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Updated / Edited by	Approved
Manoeuvring Committee of 25th ITTC	25th ITTC 2008
Date 2008	Date 09/2008

Captive Model Test Procedure

1. PURPOSE OF PROCEDURE

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.

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. Modern devices, often called "Computarized 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 through a multi-component force balance.

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

a) stationary straight line tests, performed in a towing tank, for instance:
- (a1) straight towing;
- (a2) straight towing with rudder deflection;
- (a3) straight towing with heel angle;
- (a4) oblique towing;
- (a5) oblique towing with rudder deflection;
- (a6) oblique towing with heel angle.

b) harmonic tests, requiring a towing tank equipped with a PMM or CPMC, for instance:
- (b1) pure surge;
- (b2) pure sway;
- (b3) pure yaw;
- (b4) pure roll;
- (b5) combined sway and yaw;
- (b6) yaw with heel angle;
- (b7) yaw with drift;
- (b8) yaw with rudder deflection.

c) stationary circular tests, by means of a rotating arm or CPMC-carriage:
- (c1) pure yaw;
- (c2) yaw with drift;
- (c3) yaw with rudder deflection;
- (c4) yaw with drift and rudder deflection;
- (c5) yaw with heel angle.

Tests a1, a3, a4, a6, b1 to b7, c1, c2 and c5 are carried out for determining hull forces and can be performed with and/or without appendages; a2, a5, b8, c3 and c4 yield rudder induced forces and are therefore non-applicable in case the model is not fitted with rudder and propeller (bare hull testing). Tests a3, a6, b4, b6 and c5 are carried out to determine forces due to heel/roll if the aim is to produce a mathematical model with 4 degrees of freedom (DOF), i.e. for ships with low metacentric height (*GM*).

Test b4 requires a special device for enforcing roll motions.

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 the "Recommended standard PMM test procedure" formulated by the 21st ITTC Manoeuvring Committee (1996), but also contain quantitative data which are 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 1997 (22nd ITTC Manoeuvring Committee, 1999).

The main principles of an analysis procedure for the uncertainty of the results will be presented in a separate ITTC procedure (7.5-02-06-04).

2. DESCRIPTION OF PROCEDURE

2.1 Preparation

2.1.1 Selection of model dimensions.

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

2.1.1.1 Scale

Principally, the scale should be chosen as large as possible, keeping in mind that scale effects in manoeuvring are not yet fully understood. However, it is generally accepted that they 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).

Since the model is towed by the PMM or CPMC the propeller rate of revolution rpm can be freely chosen during the tests, normally either corresponding to the self-propulsion point of the model or of the ship. In the latter case, a tow rope force is applied to account for the difference in frictional resistance. 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. However, for single screw ships it is thought that selecting the rpm corresponding to the model self propulsion point to some extent balances out the effect of the overdrawn wake in model scale, thus reducing scale effects. At present, there is no common procedure to choose the most favourable propeller rpm yet.

2.1.1.2 Model length

According to actual practice (see Figure 1) for test types (a) and (b), a model length of 3 m is frequently selected, the mean value being 4.5 m. 95 % of all captive model tests are carried out with a model length larger than 2 m.

On the average, circular tests (c) are performed with smaller models (mean length of 3 m, peak in the distribution at 2.2 m, 95% limit 1.5 m).

Due to new and larger facilities there is a trend towards considerably larger lengths than the above mentioned mean values, especially at larger commercial towing tanks.

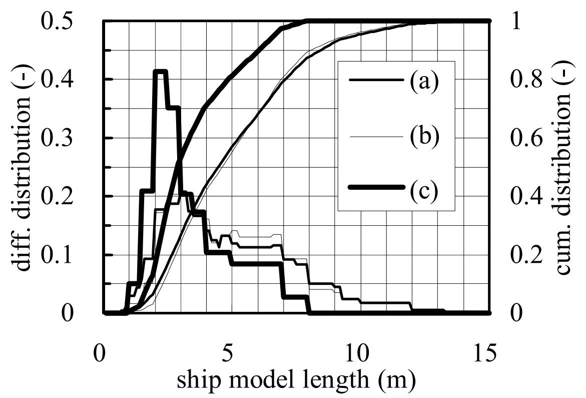

Figure 1: Differential and cumulative distribution of the length of ship models used for several types of captive model tests.

