ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Captive Model Test

7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-06	Manoeuvrability
7.5-02-06-02	Captive Model Test

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Captive Model Test Procedure

1. PURPOSE OF PROCEDURE

1.1 Reasons to perform captive model tests

In the majority of cases, captive model test techniques are applied to determine the hydrodynamic coefficients for a mathematical model of ship manoeuvring motion. It should be noted that hydrodynamic force coefficients may be determined by other means, e.g. by system identification techniques applied to free running model test results or by numerical computations. On the other hand, the results of captive model tests can be used to perform validation and/or verification of these numerical models.

Another reason to perform captive model tests is to investigate specific projects, which are mostly related to a channel or harbour layout, such as to investigate ship-bank interaction or ship-ship interaction, eventually the forces measured can also be used as an input for a ship manoeuvring simulator. An extra reason to conduct captive model tests is to perform a rapid check for ship design, to see if the ship is able to meet the IMO manoeuvring criteria. This procedure mainly addresses the use of captive model tests to obtain the hydrodynamic coefficients to simulate standard manoeuvres.

1.2 Test types

For manoeuvring captive model tests with a surface ship a horizontal Planar Motion Mechanism (PMM) equipped with force gauges is usually attached to the main carriage of the towing tank in order to perform prescribed motions and measure the hydrodynamic forces and moments acting on the ship model. Diverse PMM designs enable different kinds of motions and have different limitations. Present devices, often called "Computerised Planar Motion Carriage" (CPMC), have independent drives for the individual motions – longitudinal, transversal and rotation(s) – allowing for carrying out fully pure motions in single motion variables and almost arbitrary planar motions. In order to measure the forces, the model is often connected to the PMM or CPMC through a multi-component force balance. Alternatively, a rotating arm can be used equipped with force gauges to measure hydrodynamic forces and moment for constant yaw velocity. An emerging technique is the combination of a PMM with a hexapod. With this setup almost any trajectory in the horizontal plane can be given to the ship model, combined with a vertical variation.

Taking account of the mechanism involved and the motion imposed to the ship model, a distinction can be made between:

a) steady straight line tests, performed in a towing tank, for instance:

- straight towing, eventually with rudder deflection;
- oblique towing, eventually with rudder deflection;
- the above tests with multiple rudder and/or propeller variations (multi-modal).

For an explanation of multi-modal tests, see section 2.3.4.

b) harmonic tests, requiring a towing tank equipped with a PMM or CPMC, for instance:

- pure sway;
- pure yaw;

- pure roll;
- combined sway and yaw;
- yaw with drift;
- yaw with rudder deflection;
- other, different combinations (multi-modal).

c) steady circular motion tests, by means of a rotating arm or CPMC:

- pure yaw;
- yaw with drift;
- yaw with rudder deflection;
- other, different combinations (multi-modal).

Tests without rudder deflection are carried out for determining hull forces and can be performed with and/or without appendages; tests with rudder deflection yield rudder induced forces and are therefore non-applicable when the model is not fitted with rudder and propeller (bare hull testing).

All tests, and especially pure roll tests can be carried out with an average heel angle to determine forces due to heel/roll if the aim is to include this degree of freedom (DOF) in the mathematical model, e.g. for ships with low metacentric height ($\overline{GM}$). Pure roll tests require a special device for enforcing roll motions.

Multi-modal and hexapod tests require the possibility to continuously steer one or more control and/or kinematical parameters and may be used as a substitute for several types of straight line, harmonic or circular motion tests. For PMM equipped with hexapod all harmonic tests are possible and variations beyond, although the limited range of hexapod amplitudes calls for an integrated system.

Standard procedures for these types of tests are presented, together with recommended quantitative guidelines in order to ensure the quality of test results and to obtain reliable results. The procedure is to be used for surface ships only, where Froude scaling is applied.

These guidelines are mainly based on two sources: literature on captive testing published during the last decades, and the results of a questionnaire distributed among all ITTC member organisations in 2015 by the 28th Manoeuvring Committee. Further details on the questionnaire results can be found in the report of the 28th Manoeuvring Committee (2017).

The main principles of an analysis procedure for the uncertainty of the results is presented in a separate ITTC procedure (7.5-02-06-04), which addresses the uncertainty in measured forces, carriage kinematics, data filtering, the uncertainty due to the analysis, the data-fitting uncertainty and the uncertainty in the resulting outcome through the simulation of manoeuvres.

1.3 Hydrodynamic coefficients for simulations

In the present procedure the test parameters are defined in order to be able to simulate standard manoeuvres. However, it must be emphasized that the simulation should always be covered by tests. As such the guidance provided here is a minimal test program.

The hydrodynamic coefficients should be obtained on the basis of the mathematical model to be utilised for manoeuvring simulations. At present modular mathematical models are the most popular choice (see Figure 1).

While many different possible analysis methods exist, the following procedures may generally be employed.

