test is performed similarly to $10^o/10^o$ manoeuvre but helm and heading values are respectively altered.



Spiral tests:
Spiral tests are performed so as to easily check course stability of a tested ship. It is commenced with the steady approach with the assumed model speed.

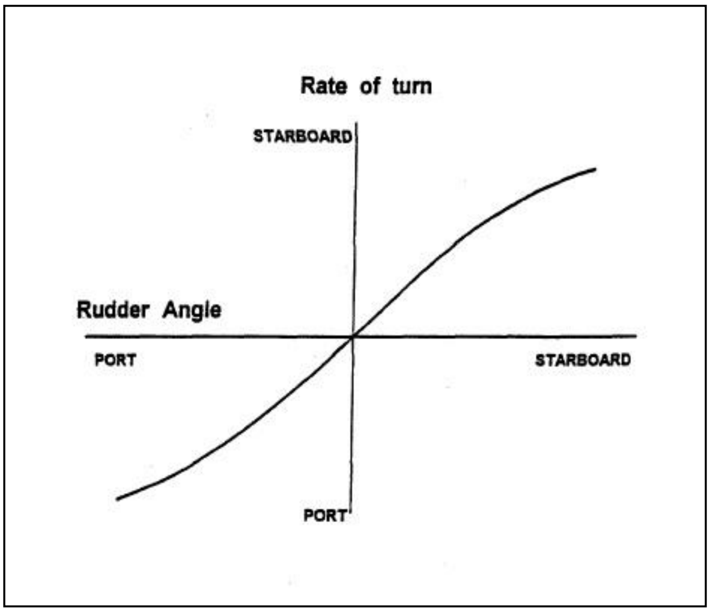
- **Direct spiral manoeuvre:**

The direct spiral manoeuvre is an orderly sequence of turning circle tests to obtain a steady turning rate versus rudder angle relation. It is a kind of testing in which various steady state yaw rate/rudder angle values are measured by making incremental rudder changes throughout a circling manoeuvre. Adequate time must be allowed for the ship to reach a steady yaw rate so that false indications of instability are avoided.

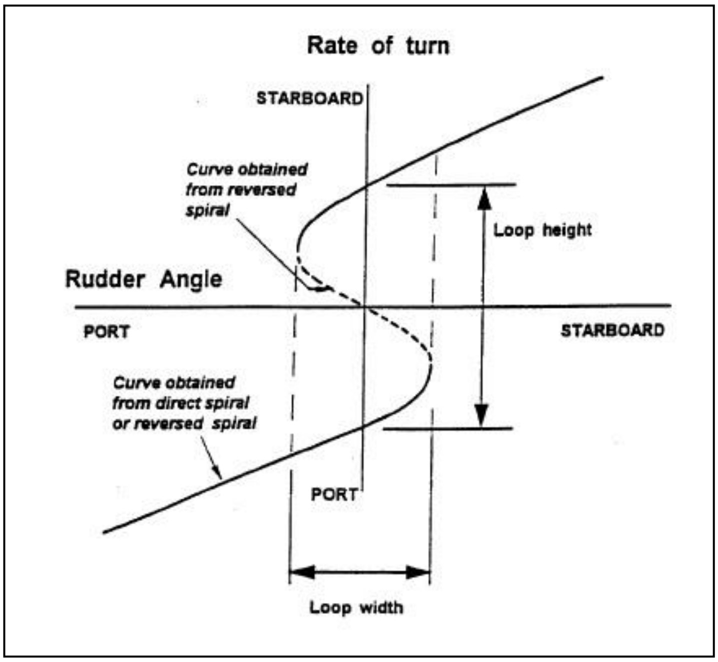
- **Reverse spiral manoeuvre:**

In the reverse spiral test the ship is steered to obtain a constant yaw rate, the mean rudder angle required to produce this yaw rate is measured and the yaw rate versus rudder angle plot is created. The reverse spiral test may provide a more rapid procedure than the direct spiral test to define the instability loop as well as the unstable branch of the yaw rate versus rudder angle relationship.

A) Example of course stable ship:

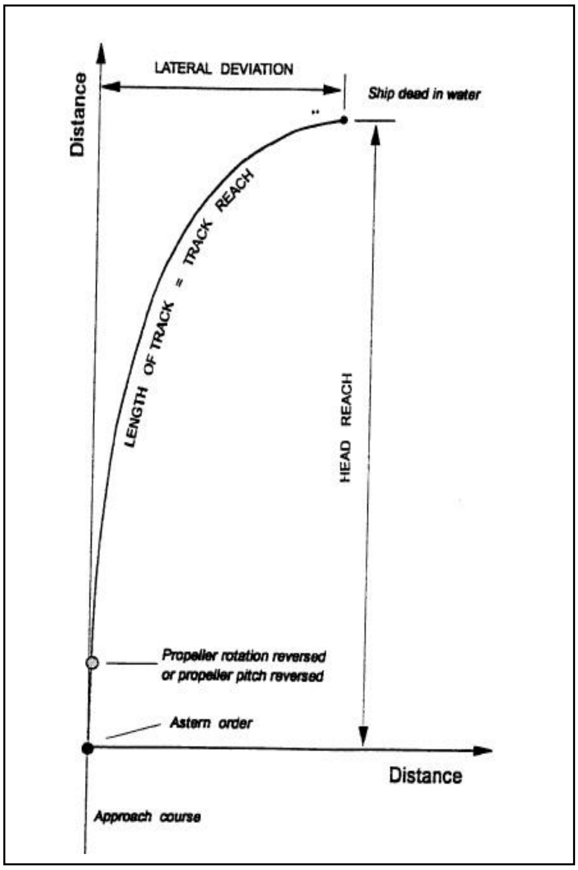


B) Example of course unstable ship:



Stopping manoeuvres:

Full astern stopping test determines the track reach of a ship from the time an order for full astern is given until the ship stops in the water. Track reach is the distance along the path described by the midship point of a ship measured from the position at which an order for full astern is given to the position at which the ship stops in the water.



Criteria

The manoeuvrability of the ship is considered satisfactory if the following criteria are compiled with:

1) Turning ability:

The advance should not exceed 4.5 ship lengths and the tactical diameter should not exceed 5 ship lengths in the turning manoeuvre.

2) Initial turning ability:

With the application of 10^o rudder angle to port/starboard, the ship should not have travelled more than 2.5 ship lengths by the time the heading has changed by 10^o fro the original heading.

3) Yaw checking and course keeping abilities:

- The value of the first overshoot angle in the $10^o/10^o$ zig –zag test should not exceed:
  - 10^o if L/V is less than 10 sec;
  - 20^o if L/V is 30 sec or more;
  - (5 + ½(L/V)) degrees if L/V is 10 sec or more, but less tha 30 sec.

