ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Captive Model Test

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Note of concern:

In the opinion of the ITTC Advisory Council, this procedure contains too many options rather than a definitive approach. This issue will be addressed by future committees.

Updated / Edited by	Approved
Manoeuvring Committee of the 28th ITTC	28th ITTC 2017
Date 01/2017	Date 09/2017

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Captive Model Test Procedure

1. PURPOSE OF PROCEDURE

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. Another 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.

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. The survey was completed by 45% of these organisations. Selected data from the questionnaire is presented to offer an insight into the present common practice of institutes all over the world. The data may not represent all cases, as such it is presented as a guide and should not be considered prescriptive. 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, the uncertainty due to the analysis, the data-fitting uncertainty and the uncertainty in the resulting outcome through the simulation of manoeuvres.

2. DESCRIPTION OF PROCEDURE

2.1 Ship model

2.1.1 Selection of ship model dimensions.

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

2.1.1.1 Scale

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).

2.1.1.2 Model length

According to the data from the 2015 questionnaire (see Figure 1) irrespective of the water depth, a ship model length of 3 m is frequently selected. Nevertheless, smaller ship models are used for shallow water tests (mean ship model length 3.6 m) compared to deep water tests (mean ship model length 4.4 m). Almost all captive model tests (95%) are carried out with a model length larger than 1.5 m. Not only the water depth, but also the test type has an influence on the ship model size. The average ship model lengths are 4.1 m (straight line tests), 4.9 m (harmonic tests) and 3.9 m (circular motion tests). Larger ship models are typically used to perform harmonic tests, but the proportion of larger ship models (> 10 m) did not change significantly over the last 20 years.

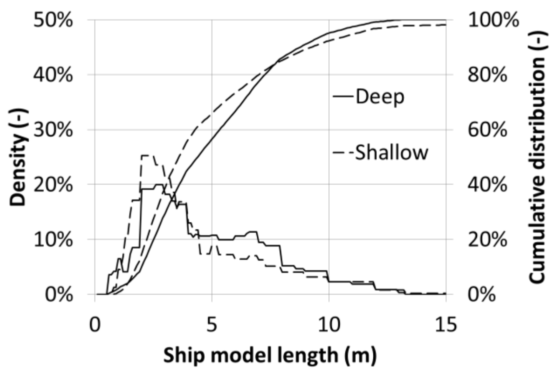

Figure 1: Influence of water depth on ship model length distribution.

Minimum ship model dimensions may be based on considerations about rudder and propeller mounting, and on a minimum Reynolds number for appendages and propeller.

2.1.1.3 Ratios of model to tank dimensions

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.

- Most steady straight line and harmonic tests are carried out in a towing tank with a length of 37 times the ship model length and more. A mean value for the model length to tank width ratio (L/b) is 0.46.
- For circular motion tests, the selection of the model length determines maximum and minimum values for the non-dimensional yaw rate $r'=L/R$, where R is the radius of the turning circle. Most circular tests are carried out in a tank with the largest dimension about 20 times the model length. As most circular tests are executed in circular or wide tanks, the mean value of L/b is smaller (0.39) compared with the other test types.

Even if the model dimensions are selected properly considering tank dimensions, the 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.

2.1.1.4 Deep, shallow, restricted or confined water

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

$Fr_{h,crit} = 1$. 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.

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

$$y_{infl} = 5B\left(Fr_h + 1\right) \qquad (1)$$

If the distance between ship and tank walls is larger than y_{infl}, ship-bank interaction effects can be neglected.

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).

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:

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

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

2.1.2 Ship model inspection

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

- principal dimensions,
- hull configuration,
- model mass,
- centre of gravity position (longitudinal; also vertical, if measurements concerning roll are required, or roll is not fixed and lateral for specific ship configurations),
- moments of inertia (about vertical z-axis if yaw tests are performed; also about longitudinal x-axis if roll is important),
- 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.

2.1.3 Ship model equipment and set-up

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 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.

Great care must be taken when aligning the 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. It must however be remembered that the asymmetry of the model (for example, appendages alignment, propeller loading…) may lead to non-zero side force/yawing moment for zero drift angle.

The loading condition of the model (fore and aft draft) should be checked before experiments and verified during and after the tests.

2.2 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.

2.2.1 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.

2.2.2 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).

2.2.3 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.

2.3 Execution of the Tests

2.3.1 Steady straight-line tests

2.3.1.1 Kinematics parameters

Forward speeds

The number of selected forward speeds depends on the purpose of the test program and the type of test. Figure 2 reflects the practice, based on the response to the 2015 questionnaire.

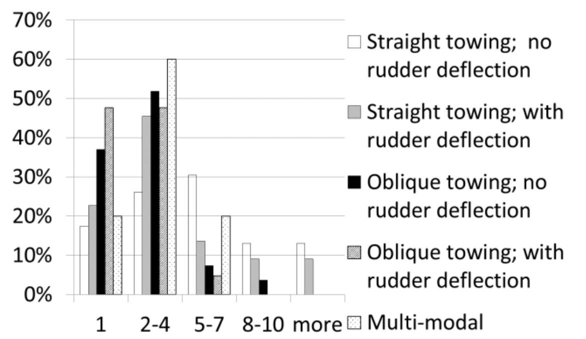

Figure 2: number of forward speeds at which straight-line tests are performed.