Minimum 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 a minimum measuring time or measuring distance, the model dimensions should not exceed some upper limit.

- Most tests of types (a) and (b) are carried out in a towing tank with a length of 35 times the ship model length and more. A mean value for the model length to tank width ratio (*L/b*) is 0.47 for stationary straight line tests (a), and somewhat smaller (0.42) for harmonic tests (b).
- For rotating arm 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 (c) are carried out in a tank the largest dimension of which is about 20 times the model length. As most circular tests are executed in circular or wide tanks, the mean value of *L/b* is much smaller (0.09) compared with tests of types (a) and (b).

2.1.1.4 Water depth

For the deep water case, the depth to draft ratio should be 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 model tests. The test speed should be below 0.5 $(gh)^{1/2}$.

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

2.1.2 Model inspection

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

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

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

2.1.3 Model equipment and set-up

The 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 simulations in which roll is not included, and is therefore assumed to be negligible, it is often decided, and may be better, to prevent roll motions than to let the model roll freely.

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 (a and b), 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 minimum. It must however be remembered that the dissymmetry of the model (appendages alignment, propeller loading…) may lead to non zero side forces/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.

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-stationary techniques are applied (e.g. PMM testing), the quasi-stationary character of the mathematical models should be taken into account. In order to comply with the quasi-stationary assumption the test results should not be affected by memory effects; this will permit their extrapolation to zero frequency.

	forward speeds					propeller loadings				
	cum. distr. (%)				max freq	cum. distr. (%)				max freq
	0	50	80	100		0	50	80	100	
b	1	1	3	10	1	1	1	1	10	1

	drift angles					rudder angles				
	cum. distr. (%)				max freq	cum. distr. (%)				max freq
	0	50	80	100		0	50	80	100	
b2	-	-	-	-	-	1	1	1	10	1
b8	-	-	-	-	-	2	3	4	6	3
b7	2	4	6	10	4	1	1	4	10	1

Table 1: Test typ (b): number of test parameters

2.2.2 Ship control parameters

The second kind of parameters is 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. 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 ships 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, does not influence the model's kinematics, but may affect accuracy and validity of the test results (e.g. measuring time/length, number of harmonic cycles, waiting time between runs).

2.3 Execution of the Tests

2.3.1 Stationary 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. Table 2 reflects the actual practice, based on the response to the 1997 questionnaire (22nd ITTC Manoeuvring Committee, 1999).

Drift angles

In tests (a4) to (a6), 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.

The maximum drift angle should not exceed the one which causes interference of the model with the tank walls. Mean ranges appear to be [-20°, +20°] (a4) or [-15°, +15°] (a5); drift angles exceeding ±35° are only rarely applied and at low speed only.

	forward speeds					propeller loadings				
	cum. distr. (%)				max	cum. distr. (%)				max
	0	50	80	100	freq	0	50	80	100	freq
a1	1	3	9	15	1	1	2	5	20	1
a2	1	2	4	6	1	1	1	5	10	1
a4	1	2	3	9	1	1	1	5	10	1
a5	1	1	3	5	1	1	1	8	10	1

	drift angles					rudder angles				
	cum. distr. (%)				max	cum. distr. (%)				max
	0	50	80	100	freq	0	50	80	100	freq
a2	-	-	-	-	-	2	10	15	17	9
a4	3	11	15	23	12	-	-	-	-	-
a5	3	8	14	20	5	2	8	14	20	10

Table 2. Tests type (a): number of tests parameters

The applied range is not necessarily symmetric to zero drift. In test (a4), drift angles to both port and starboard should be tested to check for possible propeller induced asymmetry effects.