  Where L and V are expressed in [m] and [m/sec] respectively.
- The value of the second overshoot angle in the $10^o/10^o$ zig-zag test should not exceed:
  - 25^o if L/V is less than 10 sec;
  - 40^o if L/V is 30 sec or more;
  - $(17.5 + 0.75(L/V)^o$, if L/V is 10 sec or more, but less than 30 sec.
- The value of the first overshoot angle in the $20^o/20^o$ zig-zag test should not exceed 25^o.

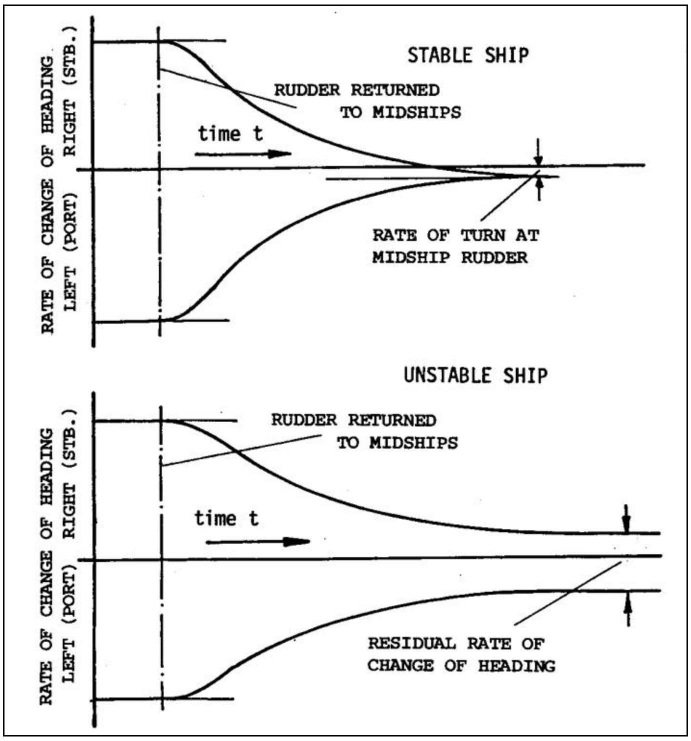
4) Stopping ability:

The track reach in the full astern stopping test should not exceed 15 ship lengths. However, this value may be modified by the administration where ships of large displacement make these criterion impractical, but should in no case exceed 20 ship lengths.

3.2.4 Other practiced manoeuvres

Pull -out Test

The pull out test gives, apart from the zig-zag and reverse spiral tests, information on course keeping characteristics. It presents a simple indication of a ship dynamic stability on a straight course. The ship is first made to turn with a certain rate of turn in either direction by applying rudder angle of approximately 20 degrees upon which the rudder is returned to midship. If the ship is stable, the rate of turn with decay to zero for turns to both port and starboard. If the ship is unstable, then the turn will reduce to some residual rate of turn. The pull-out tests should be performed to both port and starboard to show a possible asymmetry (see figure below). Normally, pull-out tests are performed in connection with the turning cycle tests, but they may be carried out separately.



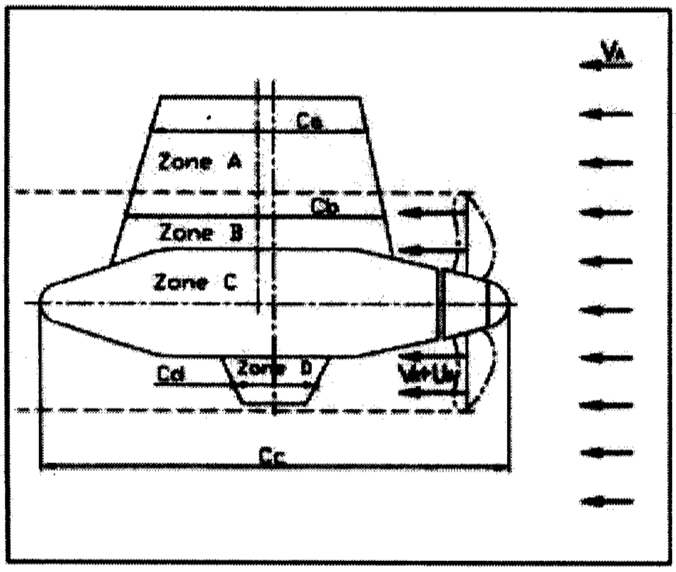
3.3 New procedure elements and new quality introduced by azimuthing propulsion to existing procedures

3.3.1 New self propulsion aspects

Installation of podded propulsors in the ship afterbody region results in new hydrodynamic qualities depicted by new interactions absent in the classical screw based propulsion systems.
Podded propulsors are volumetric constructions, playing a role of both propulsor unit and steering device. That is why the flow along a pod body and resulting loads should be analysed not only for propulsive reasons but from manoeuvrability point of view as well.
Generally, four different flow zones along a pod unit can be distinguished, presenting different flow speeds and Reynolds numbers. Such phenomena may result in laminar or turbulent flow specificities. In propulsive aspects such a situation gives differentiated resistance characteristics of the pod housing. In manoeuvrability aspects, it results in different steering forces in pod-unit angular positions.

The inflow velocity to a zone is:
either: $V_i = V_A = J \bullet n \bullet D$ if zone is located outside the propeller slipstream
where:
V_A - propeller advance speed
J - advance coefficient
n - shaft speed
D - propeller diameter

or: $V_i = V_A \bullet \left(1 + C_{Th}\right)^{0.5}$ if zone is located inside the propeller slipstream
where:
C_{Th} - propeller disc thrust loading coefficient



The Reynolds number of a zone is:

$$R_{n,i} = \frac{V_i \bullet c_i}{\nu}$$

where:

c_i - mean length of each zone
ν - kinematic viscosity of water

During the model manufacture, the surface of the pod housing is carefully polished to be treated as hydrodynamically smooth. In order to determine the friction forces on each zone of the pod housing, the friction coefficient c_F can either be prescribed or it can be determined as function of the Reynolds number. Only flow specificity, laminar or turbulent, to be precisely identified. For instance:

Laminar or transition flows:

$$\mathrm{Re} < 5.25 \bullet 10^4$$

$$C_F = 1{,}327 / \mathrm{Re}^{0.5}$$

$$5.25 \bullet 10^4 \le \mathrm{Re} < 2.0 \bullet 10^6$$

$$C_F = C_F^* \bullet 10^{0.117 \bullet f(\mathrm{Re})}$$

$$2.0 \bullet 10^6 \le \mathrm{Re}$$

$$C_F = 1/(3.46 \bullet \log_{10} \mathrm{Re} - 5.6)^2 - 1700 / \mathrm{Re}$$

where:

$$C_F^* = 1/(3.46 \bullet \log_{10}(2.0 \bullet 10^6) - 5.6)^2 - 1700/(2.0 \bullet 10^6)$$

$$f(\mathrm{Re}) = \{\log_{10} \mathrm{Re} - \log_{10}(2.0 \bullet 10^6)\}^2$$

Turbulent flow:

$$C_F = 0.075/(\log_{10} \mathrm{Re} - 2)^2$$

It is recommended to use laminar/transition for the outer zone of the propeller slip stream and turbulent for the inner zone.