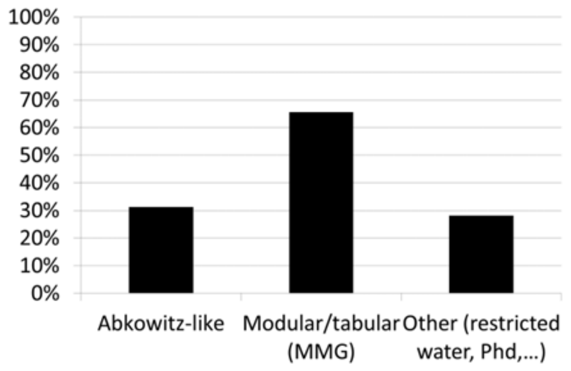

Figure 1: Types of mathematical models built, among institutes who build models (28th Manoeuvring Committee, 2017).

For hull forces:

- resistance and propulsion data from (multi-modal) straight towing tests;
- coefficients for sway velocity from oblique towing or pure sway tests;
- coefficients for yaw rate from pure yaw tests (harmonic or circular motion);
- coefficients for sway velocity and yaw rate from combined sway and yaw tests or yaw with drift tests;
- inertia coefficients from harmonic (multi-modal) tests.

The frequency dependence of hydrodynamic forces should be checked (see section 4.3.1.3), and it should be ensured that the coefficients are equivalent to those at zero frequency. Where possible this can be done by comparison with steady tests.

For rudder forces, e.g.:

- coefficients of the forces induced on a ship hull due to rudder deflection from straight towing tests with (multi-modal) rudder deflection;
- coefficients expressing the effect of lateral motion of the stern on rudder induced forces from oblique towing tests with (multi-modal) rudder deflection and/or harmonic/circular yaw tests with rudder deflection.

The number of tests needed to derive the coefficients of a mathematical model is shown in Figure 2. A distinction can be made between deep water and shallow water tests. Almost all institutes who perform tests in shallow water, need at least 100 tests to build a manoeuvring model, while, on average, less tests are needed in deep water. The average number of tests mentioned in deep water is 144 and in shallow water it is 170.

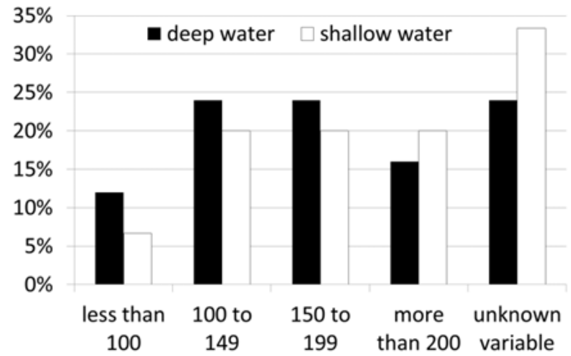

Figure 2: Number of tests needed to build a mathematical model for one ship at one draft and one water depth, (28th Manoeuvring Committee, 2017).

1.4 Parameters to be taken into account

In the following sections general parameters valid for all tests will be discussed, such as the water depth & blockage (section 2) and the ship model (section 3). Considerations on test execution are given in section 4:

- 4.1 general considerations, valid for all tests
- 4.2 for steady straight line tests
- 4.3 for harmonic tests
- 4.4 for steady circular tests
- 4.5 for multi-modal tests
- 4.6 for hexapod tests
- 4.7 for data acquisition

Finally, section 5 will discuss the post processing of the tests.

2. WATER DEPTH & BLOCKAGE

Tests in *deep water* should be performed with a water depth to draft ratio that is large enough to be free from shallow water effects. Referring to IMO (MSC/Cir 644), a minimum value of h/T = 4 is considered as acceptable. This figure, which accounts for practical issues of full scale trials, must be considered as a strict minimum for deep water model tests. The critical speed in open water is defined as $\sqrt{gh}$ or $Fr_{\mathrm{h,crit}} = 1$. In deep water the test speed should be below 50% of the critical speed.

For *shallow water* tests (h/T < 4) the water depth should be scaled correctly; this may impose a restriction on the maximum draft. At very small h/T, the vertical variations of the tank bottom should be less than 10% of the under keel clearance, which may determine the minimum draft.

Some towing tanks use a false bottom to execute shallow water tests. In this case attention should be paid to a sufficient stiffness of the false bottom. Also, water recirculation around the boundaries of the false bottom can jeopardize the measurements. For the latter Li et al. (2019) showed, based on steady straight line tests with potential flow computations, that the width of the false bottom should preferably be larger than the influence width, see Eq. 1, on each side of the ship model and that the steadiness of the measurements has to be checked in case the false bottom has a limited length.

Shallow water implies a finite water depth. The tank walls can have an undesired lateral effect on the tests. Based on a comprehensive set of model tests using 11 different ship models and 25 different lateral bank geometries, Lataire (2014) introduces an influence width of

$$y_{\mathrm{infl}} = 5B(Fr_h + 1) \tag{1}$$

If the distance between ship and tank walls is larger than y_{infl}, ship-bank interaction effects can be neglected. The above formulation is valid for steady straight line tests. Oblique or dynamic motions will probably cause larger influence widths.