2.3.1.2 Ship control parameters

Propeller rates of revolutions

Most tests should be carried out at the (model or ship) self-propulsion point. Especially for straight towing tests without rudder action (a1) and rudder force tests (a2), other propeller loadings should be applied as well, as described in Section 2.2.2.

Rudder angles

In tests (a2) and (a4), the rudder(s) should be deflected from a maximum rudder angle in one direction, to at least 5° in the other direction, so that the rudder angle resulting into zero lateral force and yawing moment can be determined. The maximum rudder angle should be determined according to the purpose of the tests, and in most cases coincides with "hard over", although a lower deflection could be sufficient for some purposes. Rudder angles should be varied with an appropriate step.

2.3.1.3 Operational and analysis parameters

Typically, a run consists of an acceleration phase, one or more stationary conditions, and a deceleration phase. Each stationary phase can be subdivided in a settling phase and a steady phase. Typical values for these phases, expressed as the non-dimensional distance covered by the ship model, are given in Table 3. Mostly, no distinction is made between the different types of stationary 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.

	cumul. distr. P (%)				max freq
	0	50	80	100	
acceleration (L)	0.07	1.7	5.5	33.3	0.8
settling (L)	0.10	2.2	5.5	13.3	1.5
steady (L)	0.30	8.7	17.2	80.0	3.5
deceleration (L)	0.07	1.7	5.3	20.0	0.7
waiting time (min)	15	15	20	20	15

Table 3: Stationary straight-line tests (a): experimental parameters (L denotes ship model length)

2.3.2 Harmonic tests

The number of parameters determining a PMM or CPMC test is larger than in the case of a stationary test (see 2.1.3); 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 Table 1).

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:

$$\begin{aligned} v'_{\mathrm{A}} &= y'_{0\mathrm{A}}\,\omega'_1 \\ \dot{v}'_{\mathrm{A}} &= y'_{0\mathrm{A}}\,\omega'^2_1 \end{aligned} \qquad (1)$$

while for yaw tests, the following approximation can be made for small and moderate amplitudes (note: this does not apply for CPMC):

$$\begin{aligned} r'_{\mathrm{A}} &= \psi_{\mathrm{A}}\,\omega'_1 \approx y'_{0\mathrm{A}}\,\omega'^2_1 \\ \dot{r}'_{\mathrm{A}} &= \psi_{\mathrm{A}}\,\omega'^2_1 \approx y'_{0\mathrm{A}}\,\omega'^3_1 \end{aligned} \qquad (2)$$

which implies that the range of non-dimensional sway and yaw kinematical parameters depend on:

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

which are subject to restrictions.

The lateral amplitude may be restricted due to limitations of the mechanism or, if not, should be selected to be less than the one which causes 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 is discussed in Section 2.3.2.3.

Drift angle

The range of the drift angles β to be applied in test type (b7) has to be selected according to the application domain. The mean range appears to be [0°, +16°].

2.3.2.2 Ship control parameters

Propeller rates of revolution

Tests are usually carried out at the self-propulsion point of the model or of the ship.

Rudder deflection

The range of rudder angles δ to be applied in test type (b8) has to be selected according to the application domain. The mean range appears to be [–20°, +30°] but should at least cover the rudder angles for which the manoeuvres have to be predicted.

2.3.2.3 Operational and analysis parameters

Oscillation frequency

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

$$\omega_1' = \frac{\omega L}{u}$$
$$\omega_2' = \omega\sqrt{\frac{L}{g}} = \omega_1' Fr \qquad (3)$$
$$\omega_3' = \frac{\omega u}{g} = \omega_1' Fr^2$$

Restrictions of ω_1' can be interpreted as follows.

- Restrictions due to tank length: the number of oscillation cycles c is limited by: $c \leq \frac{1}{2\pi}\frac{L_{tank}}{L}\omega_1'$ (4)
  L_{tank} being the available tank length

- Avoiding non-stationary 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).
- 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.