3.3.2 Forces acting on pod housings in angular positions

General

Pod-units can be treated as very representative azimuthing propulsors due to highly developed interactions towards inner elements and the ship afterbody. Such a propulsor plays a double role of powerful propulsor and steering device. It is evident that majority of pod vessel performances depend on main pod elements. That is why a lot approaches have been so far presented in the professional press and thematic conferences. One of such approaches is presented below [Fig 1.]; its author presents pod load forces in pod angular positions as function of its geometry.

Method description

A generic pod propulsor is shown on the drawing below. It is composed of a *strut* having its span *b,* mean chord *c,* distance from leading edge to the vertical axis c_f and maximum thickness *t,* a pod having length *t,* distance from forward end to vertical axis l_j and maximum diameter *p,* an optional fin underneath the pod, having span *s,* mean chord *f,* distance from leading edge to vertical axis f_f and maximum thickness *g* and a propeller, characterised by number of blades *z,* diameter *D,* blade area ratio A_E/A_0 and mean blade pitch *H.*

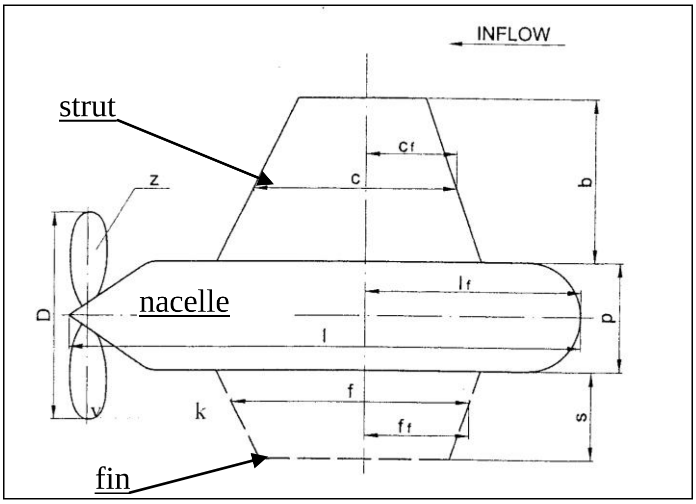


Fig. 1: Sketch of a generic pod propulsor

Operational parameters are as follows: inflow velocity V, drift angle at propulsor β, propeller number of revolutions per second *n* and pod deflection angle δ.

A. Pulling pod unit

Pulling pod-units dominates presently among azimuthing propulsors. It results from the fact that such a solution guarantees the maximally uniform inflow to pod propeller disc.

From the other side, pod unit struts and possible fins are situated in the turbulent flow, eliminating the risk of flow local separation, and hence negating the need for turbulent flow generation during propulsive testing.

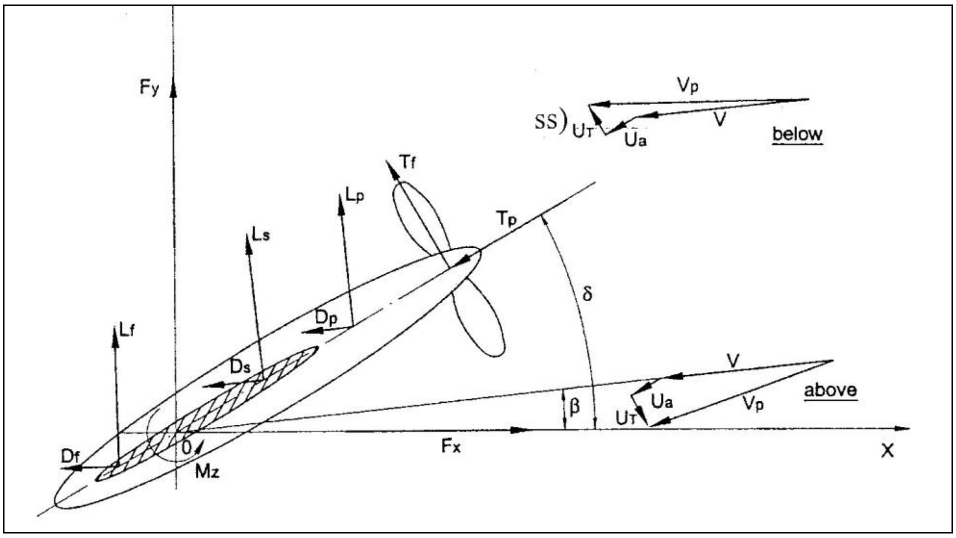


Fig. 2 Velocity and force components on pulling pod unit

Thrust of the podded propeller;

$$T_P = \rho n^2 D^4 \left(A_0 + A_1 J + A_2 J^2 + A_3 J^3 \right)$$

where: $J = \dfrac{V \cos(\delta - \beta)}{nD}$ is the advance coefficient

$\rho -$ is a specific density of water

$A_{0,}, A_1, A_2, A_3$ are the thrust coefficients dependent on propeller pitch, blade area ratio and number of blades

The transverse force on the propeller in inclined flow T_f may be calculated as:

$$T_f = 4\rho n^3 D^6 \left(B_0 + B_1 J + B_2 J^2 + B_3 J^3 \right) \left[\frac{1}{4.4Dn - V \sin(\delta - \beta)} - \frac{1}{4.4Dn + \sin(\delta - \beta)} \right]$$

where : B_0 ,B_1, B_2 ,B_3 are the torque coefficients analogical to $A_{0,}, A_1, A_2, A_3$

The mean axial propeller induced velocity u_a is equal to :

$$u_a = V \left\{ \sqrt{1 + \frac{8T_p}{\pi \rho V^2 D^2 \cos^2(\delta - \beta)}} - 1 \right\}$$

The mean tangential propeller induced velocity may be calculated as:

$$u_t = \frac{-4.4nD + \sqrt{(4.4nD)^2 - 4u_a \left(V \cos(\delta - \beta) + u_a \right)}}{2}$$