Tests where lateral restrictions are desired, are referred to as *restricted water* tests (e.g. banks, other ships, harbour layout). In most cases restricted water is associated with shallow water, but not always (e.g. ship lightering or replenishment at sea).

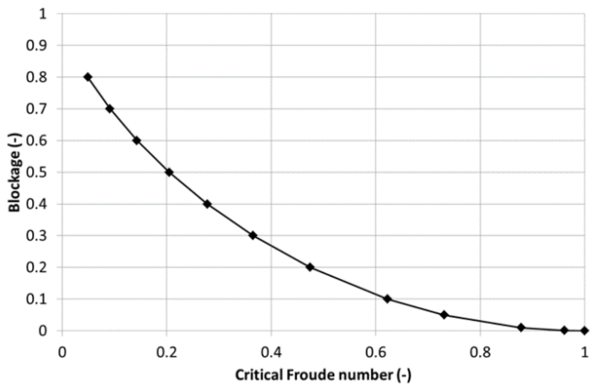

Figure 3: Effect of the blockage on the critical Froude number.

In *confined* (which is both shallow and restricted) *water* the blockage m (the ratio cross section of the ship to the cross section of the navigation area) has an influence on the critical speed. Based on Schijf (1949) the critical Froude number can be more generally written as (Figure 3):

$$Fr_{\mathrm{h,crit}} = \left(2sin\left(\frac{arcsin(1-m)}{3}\right)\right)^{3/2} \leq 1 \tag{2}$$

In confined water the test speed should be below 80% of this critical speed, unless it is the aim to explore such speed range.

3. SHIP MODEL

3.1 Dimensions

The following considerations should be made for selecting the scale and, therefore, the model dimensions.

Principally, for a given towing tank size and speed distribution, the scale should be chosen as large as possible, meaning the ship model size should be as large as possible, keeping in mind that scale effects in manoeuvring are not yet fully understood, and the larger the model the smaller the scale effect. However, it is generally accepted that scale effects are mainly due to a non-similar rudder inflow between model and full scale. Scale effects are also supposed to increase with increasing angle of incidence (drift angle) and decreasing water depth.

Minimum ship model dimensions may be based on considerations about rudder and propeller mounting, and on a minimum Reynolds number for appendages and propeller. Almost all captive model tests (95%) are carried out with a model length larger than 1.5 m (2015 questionnaire). This size should be regarded as a lower limit to perform captive manoeuvring tests.

In order to avoid interference between the model and the tank boundaries and to guarantee an acceptable minimum measuring time or measuring distance, the ship model dimensions should not exceed some upper limit. A tank's width should preferably be around twice the length of the ship model. If this not the case, attention is drawn to the possible blockage effects described in section 2. A tank length of at least 15 times the ship model length is recommended to have sufficient distance for acceleration, steady state and deceleration of the ship model.

3.2 Inspection

The ship model should be inspected, prior to launching and testing, for:

- principal dimensions,
- hull configuration,
- model mass,
- centre of gravity position,
- moments of inertia,
- appendage alignment.

When determining the model mass, centre of gravity and moments of inertia, possible contributions of parts of the force balance have to be taken into account.

The loading condition of the model (fore and aft draft) should be checked before experiments and verified during and after the tests, as the ship hull may absorb water during time consuming test programs.

3.3 Equipment and set-up

3.3.1 Degrees of Freedom

The ship model is usually connected to the driving mechanism such that it is free in heave and pitch, and fixed in roll. For some tests, it may be free to roll, or rolling may be forced; for 3 DOF manoeuvring simulations roll is not included, and is therefore assumed to be negligible, hence it is often decided (85% of the time according to the 2015 questionnaire), and may be better, to prevent roll motions than to let the model roll freely. When manoeuvring in waves is considered this may be the case as well, especially when corresponding tests in calm water have been carried out at fixed roll angle. If the ship model is not constrained in roll, in order to provide a meaningful comparison it is advised to do the same tests with the model free to roll in calm water conditions as well.

In particular cases, the model may be constrained in all degrees of freedom.

3.3.2 Alignment

Great care must be taken when aligning the ship model with respect to the tank reference axis; this should be checked before and after testing. For tests performed in a towing tank, the alignment can be checked using pure drift tests at small angles (between +/– 2°). The "zero drift angle" position is obtained when side forces and yaw moment are both minimal. Such tests have to be carried out with a bare hull because the asymmetry of the model (for example, appendages alignment, propeller loading…) may lead to non-zero side force/yawing moment for zero drift angle.

3.4 General Considerations

The planning of a captive model test program for determining numerical values of the coefficients considered in a mathematical manoeuvring model requires the selection of a number of parameters. Distinction can be made between three kinds of parameters; kinematic, ship control and operational and analysis parameters.

3.4.1 Kinematic parameters

A first series of parameters is related to the range of kinematical variables occurring in the mathematical model:

- value(s) of the forward speed component u
- values of the parameters characterising sway, yaw and, when applicable, roll motions, depending on the type of experiment, and the kind of motions the mechanism is able to perform, and should be selected taking account of the application field of the mathematical model (e.g. indication of course stability, prediction of standard manoeuvres, simulation of harbour manoeuvres).