If only one speed is selected it mostly corresponds to full ahead. If multiple speeds are selected, common values are expressed as a percentage of this full ahead speed. Only a limited number of institutes perform tests at astern speeds.

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 90% of the cases oblique tests are carried out for at least 5 different drift angles, see Figure 3.

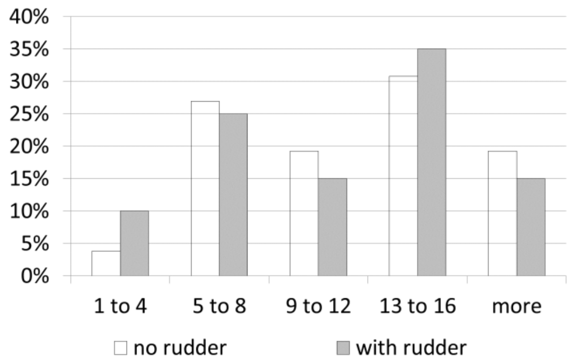

Figure 3: number of drift angles at which oblique tests are performed.

The maximum drift angle should not exceed the one which causes interference of the model with the tank walls. The most common selection of drift angles, for 70% of the institutes, is within the range -30° to 30°. There is a slight preference to perform tests at positive drift angles, however, drift angles to both port and starboard should be tested to check for possible propeller induced asymmetry effects.

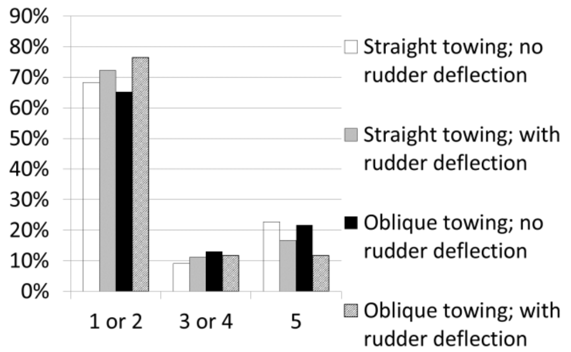

Figure 4: number of heel angles at which straight-line tests are performed.

The most common range of drift angles is somewhat larger when no rudder action is present. In 20% of the cases a drift angle of ±90° or larger (i.e. astern speeds) is considered.

Heel angles

The number of heel angles at which straight line tests are performed is presented in Figure 5. The majority of the straight line tests are carried out at one heel angle, namely fixed at zero in 85% of these cases or free heel. Multiple heel angles are mostly tested at a fixed position in the range of -15° to 15°. In this range more tests are carried out at positive heel angles.

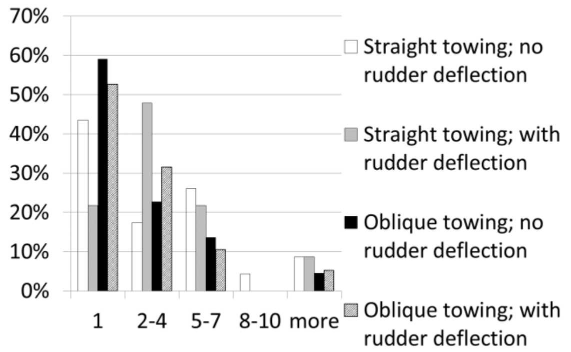

Figure 5: number of propeller rates at which straight-line tests are performed.

2.3.1.2 Ship control parameters

Propeller rates of revolutions

The number of tested propeller rates is shown in Figure 5. In most cases tests are only executed 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. For instance, straight towing tests with rudder deflection are carried out at more than one propeller rate in almost 80% of the cases. In other cases, as described in Section 2.2.2, multiple propeller loadings should be applied as well.

Rudder angles

Straight-line tests with rudder angle are frequently performed with 15 or less rudder angles, see Figure 6. This number corresponds to a variation in steps of 5° between -35° and +35°

("hard over"), although a lower deflection could be sufficient for some purposes.

As for the drift angle, some institutes tend to only consider larger positive rudder angles, however at least 5° in the other direction should be tested, so that the rudder angle resulting in zero lateral force and yawing moment can be determined.

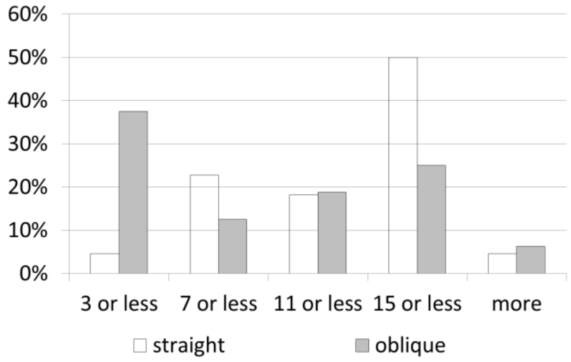

Figure 6: number of rudder angles at which straight-line tests are performed.