Consequently, in case of a right handed pulling propeller the inflow velocity V_p and angle of attack α for the strut (i.e. above propeller axis) may be expressed as:

$$V_p = \sqrt{\left[-V \cos\beta + u_t \sin\delta - u_a \cos\delta \right]^2 + \left[-V \sin\beta - u_t \cos\delta - u_a \sin\delta \right]^2}$$

$$\alpha = \delta - \arctan \frac{-V \sin\beta - u_t \cos\delta - u_a \sin\delta}{-V \cos\beta + u_t \sin\delta - u_a \cos\delta}$$

while the inflow velocity and angle of attack for the optional fin (i.e. below propeller axis) may be calculated as:

$$V_p = \sqrt{\left[-V\cos\beta - u_t\sin\delta - u_a\cos\delta\right]^2 + \left[-V\sin\beta + u_t\cos\delta - u_a\sin\delta\right]^2}$$

$$\alpha = \delta - \arctan\frac{-V\sin\beta - u_t\cos\delta - u_a\sin\delta}{-V\cos\beta + u_t\sin\delta - u_a\cos\delta}$$

Similar formulae are used for estimating inflow to the pod. However, in this case only the axial component of the induced velocity is taken into account in evaluation of V_p and α. The strut is treated as an airfoil of infinite span and consequently the lift (perpendicular to V_p) and drag (parallel to V_p) on the strut may now be calculated as:

$$L_S = \pi\rho\alpha kbcV_p^2$$

$$D_S = \frac{\left(c_{D0} + c_D\alpha^2\right)\rho bcV_p^2}{2}$$

where: k is the correction for viscous effects

c_{D0} is the profile drag at zero angle of attack

c_D is the increment of drag with angle of attack

while the optional fin is treated as semi-infinite airfoil and consequently the lift and drag on it are calculated according to the following formulae:

$$L_f = \frac{\pi\kappa\rho\lambda(\lambda+1)\alpha fsV_p^2}{(\lambda+2)^2}$$

$$D_f = \frac{\rho}{2}\left\{c_{D0} + \frac{4\pi\lambda(\lambda+1)^2}{(\lambda+2)^4}\alpha^2\right\}fsV_p^2$$

where: λ is the fin aspect ratio

Finally, the lift an drag on the pod treated as an ellipsoid may be approximated in the following way:

$$L_p = \frac{2\pi^2\rho pV_p^2\sqrt{p^2+l^2}}{N}\sin\alpha$$

$$D_p = \frac{\pi\rho pc_{D0}V_p^2\sqrt{p^2+l^2}}{2\sqrt{2}}$$

where: $\alpha = \delta - \beta$

N - is the coefficient taking into account the geometry of an ellipsoid.

The components of the resultant hydrodynamic forces and moment on the complete propulsor may be calculated as:

$$F_x = -T_p\cos\delta - T_f\sin\delta - \left(L_S + L_f + L_p\right)\cos\varphi - \left(D_S + D_f + D_p\right)\sin\varphi$$

$$F_y = -T_p\sin\delta + T_f\cos\delta + \left(L_S + L_f + L_p\right)\sin\varphi - \left(D_S + D_f + D_p\right)\cos\varphi$$

$$M_z = T_f l_f - \sum_{s,p,f}\left[L\left(\cos\varphi\sin\delta + \sin\varphi\cos\delta\right) + D\left(\sin\varphi\sin\delta + \cos\varphi\cos\delta\right)\right]\left(c_f - \frac{c}{4}\right)$$

where: φ is the angle resulting from calculating arc tan in previous equations respectively and summation over s, p, f requires appropriate modification of last equations in order to apply it to strut, pod and fin respectively.

B. Pushing pod unit

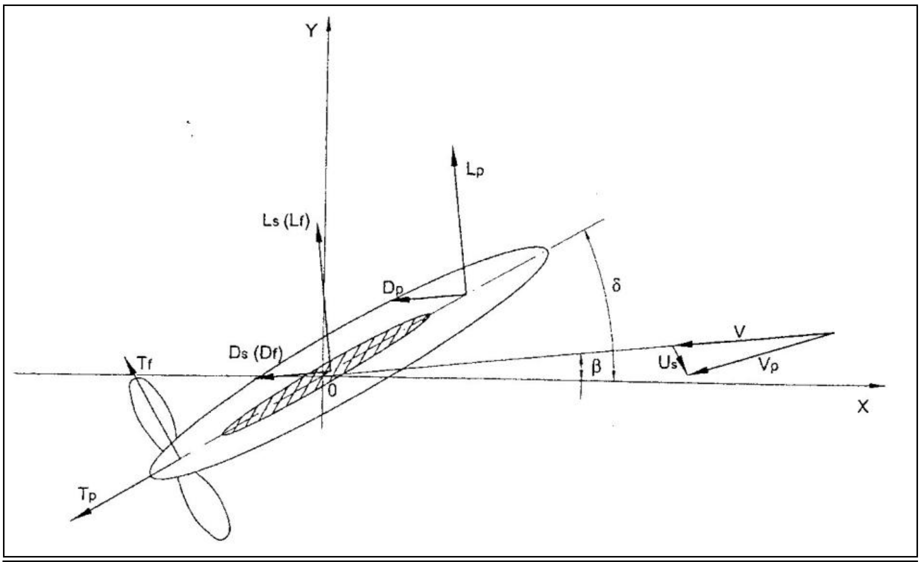


Fig. 3 Velocities and forces on a pushing podded propeller

In case of the pushing pod propulsor, the interaction between the pod and propeller looks differently - fig 3. Now the inflow velocity to the pod, strut and (and optional fin) is equal to V at angle δ - β. At the same time the inflow to the propeller V_p is the resultant of V and the strut (or fin) induced velocity u_S . The induced velocity may be related to the lift on the strut (or fin) and calculated according to the following formula:

$$u_S = \frac{L_S}{4\pi\rho V\left(l - l_f + c_f - 0{,}25c\right)^2}$$

Apart from the induced velocity u_S , there is another important velocity component parallel to V , resulting from the viscous wake behind strut (and fin). This velocity may be approximated after Schlichting 1964 in the following way:

$$u_w = \frac{1.4\sqrt{C_{D0}t}}{\sqrt{l + c_f} - c - l_f}$$

where: t is the maximum thickness of strut (g in case of fin)

Wake velocity u_w causes an additional asymmetry of flow around propeller blades in upper and lower positions and leads to the non-zero side force and moment on the pod propulsor even at zero angle of attack δ - β.

3.3.3 New possibility of stopping manoeuvres

Azimuthing Control Devices give wider possibility of stopping manoeuvres making use of combinations of lifting forces generated on their struts with positive or negative thrust forces of podded propellers.