Concerning the selection of kinematic parameters, a number of common requirements can be formulated:

- The ranges of the non-dimensional values for sway and yaw velocity should be sufficiently large. The lower limit should be sufficiently small for an accurate determination of the course stability derivatives. The determination of the complete mathematical model requires maximum values that are large enough to cover the range explored during simulations.
- The order of magnitude of the velocity and acceleration components should be in the range of the values of the real full scale ship.
- The induced wake patterns should be in accordance with the application field of the mathematical model. Past viscous wake and wave patterns should not interfere with the model trajectory.
- If non-steady techniques are applied (e.g. PMM testing), the quasi-steady character of the mathematical models should be taken into account. In order to comply with the quasi-steady assumption, the test results should not be affected by memory effects; this will permit their extrapolation to zero frequency.

3.4.2 Ship control parameters

The second kind of parameters are related to the means of ship control, such as rudder angle and propeller rate of revolution.

Their range should be selected taking into account the application domain. Since the model is towed by the PMM or CPMC the propeller rpm of an appended ship model can be freely chosen during the tests, normally either corresponding to the self-propulsion point of the model or of the ship. Naturally, the choice of the propeller rpm influences the inflow to a rudder placed in the propeller slipstream. Thus, selecting the propeller rpm according to the self-propulsion point of the ship instead of the model may be advantageous in some cases. At present, there is no common procedure to choose the most favourable propeller rpm.

It is clear that a broad range of rates of revolutions of the propeller should be selected if engine manoeuvres are to be simulated. For the simulation of standard manoeuvres, some rpm variation in the test runs should be considered in order to allow for variations of the rate of revolutions of the propeller that take place in a turning circle due to increased propeller loading as the speed decreases. The applied strategy for change of propeller rpm should be in accordance with the ship's engine/propeller installation i.e. either maintaining fixed torque (normal for fixed pitch propeller installations), fixed power (normal for controllable pitch) or fixed rpm (for ships with a large power reserve installed).

3.4.3 Operational and analysis parameters

The third kind of parameters, related to the experimental or analysis technique, do not influence the model's kinematics, but may affect measuring time/length, number of harmonic cycles, waiting time between runs.

3.5 Steady straight-line tests

3.5.1 Kinematic parameters

3.5.1.1 Forward speeds

If only one speed is selected it should correspond to the approach speed at which the standard manoeuvres are carried out (e.g. full ahead).

To be able to correctly simulate the manoeuvring behaviour at different speeds at least three speeds are needed to determine a quadratic relationship. More information on speed selections for other purposes can be found in the report of the 28th Manoeuvring Committee.

3.5.1.2 Drift angles

In oblique straight line tests, the drift angle should be varied from zero to the maximum drift angle, which may be determined according to the purpose of the tests, with an appropriate step. In practice at least 5 different drift angles, including 0° and angles to both port and starboard should be tested to check for possible propeller induced asymmetry effects. The maximum drift angle should not exceed the one which causes interference of the model with the tank walls.

3.5.1.3 Heel angles

For most ships it is sufficient to perform tests at a fixed heel position of 0°. For ships with a low GM, it is important to repeat the tests at different fixed heel angles using the same methodology as for the drift angles.

3.5.2 Ship control parameters

3.5.2.1 Propeller rates of revolutions

For an appended ship tests should be at least performed at one propeller rate, namely at the self-propulsion point of the model or of the ship. Tests involving more than one propeller rate are more common when the rudder is involved because of the changing self-propulsion point due to rudder drag and the changing rudder effectivity due to propulsion. In other cases, as described in Section 4.1.2, multiple propeller loadings should be applied as well. In all cases care should be taken on the correct alignment of the propeller shaft.

3.5.2.2 Rudder angles

The tests should be at least performed at the following rudder angles used during the standard manoeuvres: 0°, 10°, 20° and 35°. This range allows also to capture the typical 3rd order polynomial of the rudder angle. Ideally all rudder angles are tested in both directions, however at least 5° in the other direction should be tested as well, so that the rudder angle resulting in zero lateral force and yawing moment can be determined.

3.5.3 Operational and analysis parameters

Typically, a run starts after a certain waiting time and consists of an acceleration phase, one or more steady conditions, and a deceleration phase.

The waiting time in between tests depends on the basin layout and wave damping capabilities and will mostly be between 10 to 20 min. For shallow water basins larger waiting times are needed.

The ship model should be accelerated gradually to avoid wave generation. Waves generated by the model cause wave reflection from the tank boundaries and influence measurements of hydrodynamic forces. A rule of thumb is to have an acceleration time of 20 s which corresponds to an acceleration distance of one to three ship lengths (used by most institutes according to the 2015 questionnaire).

The constant speed phase can be subdivided into a settling phase and a steady phase. The settling phase frequently takes 1 to 2 ship lengths. The length of the steady phase may influence the accuracy of analysis results; in this respect, Vantorre (1992) considers a measuring length of 3 times the ship model length as a minimum. In shallow water the measurement time necessary to reach converged results may be longer than in deep water.