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 wavelength λ of the wave system induced by the oscillation equals $2b/n$ (n = 1, 2, ...), b being the tank width. Figure 2 displays the frequency *fulfilling* $\lambda = 2b$ as a function of water depth and tank width; in case of infinite depth, tank resonance occurs at $\omega_2'^2 = \pi L/b$.

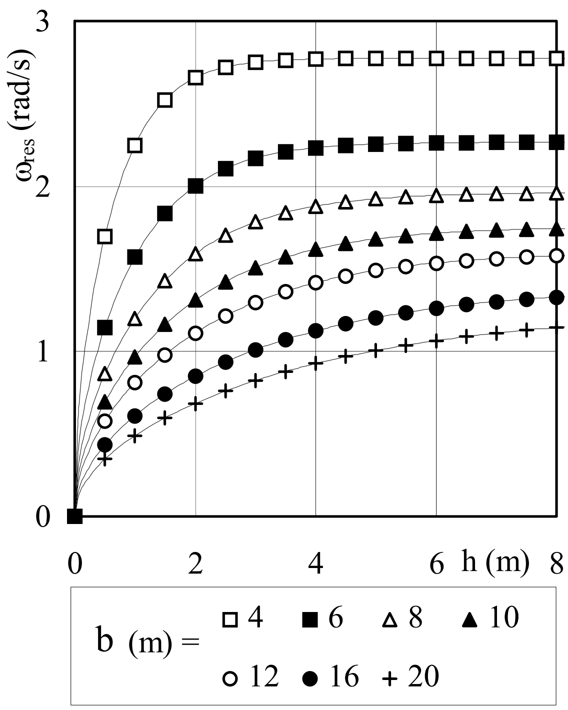

Figure 3: Lowest tank resonance frequency as a function of water depth h for several tank width values b.

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 2.

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

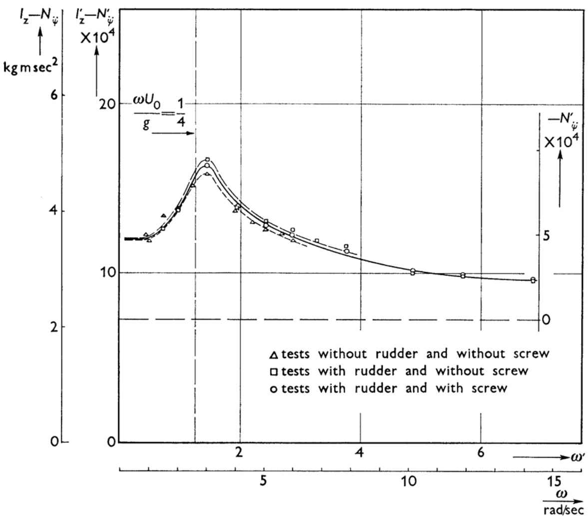

Figure 4: Influence of ω_3' on added moment of inertia from PMM yaw tests (van Leeuwen, 1964)

Table 4 summarises the actual practice concerning the selection of test frequencies expressed in a non-dimensional way. (3) reveals that limitations of ω_1' will be overruled by those of ω_2' and ω_3' for larger Froude numbers.

	max.freq	P=50%	P=80%	empiric
ω_1'	0.5 - 1.5	5.0	14	1 - 4
ω_2'	0.1 - 0.2	0.5	0.9	0.15-0.2
ω_3'	0.02- 0.04	0.08	0.22	<< 0.25

Table 4: Harmonic tests (b): frequency selection

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). Common practice concerning the number of cycles considered for analysis is given in Table 5, which also gives an indication about the number of cycles skipped in order to obtain a periodic or statistically stationary state.

	P = 50%	P = 80%	max. freq.
transient	1 cycle	3 cycles	1 cycle
steady	2 cycles	4 cycles	2 cycles

Table 5: Harmonic tests (b): experimental parameters.

For some purposes, e.g. validation of CFD, more cycles could be necessary.

2.3.3 Stationary circular tests

2.3.3.1 Kinematics parameters

Forward speeds

The number of selected forward speeds is the same for tests (c1) to (c5) as for tests type (a2) to (a6). When dealing with large yaw rates, the speed loss of the manoeuvring ship can be considered to determine the test speed range.