2.3.1.3 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 most frequently mentioned waiting time, Figure 7, is 1200 s or 20 min (26% of the questionnaire responses), but 74% of the institutes wait between 600 s (10 min) and 1200 s (20 min) to start a new test.

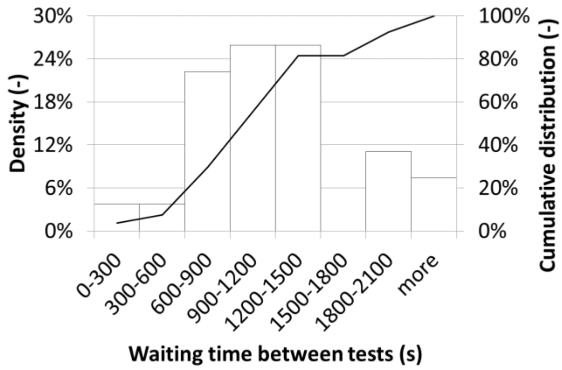

Figure 7: waiting time between two straight-line tests.

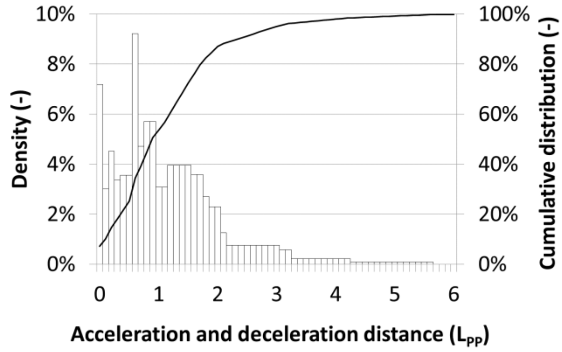

Figure 8: acceleration and deceleration distance in straight-line tests.

Figure 8 shows that acceleration is performed within 1 ship length in 55% of the cases and within 2 ship lengths in 87% of the cases. Small acceleration lengths have a significant frequency, but can be ascribed to tests carried out with large ship models at low speeds.

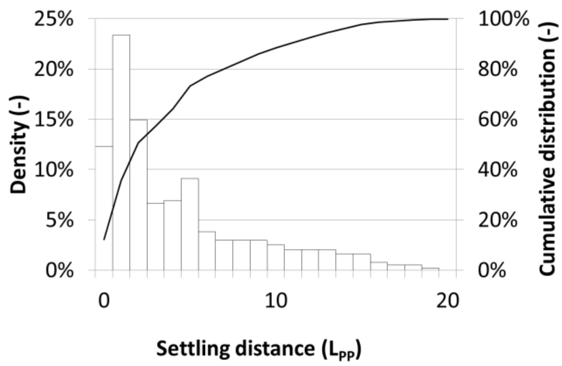

Figure 9: settling distance in straight-line tests.

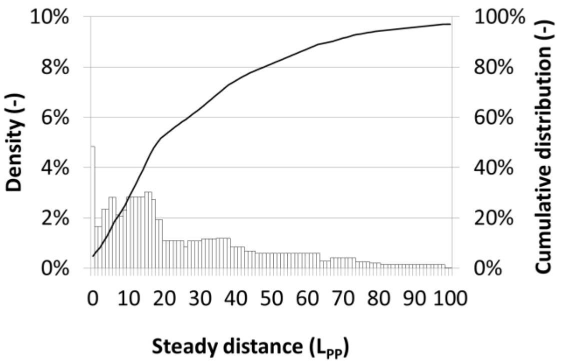

Figure 10: steady distance in straight-line tests.

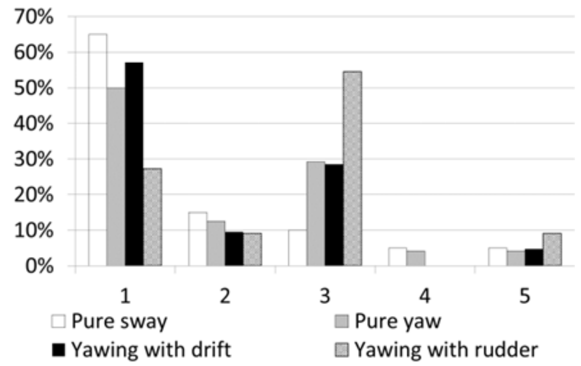

Figure 11: number of forward speeds at which harmonic tests are performed.

The constant speed phase can be subdivided into a settling phase (Figure 9) and a steady phase (Figure 10). The settling phase frequently takes 1 to 2 ship lengths. Mostly, no distinction is made between the different types of straight-line tests, although 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, which is fulfilled in 90% of cases.

2.3.2 Harmonic tests

The number of parameters determining a PMM or CPMC test is larger than in the case of a straight-line test (see 2.3.1); furthermore, the parameters cannot always be chosen independently, or the choice may be restricted by the concept of the mechanism or the tank dimensions.

2.3.2.1 Kinematic parameters

Forward speed

Forward speed should be selected according to the application domain. For a large range of applications, only one forward speed value is selected (see Figure 11), which often corresponds with the design speed of the vessel.

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, amplitudes of lateral velocity and acceleration can be written non-dimensionally as follows:

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

while for yaw tests

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

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 $\omega_1^{'} = \omega L / u$.