Apart from classical stopping by means of reverse propeller revolutions, podded ships can be stopped:

- by changing the direction of propeller rotation;
- by turning the pod around;
- by turning the pod to generate steering forces (indirect mode) that oppose forward motion.

3.4 Model testing

Model tests to evaluate manoeuvrability are usually performed with models ranging between 2.5m and 9m in length. The models are usually equipped with propeller(s) and rudder(s), electrical motor and rudder gear. Small models are subject to considerable scaling-errors and usually do not yield satisfactory agreement with the full-scale ship, because the too small model Reynolds number leads to different flow separation at the model hull and rudder and thus different non-dimensional forces and moments, especially the stall angle (angle of maximum lift force shortly before the flow separates completely on the suction side), which will be smaller in models (15 to 25 deg) than in the full-scale ship (> 35 deg). Another scaling error also influences tests with large models: the flow velocity at the rudder outside the propeller slipstream is too small (due to a too large wake fraction in model scale) and the flow velocity inside the propeller slipstream is too large (because the too large model resistance requires a larger propeller thrust). These effects cancel each other partially for single screw ships, but usually the propeller effect is stronger. This is also the case for twin-screw twin rudder ships, but for twin-screw central-rudder ships the wake effects dominates for free running models. For a captive model, propeller thrust minus thrust deduction does not have to equal resistance. Then the propeller loading may be chosen lower such that scale-effects are minimised. However, the necessary propeller loading can only be estimated.

Model tests are usually performed at Froude similarity. For small Froude numbers, hardly any waves are created and the non-dimensional manoeuvring parameters become virtually independent of the Froude number. For Fn< 0,3, e.g., the bode forces Y and N may vary with speed only by less than 10% for deep water. For higher speeds the wave resistance changes noticeably and the propeller loading increases, as does the rudder effectiveness if the rudder is placed in the propeller slipstream. Also, in shallow water, trim and sinkage change with Fn influencing Y and N. If the rudder pierces the free-surface or is close enough for ventilation to occur, the Froude number is always important.

3.5 Specificity of manoeuvrability tests in towing tanks

3.5.1 General

Captive-model tests belong to main manoeuvrability investigations that are intended to determine the body-force coefficients by measuring the forces and moments for prescribed motions. Afterwards they are used to determine the hydrodynamic coefficients for a mathematical model of a ship manoeuvring motion. The subject models are also equipped with rudders, propellers and electric motors for propulsion and dedicated dynamometers. The model is located under the PMM or rotating-arm and connected together by means of load cells. The PMM and rotating-arm are able to generate linear and yawing cyclic movements.

- Oblique tests can be performed in a regular towing tank. For various yaw and rudder angles, resistance, transverse force and yaw moments are measured, sometimes the heel moment.
- Rotating arm tests are performed in a circular basin. The carriage is then typically supported by an island in the centre of the basin and at the basin edge. The carriage rotates around the centre of the circular basin. The procedure is otherwise similar to oblique towing tests. Due to the disturbances of the water by the moving ship, only the first revolution should be used to measure desired coefficients. Large non-dimensional radii of

the turning circle are only achieved for small models (inaccurate) or large basins (expensive). The technology is today largely obsolete and replaced by planar motion mechanisms (PMM) that can also generate accelerations, not just velocities.
- Planar motion mechanisms (PMMs) are installed on a towing carriage. They superimpose sinusoidal transverse or yawing motions (sometimes sinusoidal longitudinal motions) to the constant longitudinal speed of the towing carriage. The periodic motion may be produced mechanically from circular motion via a crankshaft or by a computer controlled electric motors (computerized planar motion carriage (CPMC)). The CPMC is far more expensive and complicated, but allows the extensions of model motions over the full width of the towing tank, arbitrary motions and precise measuring of the track of a free-running model.

3.5.2 ITTC procedures

Captive tests

Hull models possessing mean length ab. 4.5m are usually the subject of captive tests. The model-basins must be long; ab. 35 hull model lengths. The mean ratio between the model length and tank width (L/b) to be ab. 0.47. The model is equipped with the electric model based propulsive system with respective propulsor models. A steering system is precisely modelled according to the technical documentation delivered by a customer. Also tested load states correspond with the customer's documentation.

Flow chart of a captive test:

Step 1
Preparation of captive model tests in scope of mathematical model, hull model and testing set-up

↓

Step 2
Inspection of model equipment and set-up

↓

Step 3
Inspection of hull model in range of kinematic parameters, ship control parameters and operational and analysis parameters

↓

Step 4
Execution of the tests:

a. Stationary straight-line tests
- straight towing
- straight towing with rudder deflection
- oblique towing
- oblique towing with rudder deflection

b. Harmonic tests
- pure sway
- pure yaw
- pure yaw with rudder deflection
- pure yaw with drift

c. Stationary circular tests (with rotating arm or xy carriage)
- pure yaw
- yaw with drift
- yaw with rudder deglection
- yaw with drift and rudder deflection.

↓

Step 5
Data acquisition and analysis

↓

Step 6
Use of prediction procedures

↓

Step 7
Documentation

Controlled parameters

General:

- scale coefficient;
- model scale;
- model dimensions
- ratios of model to tank dimensions, water depth
- hull configuration (hull, rudder, propeller)
- model mass
- position of gravity centre of ship model
- moment of inertia of ship model
- degrees of freedom
- loading condition of ship model

Stationary straight line tests:

- number of conditions
- forward speeds
- range of drift angles
- propeller rate
- range of rudder angles
- time/distance required for acceleration, settling, steady phase, deceleration.

Harmonic tests

- forward speeds
- amplitudes of sway/yaw motion, velocity and accelerations.
- range of drift angles
- propeller rates
- range of rudder angles
- circular frequency or period of oscillations
- number of cycles.

Stationary circular tests

- number of conditions
- forward speed
- non-dimensional rate of turn
- range of drift angles
- propeller rate
- range of rudder angles
- time/distance required for acceleration, settling, steady phase, deceleration.

3.6 Specificity of free-sailing manoeuvrability tests on open lakes;

3.6.1 General

Free-running model tests, with free-running models, are usually performed indoors to avoid wind effects.

The track of tested models is recorded either by cameras (two or more) or from a carriage following the model in longitudinal and transverse directions. Turning-circle tests can only be performed in broad basins and even usually only with rather small models. Often, turning circle tests are also performed in towing tanks with an adjacent ‘round basins’ at one end. The manoeuvre is then initiated in the towing tank and ends in the round basin.

Spiral tests and pull-out manoeuvres require more space than usually available in towing tanks. However, towing tanks are well suited for zig-zag manoeuvres. If the ship's track is precisely measured in these tests, all necessary body-force coefficients can be determined and the other manoeuvres can be numerically simulated with sufficient accuracy.