Yaw rate

Based on actual practice reported by the 1997 questionnaire (22nd ITTC Manoeuvring Committee, 1999), non-dimensional yaw rate values *r'* for circular motion tests vary from 0.07 to 1; median range being between 0.20 and 0.75.

Drift angles

Experience shows that there is a close relationship between drift angle and non dimensional yaw rate for a free running manoeuvring ship. Figure 4 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 $\beta = 26\ r'$ 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).

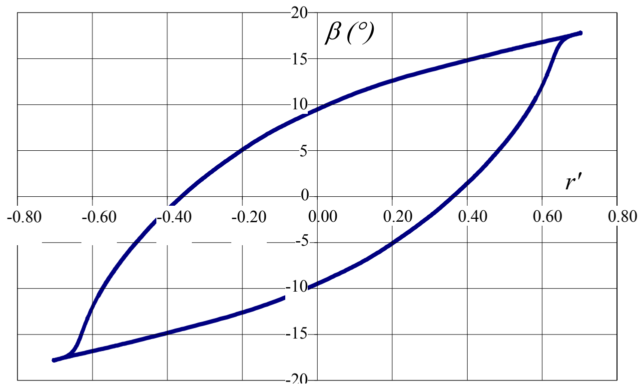

Figure 5: Yaw rate, drift angle envelope for a surface ship

1.1.1.1 <u>Ship control parameters</u>

Propeller rates of revolutions.

As for straight towing tests, tests should be carried out at the (model or ship) self-propulsion point. Especially for straight towing tests without rudder action (a1) and rudder force tests (a2), other propeller loadings should be applied as well, as described in Section 2.2.2..

Rudder angles

During yaw, drift and rudder deflection tests (c4), 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.

1.1.1.1 <u>Operational and analysis parameters</u>

Typically, a run consists of an acceleration phase, a stationary condition, and a deceleration phase. For rotating arm tests there is no limitation for the deceleration, but the stationary phase should be limited in order to avoid that the model runs in its own wake after a complete turn. Figure 5 illustrates the influence of speed and radius of turn for a given ship on the "available" stationary conditions in a single turn.

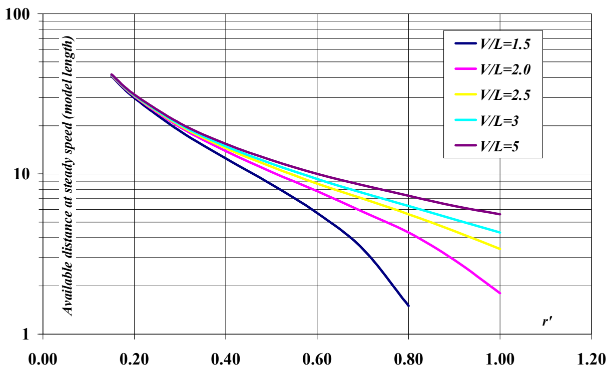

Figure 6: Influence of speed and *r'* on duration of stationary conditions (ship length) for a complete turn.

2.4 Data acquisition and analysis

2.4.1 Measured data

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

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

together with, - at least for particular purposes:

- roll moment.

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

- rudder angle,
- propeller rpm,
- other steering/manoeuvring devices' action.

Measurement of position/speed of the driving mechanism results in useful information on the actual trajectory of the model.

- trajectory,
- speed.

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.

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.

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 4 and 250 Hz, 20 Hz being a mean value.

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.

2.4.4 Analysis methods

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

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.

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

For hull forces:

- resistance and propulsion data from (a1);
- coefficients for sway velocity from (a4) or (b2);
- coefficients for yaw rate from (b3) or (c1);
- coefficients for sway velocity and yaw rate from (b5) or (b7) or (c2);
- inertia coefficients from (b1), (b2) and (b3).

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 stationary 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 (a2);
- coefficients expressing the effect of lateral motion of the stern on rudder induced forces from (a4), (b3) and/or (c3), (c3).