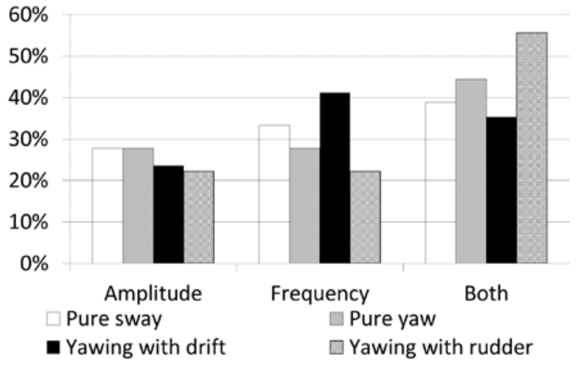

Figure 12: strategy to achieve the variation of the maximal sway or yaw speed in harmonic tests.

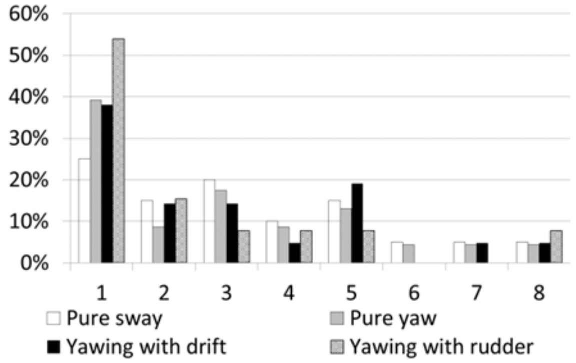

Figure 13: number of frequencies at which harmonic tests are performed.

It is common to vary either the frequency or both the frequency and amplitude (see Figure 12). A single frequency is a dominant choice (Figure 13), 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.

Oscillation frequency

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

$$\omega_1^{'} = \frac{\omega L}{u}$$
$$\omega_2^{'} = \omega \sqrt{\frac{L}{g}} = \omega_1^{'} Fr \tag{5}$$
$$\omega_3^{'} = \frac{\omega u}{g} = \omega_1^{'} Fr^2$$

Restrictions of $\omega_1^{'}$ can be interpreted as follows:

Restrictions due to tank length: the number of oscillation cycles c is limited by:

$$c \leq \frac{1}{2\pi} \frac{l}{L} \omega_1^{'} \tag{6}$$

l being the available tank length.

- Avoiding non-steady lift and memory effects yields a maximum $\omega_1^{'}$ (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 $\omega_1^{'}$ 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.

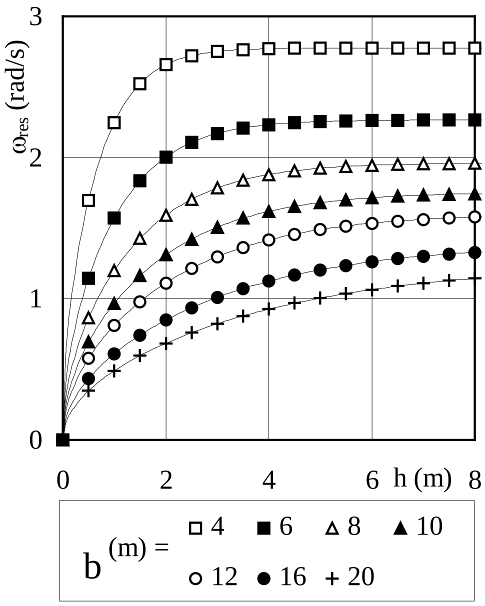

Figure 14: Lowest tank resonance frequency as a function of water depth *h* for several tank width values *b*.

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 $\omega_2' = \frac{\pi}{b}\sqrt{Lh}$.

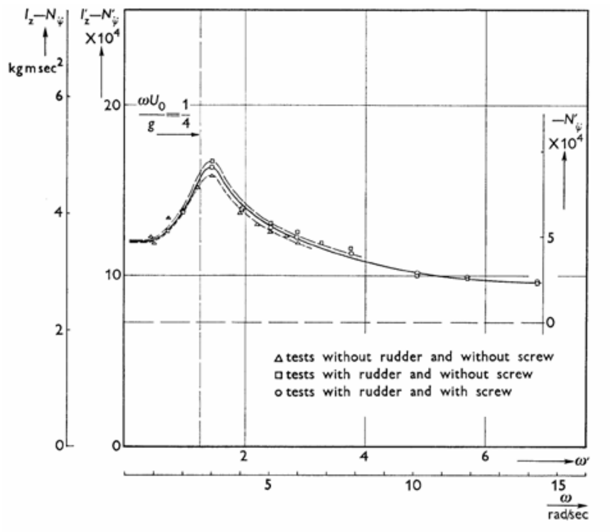

Figure 15: Influence of ω_3' on added moment of inertia from PMM yaw tests (van Leeuwen, 1964)

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 15.