If sufficient tank length is available different conditions can be tested during the steady phase, e.g. the rudder angle can be changed to a new value, after which the process of settling and steady measurement is repeated.

3.6 Harmonic tests

The number of parameters determining a PMM or CPMC test is larger than in the case of a straight-line test (see 4.2); furthermore, the parameters cannot always be chosen independently, or the choice may be restricted by the concept of the mechanism or the tank dimensions.

3.6.1 Kinematic parameters

3.6.1.1 Forward speed

Forward speed should be selected according to the application domain, but for most applications, only one forward speed value is selected, which often corresponds with the approach speed of the standard manoeuvre. The same remarks can be made as for straight line tests.

3.6.1.2 Sway and yaw characteristics

In principle, the application domain should also be taken into account for selecting sway and yaw characteristics. On the other hand, possible selections are limited by mechanism and tank characteristics. For harmonic sway tests (these have a harmonic variation of the sway velocity while maintaining a constant surge velocity and zero yaw rate), amplitudes of lateral velocity and acceleration can be written non-dimensionally as follows:

$$\begin{aligned} v'_A &= y'_{0A}\omega'_1 \\ \dot{v}'_A &= y'_{0A}\omega'^2_1 \end{aligned} \quad (3)$$

while for harmonic yaw tests (these have a harmonic variation of the yaw rate while maintaining a constant surge and sway velocity):

$$\begin{aligned} r'_A &= \psi_A\omega'_1 \approx y'_{0A}\omega'^2_1 \\ \dot{r}'_A &= \psi_A\omega'^2_1 \approx y'_{0A}\omega'^3_1 \end{aligned} \quad (4)$$

The latter approximations can be made for small and moderate amplitudes when no CPMC is available.

Eq. (4) implies that the range of non-dimensional sway and yaw kinematical parameters depend on:

- the non-dimensional lateral amplitude $y'_{0A} = y_{0A}/L$, and
- the non-dimensional circular frequency $\omega'_1 = \omega L/u$.

It is common to vary either the frequency or both the frequency and amplitude. According to the 2015 questionnaire, a single frequency is a dominant choice, but 3 and 5 frequencies are also common choices.

Both the amplitude variation and frequency variation are subject to restrictions. The lateral amplitude may be restricted due to limitations of the mechanism or, if not, should be selected to prevent interference of the model with the tank walls. With respect to the latter, half the tank width may be considered as an upper limit for the trajectory width (van Leeuwen, 1964).

Limitations for the dynamic test frequencies are discussed in the next section.

3.6.1.3 Oscillation frequency

Restrictions of the oscillation (circular) frequency ω are usually expressed in a non-dimensional way, using one of the following formulations:

$$\begin{aligned} \omega'_1 &= \frac{\omega L}{u} \\ \omega'_2 &= \omega\sqrt{\frac{L}{g}} = \omega'_1 Fr \\ \omega'_3 &= \frac{\omega u}{g} = \omega'_1 Fr^2 \end{aligned} \quad (5)$$

Restrictions of ω'_1 can be interpreted as follows:

- Restrictions due to tank length: the number of oscillation cycles c is limited by:
  $$c \le \frac{1}{2\pi}\frac{l}{L}\omega'_1 \quad (6)$$
  l being the available tank length.
- Avoiding non-steady lift and memory effects yields a maximum ω'_1 (Nomoto, 1975; Wagner Smitt & Chislett, 1974; Milanov, 1984; van Leeuwen, 1969), typically 1-2 for sway and 2-3 for yaw tests. Comparable values result from considerations on lateral wake patterns (Vantorre & Eloot, 1997). These restrictions become more important in shallow water (Eloot, 2006).

- Considerations on the influence of errors of the imposed trajectory on the accuracy of the hydrodynamic derivatives lead to compromise values for ω_1' which are in the range mentioned above for yaw tests (2-4), but which are very low (0.25-2) for sway tests. It is therefore recommended to derive sway velocity derivatives from oblique towing tests, so that the accuracy of the inertia terms can be improved by increasing the test frequency (Vantorre, 1992; see also 4.2). However, CPMC devices where trajectories and motions can be imposed with extreme accuracy do not suffer from this restriction.

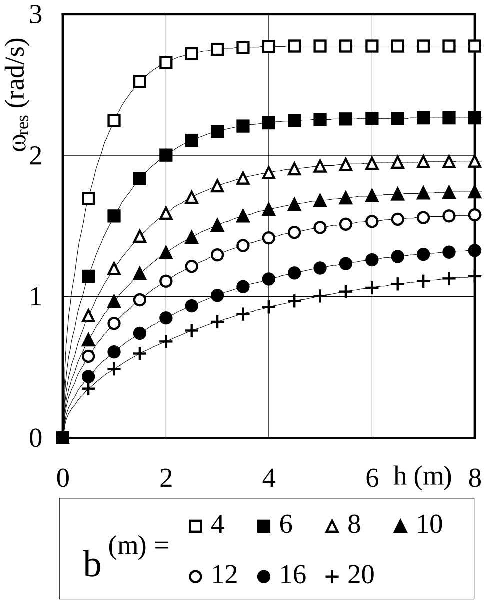

Figure 4: Lowest tank resonance frequency as a function of water depth *h* for several tank width values *b*.