2.5 Prediction procedure

The simulation of ship manoeuvring motion may generally be performed by applying the mathematical model with which the test results are analysed, 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 Model

General characteristics

The following characteristics must be specified:

- main particulars of the ship:
  - length between perpendiculars,
  - beam;
- scale of the model;
- moment of inertia in yaw;
- moment of inertia in roll (if roll motion is not restrained);
- engine type for the full-scale ship.

The hull

Following hull data should be included in the documentation:

- the loading condition, to be specified as draught at AP and draught at FP or, alternatively, as mean draught amidships and trim or trim angle;
- 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: *KB*, *KG* and *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 (P/D);
- propeller area ratio A_E/A_0;
- propeller hub position;
- open water curves showing K_T and K_Q.

1.1.1.2 <u>Tank</u>

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

1.1.1.3 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 ship self-propulsion point is chosen, then it should be described how the friction correction force is applied including the used values for different speeds.

1.1.1.4 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.

1.1.1.5 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 stationary 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;
- 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.

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

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 Stationary straight line tests

Following parameters should especially be taken into account for tests of type (a):

- number of conditions
- forward speed(s)
- range of drift angles (a4 to a6 only)
- propeller rate(s)
- range of rudder angles (a2, a5 only)
- time/distance required for acceleration, settling, steady phase, deceleration
- range of heel angles (a3, a6 only)

3.1.3 Harmonic tests

Following parameters should especially be taken into account for tests of type (b):

- 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 (b7 only);
- propeller rate(s) n;
- range of rudder angles δ (b8 only);
- circular frequency ω or period T of oscillation;
- number of cycles c.
- range of heel angles (b6 only)
- amplitude of roll motion (b4 only)

3.1.4 Stationary circular tests

Following parameters should especially be taken into account for tests of type (c):

- number of conditions
- forward speed(s) u
- non dimensional rate of turn r'
- range of drift angles β (c2, c4 only)
- propeller rate(s) n
- range of rudder angles δ (c3, c4 only)
- time/distance required for acceleration, settling, steady phase, deceleration.
- range of heel angles (c5 only)

4. VALIDATION

4.1 Causes of uncertainty

During captive manoeuvring tests, a ship model is forced by an external mechanism to undergo a prescribed trajectory in the horizontal plane. The measurement of forces acting on the model leads to the numerical value of a number of characteristic coefficients considered in the mathematical manoeuvring model, which can be used for predicting various aspects of manoeuvring behaviour, including standard manoeuvres.

The accuracy of test results is influenced by imperfections of the experimental technique. Following types may be distinguished:

4.1.1 Imperfections causing errors to the boundary and/or initial conditions

1.1.1.6 Inaccuracy of ship model characteristics

The influence of some factors (e.g. errors on main dimensions, offsets, loading condition) on the accuracy of test results is hard to estimate, while variations of other parameters (e.g. mass, moments of inertia) have a rather straightforward effect on the forces acting on the model.

1.1.1.7 Undesired facility related hydrodynamic effects

A ship model's dynamics and, therefore, test results may be affected by several influences caused by the limitations of the experimental facility, e.g. that tests are not performed in un-restricted still water. Some examples:

- Residual motion of the water in the tank may affect the model's dynamics if the waiting time between two runs is too short.
- Non-stationary phenomena occurring during transition between acceleration and steady phases or if harmonic techniques are applied may also affect the model's dynamics.
- Tank width and also length limitations induce undesired additional forces.
- In shallow water tests, bottom profile variations affect the model's dynamics.

The influence of these effects on the accuracy of test results generally increases with decreasing water depth. Although complete prevention is principally impossible, the effects can be reduced by an adequate selection of test and analysis parameters.

4.1.2 Imperfections with direct or indirect influence on the ship model's dynamics

4.1.2.1 Mechanism geometry discrepancies

The geometry of the mechanism and, therefore, the trajectory of the ship model may be influenced by elastic deformation, backlash and mechanical imperfections, causing geometrical errors $g_{i(\mathrm{E})}$ which may affect model kinematics and dynamics.