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

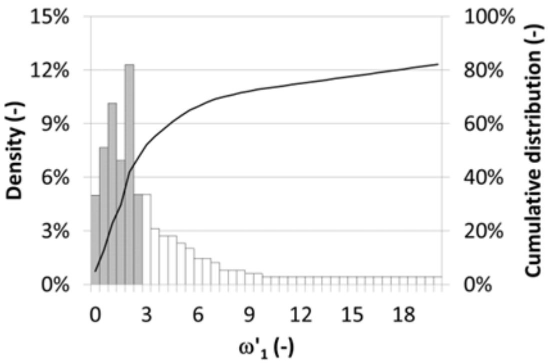

Figure 16: Distribution of the ω_1' frequency in harmonic tests.

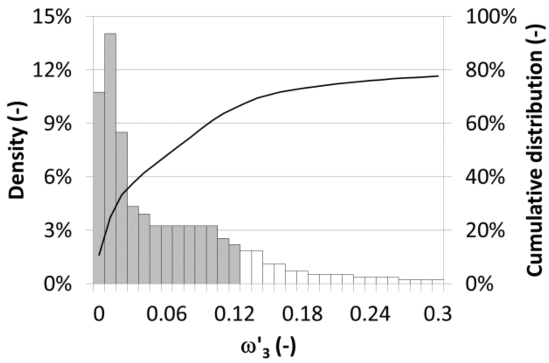

Figure 18: Distribution of the ω_3' frequency in harmonic tests.

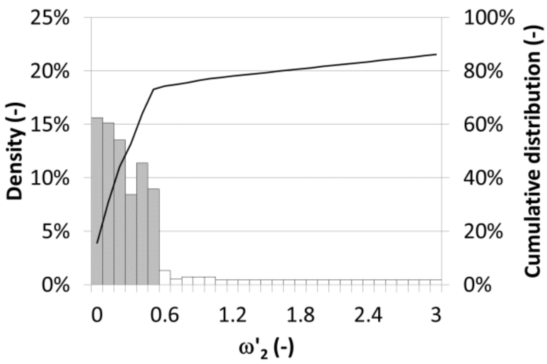

Figure 17: Distribution of the ω_2' frequency in harmonic tests.

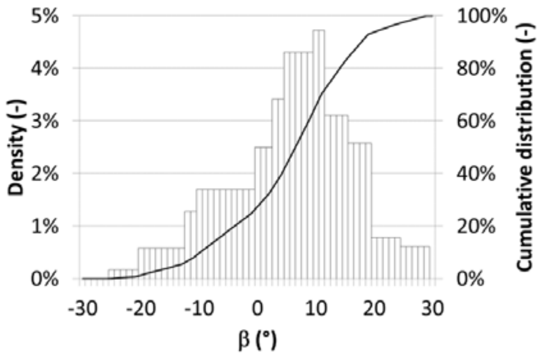

Figure 19: Distribution of the drift angles in harmonic yawing tests.

Figure 16 to Figure 18 summarise the data from the 2015 questionnaire concerning the selection of test frequencies expressed in a non-dimensional way. In the majority of frequencies the safe limits (marked in grey in the figures) are met, but the limit for ω_1' seems to be 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.

Drift angle

The range of the drift angles β to be applied in yaw with drift tests has to be selected according to the application domain. The mean range appears to be [0°, +20°] (Figure 19).

Heel angle

Most sway and yaw tests are carried out with the heel angle fixed at zero degrees, while free rolling is rather exceptional. If a variation is considered the used range is between -8° and +20°.

2.3.2.2 Ship control parameters

Propeller rates of revolution

Tests are usually carried out at a single propeller rate, which is either zero or the self-propulsion point of the model or of the ship.

Rudder deflection

When rudder deflection is considered the range of angles δ to be applied has to be selected according to the application domain. Yawing tests with rudder are performed with at least three different rudder angles, but six different rudder angles is the most frequent choice and also the maximal number reported. The rudder angles are varied between -35° to +35°, but in some cases only a smaller, positive range is tested, see Figure 20.

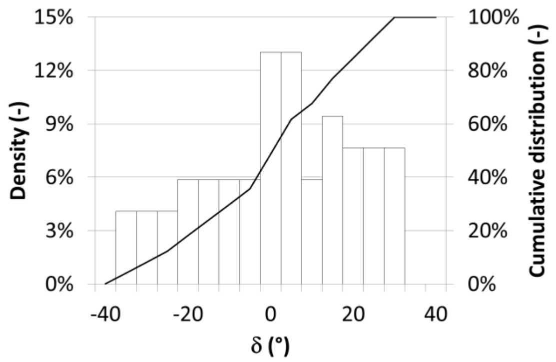

Figure 20: Distribution of the rudder angles in harmonic yawing.

2.3.2.3 Operational and analysis parameters

Waiting time

The distribution of the waiting times in between two tests is shown Figure 21. 900 s and 1200 s are the most frequent options. In 55% of the cases the waiting time is between 900 s and 1200 s (15 min and 20 min), including both limits. Smaller waiting times are uniformly distributed, while larger waiting times show larger differences and can go up to 60 minutes.