3.6.2 Recommended manoeuvres and measurements during sea-trials of full scale ships

Ship sea-trials are the moment when all contract ship performances are verified according to commonly accepted ITTC procedures. In order to quantify scheduled performances a series of manoeuvres are carried out and the received are verified with contract values prepared on the manoeuvrability model test base.

Recommended Manoeuvring Trial Measurements

	Type of test	Heading	Position	Forward speed	Rudder angle	rpm	Rate of turn	Torque
1	Turning test	√	√	√	√	√		√**
2	Z-manoeuvre test	√	√	√	√	√		
3	Modified Z-manoeuvre	√	√	√	√	√		
4	Z-manoeuvre at low speed test	√	√	√	√	√		
5	Direct spiral test	√		√	√		√*	
6	Reverse spiral test	√		√	√		√*	
7	Pullout test	√		√	√		√*	
8	Stopping test	√	√	√	√	√		√
9	Stopping Inertia test	√	√	√	√	√		
10	Man-overboard test	√	√	√	√			
11	Parallel course manoeuvre test	√	√	√	√	√		
12	Initial turning test	√	√	√	√			
13	Accelerating turning test	√	√	√	√	√		
14	Thruster test	√	√	√	√	√	√	
15	Crabbing test	√	√	√	√	√	√	

* If the rate of turn cannot be obtained using a rate gyro and/or gyrocompass, the differential of the heading angle has to be used to derive this parameter

** Recommended for trials with twin propeller ships

That is why a selected set of such tests should be carried out at early stage of the ship design in order to deliver basic data for contract clauses formulation.

3.6.3 ITTC procedure

Object of manoeuvrability tests:

A hull model, with known propulsors OW and propulsive characteristics, equipped with respective propulsion, control and measuring systems is usually the subject of manoeuvrability tests on an open lake. Its basic equipment includes:

- steering passive or/and active devices used earlier during self propulsion tests;
- hull appendages used earlier during self propulsion tests;
- model propulsion system including electric current generator and electric motors;
- respective control and model trajectory identification systems;
- respective ballast for modelling load conditions.

Flow chart:

The presented below flow chart presents typical activities presented during the manoeuvrability tests on an open lake; it concerns mainly standard model tests. In case of innovative manoeuvrability tests a usually practiced procedure is a subject of respective alterations according to obliging quality systems.

Step 1
Preparation of test program and hull model characteristics

Step 2
Model equipment and measuring set-up

Step 3
Model inspection:
- principal dimensions
- hull configurations
- model mass
- centre of gravity positions
- moments of inertia

Step 4
Preparation of the lake base for standard and dedicated manoeuvrability tests.
Identification of weather conditions

Step 5
Execution of standard and dedicated manoeuvrability model tests according to ITTC recommendations and detailed procedures:
- turning circle tests
- spiral tests (direct or reverse)
- zig-zag tests
- emergency stopping manoeuvres
- initial turning tests
- pull- out tests
- man over-board (Williamson's) tests

Step 6
Data acquisition and analysis

Step 7
Documentation

Controlled parameters

During manoeuvrability tests the following values are continuously measured with use of possessed and installed dedicated equipment:

General:

- scale factor;
- model dimensions;
- water depth;
- hull configurations;
- propulsion and steering arrangements;
- loading condition of ship model;
- model mass;
- position of centre of gravity of ship model;
- moments of inertia of ship model.

Turning circle tests:

- initial forward speed;
- initial propeller rate;
- ordered steering device angle;
- model trajectory.

Zig-zag or modified zig-zag tests

- initial forward speed;
- initial propeller rate of rotations;
- ordered steering device angles and heading angle;
- turning speed of steering device.

Spiral or reverse spiral tests:

- initial forward speed;
- initial propeller rate of rotations;
- steering device angles; or
- corresponding yaw rate.

Manoeuvrability tests results

The received test results are collected and recorded accordingly to measuring and computer equipment according to quality system requirements. Afterwards, they are verified and corrected taking into account obliging ambient conditions. The recalculated results are presented in test and technical reports in the commonly practiced ways. The necessary recalculations are done with use certified software and computer systems.

4. ANALYSES OF GATHERED MATERIALS AGAINST CRITERIA PREPARED WITHIN OTHERS WPS

4.1 Review of general expectations of other WPs from hydrodynamic fields

The general expectations, concerning dedicated ACD knowledge, coming from other packages can be mainly divided into two groups. The first of them includes expectations concerning individual needs of selected simulators. The presently met simulators can be divided into following groups:

- Full mission bridge;
- Multi task simulator;
- Limited task simulator;
- Single task simulator.

Full Mission Bridge simulators can reproduce main manoeuvre characteristics:

- Turning;
- Yaw control characteristics;
- Course keeping characteristics;
- Stopping characteristics.

Other expectations concern versatile training aspects. The respective training courses can be executed with use either simulators or manned models as well. Main training subjects include:

- Non-typical towing manoeuvres;
- Versatile control modes:
    - cruise manoeuvring mode;
    - soft manoeuvring mode;
    - strong manoeuvring mode.
- ACD application regions:
    - open sea;
    - anchor area;
    - harbour basins and terminals;
    - manoeuvres with tugs;
    - steering and course alterations;
    - crash stopping;
    - steering at low speeds;
    - mooring;
    - side stepping;
    - ship handling in ice;
    - reverse rpm.

4.2 Recognition of individual needs of selected simulators on basis of collected knowledge

4.2.1. Introduction

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

a) models for prediction of ship manoeuvrability
b) models for use in simulators.

Prediction of standard ship manoeuvres is needed at the design stage to ensure that a ship has acceptable manoeuvring behaviours, as defined by ship owner, INO or local authorities.

Simulator, or time domain models, are used in real time, man-in-the-loop simulators, or fast-time simulators for training of deck officers or investigation of specific ships operating in specific harbours or channels.
The generation of a manoeuvring model covers a series of steps, which must be validated and documented individually:

1) **Ship particulars**

It should include the following data:

- Type of a ship;
- Hull data;
- Actual loading conditions;
- Engine characteristics;
- Data on propulsors;
- Data of steering device;

2) **Prediction of the hydrodynamic forces**

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

- Translation modes:

  mass * acceleration = Σ external forces
- Rotation modes:

  mass moment of inertia * angular acceleration = Σ 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 are included as applicable in the external forces.

3) **Modelling of forces in the mathematical model (derivatives, coefficients, tables, direct simulation of forces).**

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 simulation model.
Forces are described with the following means:

- Hydrodynamic derivatives (obtained from measured or calculated forces);
- Look-up tables of the forces;
- Algebraic equations (empirical or theoretical);
- Direct simulations (CFD).