Restrictions for ω_2' can be interpreted as measures for avoiding tank resonance. If the frequency equals one of the natural frequencies of the water in the tank, a standing wave system may interfere with the tests. This occurs if the wave length λ of the wave system induced by the oscillation equals $2b/n$ (n = 1, 2, ...), b being the tank width. Figure 14 displays the frequency fulfilling $\lambda = 2b$ as a function of water depth and tank width; in case of infinite depth, tank resonance occurs at $\omega_2' = \sqrt{\pi \frac{L}{b}}$, while in shallow water it occurs at a lower frequency $\omega_2' = \frac{\pi}{b}\sqrt{Lh}$.

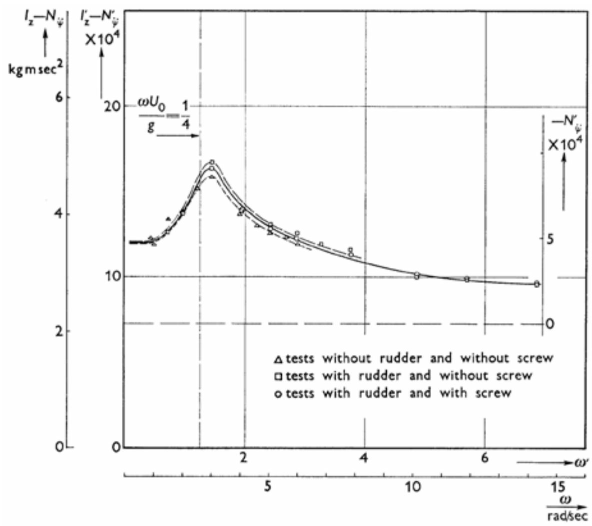

Figure 5: Influence of ω_3' on added moment of inertia from PMM yaw tests (van Leeuwen, 1964)

Restrictions for ω_3' are imposed for avoiding unrealistic combinations of pulsation and translation. The nature of a wave system induced by a pulsating source with a frequency ω, moving at constant speed u in a free surface strongly depends on ω_3', 0.25 being a critical value (Brard, 1948; Wehausen & Laitone, 1960; van Leeuwen, 1964). Therefore, ω_3' should be considerably less than 0.25 during PMM tests (van Leeuwen, 1964; Goodman et al, 1976; Wagner Smitt & Chislett, 1974), as illustrated in Figure 5.

Furthermore, the circular oscillation frequency must not be selected near a natural frequency of the carriage or measuring equipment.

The limit for ω_1' is the most difficult to satisfy, especially if large sway and yaw speeds need to be considered. In this case a compromise is needed between memory effects (large frequency) and tank wall effects (large amplitude). Eq. (5) reveals that limitations of ω_1' will be overruled by those of ω_2' and ω_3' for larger Froude numbers.

3.6.1.4 Drift and heel angles

It may be sufficient to execute the harmonic tests at a drift and heel angle equal to zero. However there is a correlation between yaw and drift which becomes more important with larger drift angles and in shallow water. If these conditions are expected in the simulation domain, the harmonic tests should be repeated at different drift angles. It is sufficient to perform the tests at 0° heel angle, but additional heel angles should be included for ships which exhibit low GM values.

For the latter the dynamic roll response can be determined by roll decay tests or captive harmonic roll tests. Compared to the sway or yaw motion, the frequencies have to be chosen considerably larger.

3.6.2 Ship control parameters

Regarding the propeller rate the same consideration regarding as for the straight line tests can be made. It is recommended to perform the tests at a limited number of rudder angles different from zero to determine the yaw effect on the rudder forces.

3.6.3 Operational and analysis parameters

3.6.3.1 Waiting time

Again the waiting time depends on the basin layout and wave damping equipment, but in general this time will be somewhat larger compared to straight line tests due to the more complex manoeuvring.

3.6.3.2 Number of oscillation cycles

The number of oscillations should be determined to be large enough to obtain periodic results, noting that the transient starting and stopping regions should not be used in the analysis.

It is recommended to perform the acceleration in half a cycle and to allow half a cycle for settling. The steady test distance is maximized for most tanks, meaning that the remainder tank length is used to execute the tests, indeed the reliability of the test results increases with the number of cycles c, although this effect is rather restricted if $c > 3$ (Vantorre, 1992).

3.7 Steady circular tests

3.7.1 Kinematics parameters

3.7.1.1 Forward speeds

Circular motion tests are mostly carried out at one to two forward speeds ahead. If one speed is concerned it is mostly the design speed of the vessel.

3.7.1.2 Yaw rate

Depending on the facilities' capability The most common yawing range is r' from 0 to 0.5. This range should be extended for ships which seems to be easily manoeuvrable to 0.8, which corresponds to a turning diameter of 2.5 L_{pp}. Within the given range 5 different yaw rates should be tested.