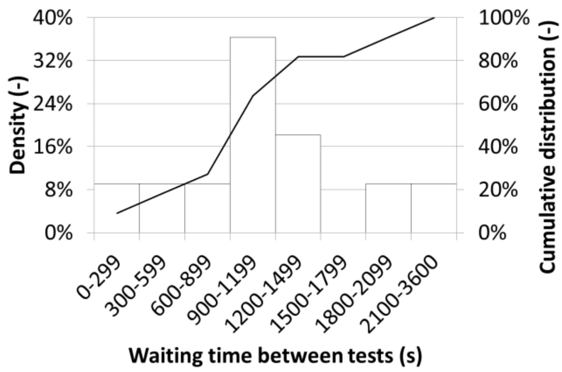

Figure 21: Distribution of the waiting times between two harmonic yawing tests.

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. The reliability of the test results increases with the number of cycles c, although this effect is rather restricted if $c > 3$ (Vantorre, 1992).

Frequent options are to accelerate and settle in a quarter, half or full cycle. On average more settling is selected for yaw tests compared to sway tests. The steady test distance is maximized for most tanks, meaning that the remainder tank length is used to execute the tests. The minimal explicit value mentioned is 1 cycle.

Analysis

Post-processing actions mentioned in the responses to the 2015 questionnaire are Fourier analysis, regression analysis (a least square method applied on the time series) or both. The analysis did not depend on the test type. The use of a Fourier analysis is a popular method (79%), which is mostly combined with a regression analysis. In most cases, 3 harmonics are considered. A higher number of harmonics was not mentioned by any institution.

2.3.3 Steady circular tests

2.3.3.1 Kinematics parameters

Forward speeds

Circular motion tests are mostly carried out at one to two forward speeds. The mentioned speeds are always positive (movement ahead). If one speed is concerned it is mostly the design speed of the vessel.

Yaw rate

The most common yawing range is r' from 0 to 0.5 (Figure 22). As the forward speed is positive, the larger frequency for positive yawing speeds means that tests are not always carried out in two rotation directions.

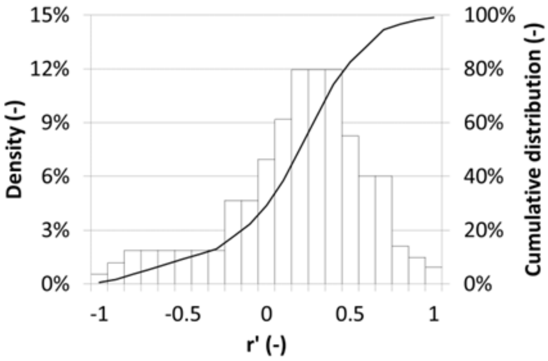

Figure 22: Distribution of the yaw rates in circular motion tests.

Heel angles

Compared to the other test types, the variation of heel angles is more common. In 60% of the cases 2 to 5 different heel angles are tested. The used ranges are similar to the other test types.

Drift angles

For tests with a drift angle a significant number of drift angles is tested, which is never below 3. The range varies between -30° and +30° and the most common values are between 0 and +15°.

Experience shows a close relationship between drift angle and non-dimensional yaw rate for a free running manoeuvring ship. Figure 23 proposes a typical sketch of the envelope of yaw rate and drift for a ship during large zigzag tests.

It is therefore not necessary to choose a range of drift angles symmetric to zero. For a given value r' of the non-dimensional rate of turn, a midrange value of $\beta = 26r'$ for the drift angle in degrees can be considered as a rough figure.

The maximum drift angle should not exceed the one which causes interference of the model with the tank walls (blockage effects).

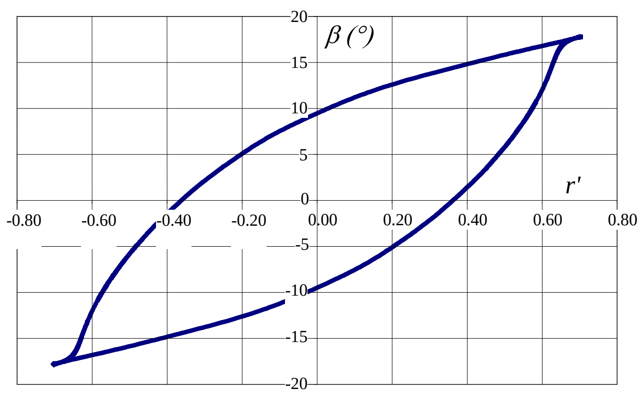

Figure 23: Yaw rate, drift angle envelope for a surface ship.

2.3.3.2 Ship control parameters

Propeller rates of revolutions.

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

Rudder angles

During yaw, drift and rudder deflection tests, rudder angle range should be defined to cover the actual range of rudder angle for a given rate of turn of the rudder. Rudder angles should be varied with an appropriate step. Most institutes test the range -35° to +35° in steps of 5° (15 rudder angles).

2.3.3.3 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.