A detailed analysis highly depends on the type and concept of the mechanism. Following factors may be of importance in the case of a PMM system with three degrees of freedom:

- deviations of the main carriage with respect to the tank:
  - horizontal deviations of the main carriage's guiding rail;
  - backlash between guiding rail and horizontal guiding wheels;
  - accuracy of the guiding wheels (radius, eccentricity, backlash);
  - vertical deviations of both rails;
  - accuracy of the main carriage's wheels (radius, eccentricity, backlash);
- deviations of the lateral carriage with respect to the main carriage:

   - alignment of guiding for lateral carriage;
   - perpendicularity of guiding for lateral carriage with respect to main carriage;
   - backlash of guiding for lateral carriage;
- deviations of the rotation table with respect to the lateral carriage:
   - alignment of rotation axis;
   - verticality of guiding for yaw table;
   - backlash;
- deviations of the model connection system with respect to the rotation table;
- inaccuracies of the connection of the ship model to the mechanism

With respect to the latter, a distinction should be made between connection inaccuracies according to either the free or the forced motion modes. Captive model tests executed for investigation of manoeuvring of surface ships require forced surge, sway and yaw motions, while the model is usually free to heave and pitch. Roll motions may be free or forced.

- Some errors are caused by imperfections of the connection system:
   - geometry imperfections and backlash may cause position errors in all motion modes;
   - mechanical friction between moving parts may result into position errors in the free motion modes;
   - inaccurate mounting may induce position errors in all forced motions modes

but even a perfectly functioning connection may induce position errors in the forced modes due to motions in the free modes. Due to the concept of some connection systems, pitch and heave indeed induce a small surge component.

4.1.2.2 Mechanism control and setting errors

The kinematics of the driving mechanism and, therefore, of the model are determined by a number of directly controllable parameters *si* which are either kept constant or controlled according to a time function during a test run. Setting and control errors *si*(E) on these parameters indirectly influence the forces acting on the model. An analysis of this influence strongly depends on the concept of the mechanism and the type of test.

Divergences between prescribed and actual trajectories can also be caused by inaccuracy of the measurement of position or speed of the (sub-)mechanisms, affecting the control system's feedback signal. Possible causes are:

- temperature influence;
- slip (of encoder wheel), backlash;
- errors/deformation in transmission to encoder;
- resolution of encoder.

Special attention should be paid to possible limitations of the mechanism concept, which may not allow the execution of some from theoretical point of view desirable trajectories. For example, small amplitude PMM systems based on the combined action of two horizontal oscillators may not be able to perform a pure harmonic yaw motion. In other cases, limitations of the control system yield deviations from the theoretically desired trajectory: this is for instance the case if a PMM system is mounted on a towing carriage which is not equipped with a variable speed control, as this leads to fluctuations of the ship's forward speed component during a harmonic yaw test. Principally, such discrepancies are predictable and can be accounted for during analysis.

4.1.2.3 Errors on ship control equipment parameters

During a test run, a number of control equipment parameters μ_i (propeller rpm, rudder angle, ...) are controlled; setting or control errors have a direct influence on the forces acting on the model.

4.1.3 Interpretation errors due to limitations of signal generation and manipulation

4.1.3.1 Measurement accuracy

The quality of force measurements may be affected by non-linearity, hysteresis, sensitivity, accuracy of calibration, Errors on position and speed measurements not only affect the mechanism's control loop (see above), but also the interpretation of the measured forces.

4.1.3.2 Data acquisition

Deformation of the measured signals may be induced by signal processing techniques, due to characteristics of e.g. filters, AD-conversion (resolution, time step).

4.1.3.3 Numerical analysis

The accuracy of calculated average values and harmonics appears to depend on test parameters (e.g. integration length, test frequency, number of cycles).

4.2 Uncertainty analysis

A new procedure on Uncertainty Analysis (UA) for captive model test has been developed (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 Am-

plitude 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)

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