3.7.1.3 Drift and heel angles

The same considerations can be made as for harmonic tests.

3.7.2 Ship control parameters

3.7.2.1 Propeller rates of revolutions.

Tests are usually carried out at only 1 propeller rate, corresponding to self-propulsion or zero.

3.7.2.2 Rudder angles

It is recommended to perform the tests at a limited number of rudder angles different from zero to determine the yaw effect on the rudder forces.

3.7.3 Operational and analysis parameters

In the majority of the cases the institutions wait 600s – 900s (10 to 15 min), including both limits, in between two tests. The waiting time is smaller compared to the other test types.

Typically, a run consists of an acceleration phase, a steady condition, and a deceleration phase. For circular motion tests there is no limitation for the deceleration, but the steady phase should be limited in order to prevent the model from running in its own wake after a complete turn.

3.8 Multi-modal tests

The aim of these kinds of tests is to subject the ship model to a large combination of velocities, rudder deflections and propeller rates in one test run. The following parameters can be varied harmonically:

- The propeller rate n;
- The rudder deflection δ;
- The longitudinal velocity u;
- The transverse velocity v;
- The rate of turn r;
- A combination of kinematical and/or control parameters.

A more thorough description is available in (Eloot, 2006).

In this way different rudder angles can be set during straight line tests, which leads to significant time savings. On the other hand, multi-modal tests can be interpreted as an extension of harmonic sway and yaw tests and as such similar problems can occur regarding non-steady phenomena.

3.9 Hexapod tests

The institutes who use a hexapod indicate that they use the same tests with the hexapod as straight line and harmonic tests. Of course, with a hexapod, also vertical harmonic tests can be carried out, but the correlation between both is not explicitly mentioned. The possibilities of the hexapod enable new test types to be explored, which are however still in the research phase and not in production.

Table 1: Range of amplitudes of hexapod units (28th Manoeuvring Committee, 2017).

Mode	Range
Surge	0.25 – 0.45 m
Sway	0.25 – 0.47 m
Heave	0.20 – 0.40 m
Roll	25 – 30°
Pitch	25 – 30°
Yaw	25 – 45°

The hexapod is attached to a common carriage and offers the additional flexibility to be used in different tanks. The combination of hexapod and carriage allows the augmentation of the number of combined degrees of freedom, which solves the problem of the maximal values for surge and yaw excursions (Table 1), however at present the maximal mentioned number of combined degrees of freedom is 7, which means that only the longitudinal movement is performed by the main carriage. The used kinematical, control and operational parameters are in the same range as for the harmonic tests.

3.10 Data Acquisition

3.10.1 Measured data

Performing captive manoeuvring tests requires direct or indirect measurement of the following data:

- longitudinal hull force,
- lateral hull force,
- hull yaw moment,

together with, at least for particular purposes, the roll moment.

The measurement of the following parameters characterising the control of ship model steering and propulsion equipment is convenient:

- rudder angle(s),
- propeller rate(s),
- action of other steering/manoeuvring devices.

Measurement of position/speed of the driving mechanism results in the following useful information:

- trajectory,
- speed.

The following data may be important, depending on the mathematical manoeuvring model:

- thrust/torque on propeller(s),
- forces and moments on rudder(s),

while the motion of the ship model according to the (non-)constrained degrees of freedom (sinkage, trim, in particular cases roll angle) may be useful for other purposes and is highly advisable in shallow water conditions

The capacity of load cells and other measuring equipment should be chosen to be appropriate to the loads expected. Ideally, the calibration of sensors and driving units should be carried out immediately before and immediately after testing. In practice the calibration frequency is lower, but should be checked at least with each change in loading condition of the ship model.

3.10.2 Data sampling

Data sampling rate and filtering details should be determined on the basis of the oscillation frequency, together with considerations of the primary noise frequencies. Sampling rates may vary between 10 and 1000 Hz. Recommended values are 50 Hz or 100 Hz, which are used in 2/3 institutes. Almost all institutes perform a filtering method, usually a low pass filter which cuts off higher frequencies. Commonly the filter reduces the sampling frequency to 10%-20% of the original rate. Data sampling and filtering may induce additional uncertainties, see ITTC procedure 7.5-02-06-04.

4. POST PROCESSING

The measured real time data should be recorded. It is recommended that real-time analysis be made immediately after each test in order to check for obvious errors in the data.

4.1 Visual inspection

After each run the data should be inspected in the time domain to check for obvious errors such as transients caused by recording too soon after starting, additional unknown sources of noise, overloading or failure of one or more sensors. Transients due to starting, stopping or changing conditions should not be included in the data to be analysed, but may provide useful information for validation of numerical techniques.

4.2 Analysis methods

For steady tests, a mean value of the measured data should be calculated over the time interval in which results are steady, see 7.5-02-01-06. Analysis of harmonic tests requires techniques such as the popular Fourier analysis up to the third harmonic, regression analysis (a least square method applied on the time series), system identification.