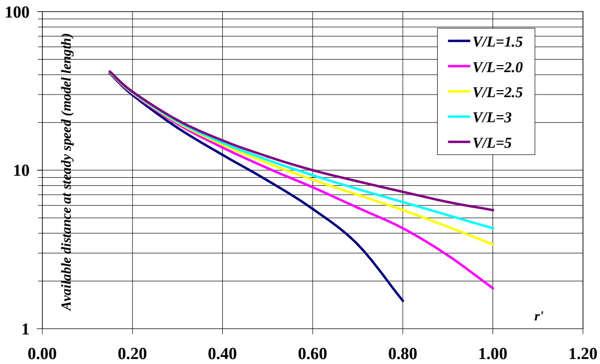

Figure 24: Influence of speed and r' on duration of steady conditions (ship length) for a complete turn.

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. Figure 24 illustrates the influence of speed and radius of turn for a given ship on the "available" steady conditions in a single turn. On average a test comprises one full circle. A half circle is dedicated to acceleration (1/6), deceleration (1/6) and settling (1/6), while the other half is used for a steady measurement.

2.3.4 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.

2.3.5 Hexapod

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.

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.

Table 1: Range of amplitudes of hexapod units.

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°

2.3.6 Special considerations for shallow and restricted water

The following factors should be considered when conducting tests in shallow and/or restricted water:

- The time between runs should be sufficient to ensure that the water condition is consistent for each test;
- Blockage considerations should be taken into account;
- The model speed should be selected considering the shallow and/or restricted water environment;
- The model should be accelerated such that unrealistic scenarios are avoided, such as grounding on take-off and/or unwanted waves caused by excessive acceleration rates;
- The measurement time necessary to reach converged results may be longer than in deep water.

2.4 Data Acquisition and Analysis

2.4.1 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. Figure 25 shows that most institutes consider the vertical degrees of freedom.

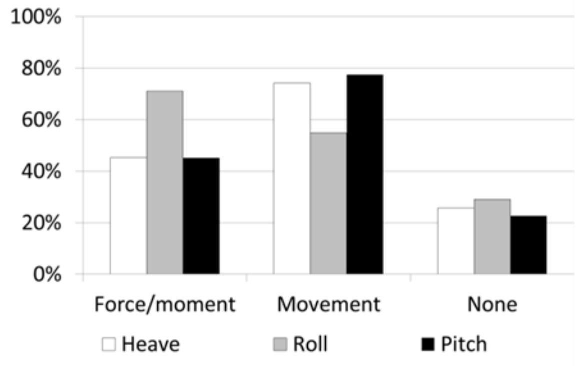

Figure 25: Details on possible measurements in vertical degrees of freedom.

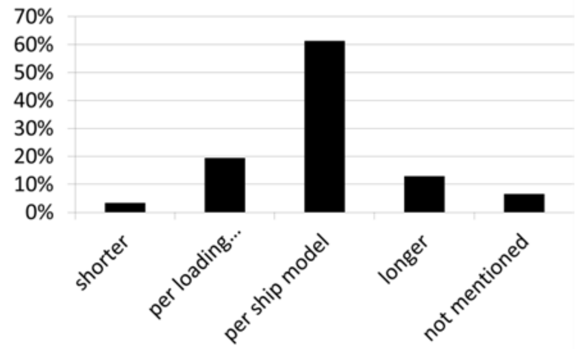

Figure 26: Calibration frequency of the ship model parameters.

The capacity of load cells and other measuring equipment should be chosen to be appropriate to the loads expected. Calibration of sensors and driving units should be carried out immediately before and immediately after testing. In practice the calibration frequency is lower as seen in Figure 26.

The number of tests needed to derive the coefficients of a mathematical model is shown in Figure 27. 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.

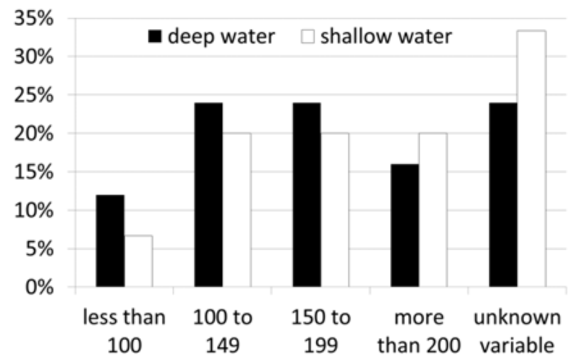

Figure 27: Number of tests needed to build a mathematical model for one ship at one draft and one water depth.

2.4.2 Data acquisition

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. The most frequent sampling rates 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.

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.

2.4.3 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.

2.4.4 Analysis methods

For steady tests, a mean value of the measured data should be calculated over the time interval in which results are steady. Analysis of harmonic tests requires techniques such as Fourier analysis, regression analysis, system identification.

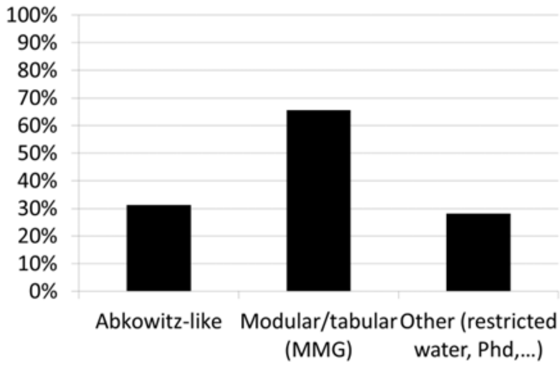

Figure 28: Types of mathematical models built, among institutes who build models.