Documentation of mathematical models should include:

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

4) **Mathematical model structure**

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

- Whole ship models;

- Modular models of components;
- Direct simulation (CFD).

5) Integration method

Once the governing differential equations are known, a large variety of integration methods exist to make a time domain simulations. 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.

6) Simulation software

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

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;
- For zig-zag 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 (degrees of freedom) model should also include roll angle.

4.2.2 Significant hydrodynamic influences

- Shallow water;
- Bank effects;
- Effect of pier/quay proximity;
- Effect of limited harbour basin;
- Surface and submerged channel effects;
- Ship to ship interactions;
- Effect of current;
- Effect of auxiliary rudder installation (thruster);
- Effect of soft bottom and mud;
- Ship - tug cooperation in harbour;
- Escorting operations with tugs;
- Anchoring operation.

4.3 Identification of knowledge ranges necessary for training on boards;

Onboard training demands a wide scope of knowledge from the following hydrodynamic domains:

4.3.1 Ship propulsion

Ship propulsion matters demands full knowledge of matters concerning:

- Basic modelling techniques;
- Respective test procedures;
- Basic characteristics of ship resistance of bare and appended hulls;
- Open water characteristics of applied propulsors;
- Basic interactions within propulsion systems;
- Propulsive characteristics on assumed service conditions;
- Scale effect influences and their compensation.
- New qualities introduced by azimuthing controlled devices.

4.3.2 Ship manoeuvrability

- Nautical manoeuvres;
- IMO and others ship manoeuvrability requirements ;
- Passive and active steering devices;
- Internal and external forces acting on manoeuvring vessel;
- Basic manoeuvrability testing techniques;
- Main manoeuvring test procedures;
- Ship motion equations;
- Specificity of simulation techniques;
- Scale effect influences and their compensation;
- New qualities introduced by azimuthing control devices;

4.4 Selection of respective knowledge drawbacks to be supplemented in the near future

Despite of many-years hydrodynamic investigations and trainings there are many noticed drawbacks in both propulsive and manoeuvrability aspects. It results from fact that only limited hydrodynamic phenomena and interactions have been so far identified and fully assessed. So called scale effect has been only partially recognised what resulted in many simplifications of full scale performances forecasting based on model testing experiments.

In order to improve the situation not only the progress of measuring techniques is recommended but wider application of CFD tools as well. It can create conditions for deeper recognition of all basic interactions. It seems indispensable to create respective data bases of ship full results so as to determine respective correlations model-ship.

5. IDENTIFICATION OF SHORTCOMINGS IN EXISTING PROCEDURES

5.1 Review of available publication to know respective remarks and comments

There are many presentations, in professional press and conference materials, manoeuvrability investigation results. Usually it is impossible to assess their quality due to lack of respective uncertainty analyses. It is very crucial conditions, because the quality of received results depends not only on general assumptions but also on many details resulted from metrology errors as well. Very often there is visible lack of information how the scale effect phenomenon was taken into account.

Usually, only the comparative tests, carried out in the same condition, represent the highest level of reliability. However, it is impossible to assess resulting full-scale prediction in the same way.

The performed respective analyses indicate that highly advanced numerical assistance can improve many aspects of conducted manoeuvrability tests.

5.2 Assessment of respective procedures applied on towing tests from the point of view of their accuracy and applied simplifications

5.2.1 Assessment of open lake tests respective procedures from the point of view of their accuracy and applied simplifications

Shortcomings of the concept and applied simplification

- only one scale factor model can be used for tests;
- inaccuracy in service condition modelling (ship or model service mode);
- dependence on weather conditions;
- inaccuracy in manoeuvres modelling of twin screw ship model;
- high costs of experiments.

Causes of tests uncertainty

- inaccuracy of ship model characteristics;
- undesired facility related hydrodynamic effects;
- unsteady approach conditions;
- errors on ship model control equipment parameters;
- disturbance from test arrangement on model measurement inaccuracy;
- non-stationary phenomena during transitory phases of measurements;
- errors on ship control equipment parameters;
- variable ambient conditions.

5.2.2 Assessment of captive tests respective procedures from the point of view of their accuracy and applied simplifications

Shortcomings of the concept and applied simplifications

- small size of tested model results in low levels of Reynolds number;
- dependency on assumed mathematical model;
- very high dependency on reliability of test-up;
- basin width and length limitation influence test accuracy;
- residual motion of water in the basin influence test accuracy;

Causes of tests uncertainty

- imperfections causing errors to the boundary and/or initial conditions;
- inaccuracy of ship model characteristics;
- undesired facility related hydrodynamic effects;
- imperfections with direct or indirect influence on the ship's model dynamics;
- mechanism geometry discrepancies;
- mechanism control and setting errors;
- errors on ship model control equipment parameters;
- measurements accuracy;
- data acquisition;
- numerical analysis.

6. CRITICAL COMPARISONS OF FREE-RUNNING AND CAPTIVE MANOEUVRABILITY MODEL TEST TECHNIQUES

As highlighted above, both captive and free-running model tests do suffer from scaling effects. Specifically, the forces acting on the ship's hull are highly dependent on the wave-making characteristics. The non-dimensional form of such characteristics, scale with respect to Froude number; which has velocity on the top and the ship length on the bottom line of the equation. Conversely, the forces acting on the propeller are dominated by fluid friction. The non-dimensional form of such characteristics, scale with respect to Reynolds number; which has velocity and ship length on the top line of the equation. The consequence of this is that, if the hull and propeller are both scaled equivalently in size, they will have conflicting scaled velocity requirement. That is to say, to comply with Froude scaling we must go slower and to comply with Reynolds number we must go faster. For both captive and free-running testing, the ship's hull forces are dominant; so the scale velocity is taken from the Froude number.

Implications for captive testing

The implications for captive testing are mostly related to:

- the pressure distribution on the stern of the hull-form as modified by the propeller action;
- the velocities experienced at the rudder due to the accelerated flow from the propeller;
- the inflow angle experiences at the propeller as a function of both hull and rudder.

Actually, all three of the above can be seen to be interdependent. Nevertheless, various strategies have been adopted that elevate these problems to such an extent as to provide satisfactory results. For captive testing this can most notably be achieved by deconstructing the tests into various components. That is, it is possible to test the hull both with and without the propeller; thus making some assessment of the difference. Similarly, it is possible to examine the inflow velocities at the rudder both with and without the propeller. Also, much understanding of the propeller velocities and forces can be obtained using cavitation tunnel tests; achieved at Reynolds scaling. Ultimately, a body of data can be obtained that can be combined in a numerical time-domain simulation of manoeuvring performance. This simulation can be first validated by comparison with free-running model tests, calculated at model-scale, and then used to make predictions about full-scale performance.