4.3 Documentation

The following should, but not restrictively, be documented and included in the test report.

4.3.1 Experimental technique

4.3.1.1 Ship model

General characteristics

The following characteristics must be specified:

- main particulars of the ship:
  - length between perpendiculars,
  - beam;
- scale of the model;
- engine type for the full-scale ship.

The hull

The following hull data should be included in the documentation:

- the loading condition, to be specified as draft at AP and draft at FP or, alternatively, as mean draft amidships and trim or trim angle;
- moment of inertia in yaw;
- moment of inertia in roll (if roll motion is not restrained);
- moment of inertia in pitch (if pitch motion is not restrained);
- a set of hydrostatic data for the tested loading condition, including, as a minimum:
  - displacement;
  - longitudinal centre of buoyancy (L_{CB}) /gravity L_{CG}) when different (heave constrained model);
  - in case roll motion is free: $\overline{KB}$, $\overline{KG}$ and $\overline{BM}$ values;
- also preferably a full set of hydrostatic data should be included;
- a body plan and stern and stem contour of the model;
- description and drawing of appendages on the hull (bilge keels, additional fins, etc.);
- any turbulence stimulation;
- photographs of the model, stern and stem equipped with all appendages.

The rudder

It should be specified whether the rudder is custom made as on the real ship or a stock rudder. In the case of a stock rudder, both the stock rudder and the full scale rudder should be documented as specified:

- rudder type (spade, horn, flap, etc.);
- rudder drawing including contour, profiles and possible end-plates;
- specification of movable area A_{Rmov} and fixed area A_{RX}
- rudder rate of turning.

The propeller

It should be specified whether the propeller is custom made as on the real ship or a stock propeller is used. In the case of a stock propeller both propellers should be documented equally well as specified:

- propeller diameter D;
- propeller type, FP or CP;
- number of propeller blades Z;
- propeller pitch ratio (P/D);
- propeller area ratio A_E/A_0;
- propeller hub position;
- open water curves showing K_T and K_Q

4.3.1.2 Tank

The following tank characteristics should be specified:

- dimensions;
- water depth and corresponding depth to draft ratio;
- water temperature.

In addition, for shallow water tests:

- bottom flatness.

4.3.1.3 Restricted water model

The following characteristics should be specified:

- configuration,
- dimensions,
- smoothness and stiffness of the restricted water model (walls and/or bottom).

4.3.1.4 Model set-up

It should be stated whether the tests are performed as:

- bare hull plus appended hull tests, or
- appended hull tests alone.

The number of degrees of freedom (model restraints for heave, pitch and roll modes) should be stated. If applicable, details of forced roll should be included.

It should be stated whether engine simulation is used. If yes, the principle for the method should be described (fixed torque or fixed power).

It should be stated how scale effects are accounted for. For appended hull tests, if the ship self-propulsion point is chosen, then it should be described how the friction correction force is applied including the values used for different speeds.

4.3.1.5 Measurements, recording, calibration

The documentation should contain the main characteristics of:

- measuring equipment including load cells;
- filters.

A complete list of channels measured during the tests should be provided, including:

- sample time;
- digitising rate.

Details of all calibrations conducted should be provided, including information on linearity and repeatability of all sensors.

4.3.1.6 Test parameters

A complete list of the runs performed for each type of test should be given. The list should at least include:

- test type;
- model speed;
- time of steady test;
- number of cycles in oscillatory tests;
- oscillation frequency, with proof of avoidance of resonance with natural frequencies of the mechanism, the measuring equipment and the water in the tank;
- drift angle;
- rudder angle;
- yaw rate;
- sway amplitude;
- propeller rpm;
- the harmonic components of (some of) the above parameters (only for multi-modal tests);
- other parameters.

4.3.2 Analysis procedure

The analysis covers the process of transferring the measured raw data into the mathematical manoeuvring model. This is a difficult process and the procedure is different for every towing tank.

The following items should be included in the documentation:

- method of force analysis;
- force coefficients, together with the mathematical model used for analysis of measured data;
- number of cycles used for analysis of oscillatory tests;
- oscillation frequency indicating the equivalence of the coefficients to those at zero frequency;
- filtering technique;
- basic principles for fairing the data if done;
- plots of measured points together with the faired curves for all tested parameters in the whole range, which should include the expected range for the manoeuvres to be predicted.

5. VALIDATION

5.1 Validation of the procedure

Because the carrying out of captive model tests, followed by the subsequent analysis by data fitting, mathematical modelling and simulation is a sensitive and intensive job, it is recommended that institutes making predictions using captive tests validate their procedures through comparison of the intermediate and final results with benchmark data.

Information on the creation of benchmark data and the availability of such data is covered in the guideline 7.5-02-06-06 Benchmark Data for Validation of Manoeuvring Predictions.

5.2 Uncertainty Analysis

In order to get an understanding of the uncertainties which are present in the captive model tests procedures of every institute, assistance is available through the procedure on Uncertainty Analysis (UA) for captive model test (ITTC procedure 7.5-02-06-04).

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