2.4.5 Analysis of forces

Detailed analysis should be carried out using the stored data. This can be performed after all the tests have been finished. 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 (Figure 26).

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

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, 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.

A possible time lag between the measured forces and the prescribed motions due to low pass filters may affect the accuracy of determined added masses and moments of inertia and has to be considered during the analysis of the data.

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.

2.5 Prediction Procedure

The simulation of ship manoeuvring motion may generally be performed with a suitable mathematical model making use of the hydrodynamic coefficients obtained through the process described above.

2.6 Documentation

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

2.6.1 Experimental technique

2.6.1.1 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 (LCB) /gravity (LCG) 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_{RF} 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.

2.6.1.2 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.

2.6.1.3 Restricted water model

The following characteristics should be specified:

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

2.6.1.4 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.

2.6.1.5 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.

2.6.1.6 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.

2.6.2 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.

3. PARAMETERS

3.1 Parameters to be taken into account

3.1.1 General

The following parameters should be taken into account for all captive model tests:

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

3.1.2 Steady straight line tests

The following parameters should especially be taken into account for these tests:

- number of conditions;
- forward speed(s);
- range of drift angles (for oblique towing only);
- propeller rate(s);
- range of rudder angles (for tests with rudder deflection only);
- time/distance required for acceleration, settling, steady phase, deceleration;
- range of heel angles.

3.1.3 Harmonic tests

The following parameters should especially be taken into account for these tests:

- forward speed(s) u;

- amplitudes of sway/yaw motion (y_{0A}, ψ_A) and, thereby, of velocity (v_A, r_A) and acceleration ($\dot{v}_A, \dot{r}_A$);
- range of drift angles β (for yaw with drift);
- propeller rate(s) n;
- range of rudder angles δ (for tests with rudder deflection);
- circular frequency ω or period T of oscillation;
- number of cycles c;
- range of heel angles;
- amplitude of roll motion (pure roll only).

3.1.4 Steady circular tests

The following parameters should especially be taken into account for these tests:

- number of conditions;
- forward speed(s) u;
- non dimensional rate of turn r';
- range of drift angles β (yaw with drift);
- propeller rate(s) n;
- range of rudder angles δ (for tests with rudder deflection);
- time/distance required for acceleration, settling, steady phase, deceleration;
- range of heel angles.

3.1.5 Multi-modal and hexapod tests

The following parameters should especially be taken into account for multi-modal and hexapod tests, in addition of the before mentioned parameters:

- Mean value;
- Harmonic amplitude;
- Harmonic frequency;
- Harmonic phase shift.

4. VALIDATION

4.1 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. This benchmark data has been made available and allows extensive comparison. Many benchmarks have been created in the past, summarised in section 4.3. It is however recommended to use the SIMMAN2008 and SIMMAN 2014 benchmarks, because they are much better documented and applicable to modern ship hull forms (Stern and Agdrup, 2008; www.simman2008.dk and www.simman2014.dk).

4.2 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).

4.3 Benchmark Tests

1) Preliminary Analysis of ITTC Co-operative Tests Programme (11th 1966 pp.486-508) A Mariner Class Vessel

2) The I.T.T.C. Standard Captive-Model-Test Program (11th 1966 pp.508-516) A Mariner Type Ship "USS COMPASS ISLAND"

3) Co-operative Tests for ITTC Mariner Class Ship Rotating Arm Experiments (12th 1969 pp.667-670) A MARINER Model

4) The Co-operative Free-Model Manoeuvring Program (13th 1972 pp.1000)

   4-1) Co-operative Test Program - Second Analysis of Results of Free Model Manoeuvring Tests (13th 1972 pp.1074-1079) A MARINER Type Ship

5) The Co-operative Captive-Model Test Program (13th 1972 pp.1000**)** To Determine the Ability with which Full-Scale Ship Trajectories Could Be Predicted from the Test Data Acquired.

   5-1) Co-operative Tests Program - Review and Status of Second Phase of Standard Captive-Model Test Program (13th 1972 pp**.** 1080-1092)

6) The Mariner Model Cooperative Test Program - Correlations and Applications (14th 1975 Vol.2 pp.414-427) A New Large Amplitude PLANAR MOTION MECHANISM, The MARINER Model

7) Comparative Results from Different Captive Model Test Techniques (14th 1975 Vol.2 pp.428-436) A MARINER CLASS Vessel and a Tanker Model

8) Ship Model Correlation in Manoeuvrability (17th 1984 pp.427-435) To Conduct Model Tests and Compare Their Results with "ESSO OSAKA" Deep and Shallow Water Trials Joint International Manoeuvring Program (JIMP). A Working Group Called JAMP (Japan Manoeuvrability Prediction)

9) Free-Running Model Tests with ESSO OSAKA (18th 1987 pp.369-371)

10) Captive Model. Tests with ESSO OSAKA (18th 1987 pp.371-376)

11) Free running and Captive model Tests, SIMMAN 2008 Workshop

12) Free running and Captive model Tests, SIMMAN 2014 Workshop

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