When it comes to azimuth control devises, and specifically pods or mechanical drives, there is a very important difference. Specifically, the propeller changes both its position and angle to the flow when steering. This has various implications:

- The inflow velocities to the propeller are dependent on both the helm angle and the ship velocities (mostly, yaw rate, sway and surge velocities); which are themselves time-varying.
- The flow experienced at the "rudder" (nacelle and strut) is modified by the propeller angle and loading which is itself dependent on 1. Both 1 and 2 modify the hull pressures, which in turn modify both 1 and 2.
- It is clear from the above that the scaling issues associated with the over-loaded propeller cannot be ignored. In fact, while little full-scale validation is published, that which is available would indicate that prediction is not as good as one would hope.
- While it is not impossible to conduct sufficient tests, with sufficient combinations of condition, to make useful predictions, it is certainly not cost effective. In fact, for conventional arrangement, the test matrix can be very large, especially if unusual

condition must be considered. Examining a variety of drift angles for a variety of yaw rates for a variety rudder angles, and the tests needed quickly become extensive. Repeat all of these tests for a range of roll angles and propeller loading conditions and the test matrix becomes very costly indeed. Further, taking the above and repeating all for a range of shallow water condition or bank-effects or any other specific phenomenon, can be prohibitively expensive and insurmountably time consuming.

- For ships with azimuth devices, the test matrix must be bigger still. Notably, the effect of roll cannot be neglected; especial for cruise ships that tend to have a small metacentric height. Also, as these ships are designed to operate effectively in close quarters, neglecting the effects of squat and trim would be unwise.
- Ultimately, this means that, for a comprehensive understanding of the manoeuvring performance of ships equipped with azimuth control devices, a very costly and time consuming test program would be necessary. And understandably, such tests are not routinely being conducted.

Implication for free-running testing

The implications for free-running model tests are mostly related to the same problems highlighted for captive model tests. Specifically, the propeller loading is incorrect at the model-scale, resulting in incorrectly modelled pressures and thus forces on the hull, rudder and propeller itself. Attempts to elevate this problem have included such measures as using an air-propeller atop the model to take some of the load. For conventional arrangements, this has been implemented with a constant load on the air-propeller that, while not adjusting with speed, can give useful results. However, the significantly greater speed changes associated with azimuth control ships may well invalidate this simplification. In any even, no published results are currently know to have examined the effectiveness for of air-propeller assistance for ACD ship; either with or without a speed compensation.

As with captive testing, very little validation is published when compared to full-scale results. In addition, what does exist indicates limited predictive success. Nevertheless, free-running model testing is still a perfectly good way of validating the captive model test derived simulation, which can then be repeated at full-scale with more confidence. Nevertheless, a comprehensive study of the exact implications of various physical components on scaling prediction is still necessary if progress is to be made with any degree of confidence.

7. RECOGNITION OF PRACTICALLY NEW QUALITIES INTRODUCED BY AZIMUTHING PROPULSORS

The previous section considered the main problem with both free-running and captive model testing and specifically with the associated scaling issues. This section will outline some options that are known to be in practice that attempted to address some of the problems outlined.

Method used in captive model testing
One of the key characteristics of manoeuvring performance prediction using simulation based on captive testing is that various components can be tested separately. Such components can then be tested in the most appropriate way and using the most appropriate scaling method for the dominant physics in question. For example, the hull-form can be tested (as a bare-hull) using Froude-scaling and the propeller can be tested in a Cavitation tunnel using Reynolds-scaling. The two can then be numerically combined to obtain the correctly scaled results. Such test can be supplemented with additional captive tests that include the propeller; testing at various load conditions. The hull pressure forces can then be modelled and the most appropriate condition selected to predict the full-scale results.

For azimuth pod-drives, two alternative methods are known to have been used. One is in a cavitation tunnel and one in a towing tank. In the cavitation tunnel example, a pod-dynamometer was manufactured that can place the pod and propeller at any helm-angle. The unit was designed to measure, in addition to the usual propeller thrust and torque, the total unit horizontal forces and moments. In this way a large range of coefficients can be derived for a range of propeller loadings at a range of helm-angles. The result can then be numerically combined with captive model test results to simulate manoeuvring behaviour.

In the towing tank example, a flat plate was mounted to the tank carriage; submerged slightly below the free surface. Below this plate, two azimuth pod units were mounted side-by-side. In this case, two possible options for towing exist including: turning the individual pods (helm angle) or by rotating the whole plate (yawing). Again, a range of coefficients can be derived that can be used in combination with hull data to simulate the full-scale manoeuvring performance. Both of the above methods have been used in practice and have results published in the open literature. Both do still have some unknown and further validation is necessary before standards can be agreed on a suitable testing standard.

8. FINAL ASSESSMENT OF PROS AND CONS OF ANALYSED PROCEDURES VERSUS RESPECTIVE REQUIREMENTS

8.1 Summary of respective requirements and criteria;

Main requirements concerning manoeuvring models tests are connected with their accuracy, repeatability and validity with full scale ship performances; each of these groups of tests has its main advantages and noticed drawbacks. As a general criterion of ship manoeuvrability, the commonly known IMO criteria are taken into account. It makes the assessed ship predictions depend indirectly on qualities of performed tests, their recalculations and validations.

As a very important factor, the applied simplifications should be assessed and due correction implemented. Uncertainty analyses should be performed at all stages so as to evaluate their weakest sides and to introduce necessary improvements. The better forecasting accuracy can be achieved not only by use of more reliable measuring equipments but by application of more advanced recalculation formulas as well.

8.2 Verification of due outcomes with adequate requirements;

At present, it is really difficult to compare ratios between requirements and respective outcomes. The detailed comparisons can be carried out when respective full scale results can be known. There is a big problem to have available such reference data what makes use only approximated information. It suggests the creation of databases, supported by due numerical tools, in a really uniform way making possible to conduct easily necessary analyses and comparisons. Identical approaches can result in respective ratios between analysed performances.

8.3 Respective final assessments and comments

Since, the ship safety depends meaningfully on ship manoeuvrability properties, it is indispensable to have reliable tools on each stage of their analyses. The most important are tools used for practical investigations and numerical analyses. It can be said that the both domain are developed in a really ordered ways which correspond with respective technologies developments. It is natural that any gaps may be met but their recognition to be considered as a good sign of their future eliminations. The total improvements are usually functions of the money and time.

The best practice in particular domain can be achieved by:

- Proper recognition of investigated phenomena:
- Selection of respective tools for practical experiments or theoretical analyses;
- Implementation of due tools and uncertainty analyses:
- Correction of measurement results;
- Determination of possible gaps and ways of their compensation;
- Correction of identified gaps.

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