ITTC Quality System Manual
Recommended Procedures and Guidelines

Procedure

Model Tests on Intact Stability

Updated / Edited by	Approved
Stability in Waves Committee of the 30th ITTC	30th ITTC 2024
Date 08/2024	Date 09/2024

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1. PURPOSE

This procedure is for carrying out experiments on an intact ship model in waves to determine its behaviour in extreme conditions and to establish thresholds for extreme motions including capsizing. The capsizing modes of an intact ship include loss of static and dynamic stability and broaching, where loss of dynamic stability may be associated with dynamic rolling, parametric excitation, resonant excitation, impact excitation and bifurcation. The definitions of the phenomena mentioned above are given in the 22nd ITTC final report of the Specialist Committee on Stability.

The intended extreme motions and capsizing should be clearly defined in the report. As an indication, down-flooding points, the shifting of cargo, *GZ* curve characteristics, relevant stability criteria, design requirements and operational limits should be given consideration.

To determine the parameters in tests on parametric rolling, the fundamental dynamics of this phenomenon, stated in ITTC Recommended Procedures and Guidelines 7.5-02-07-04.3 “Predicting the Occurrence and Magnitude of Parametric Rolling” and summarized in section 3.7 below are taken into account.

2. SELECTION OF MODEL BASIN

The size of the model basin should be appropriate to the size of the model and to the type of tests to ensure sufficient run length for identifying dangerous phenomena and avoid blockage, reflection and unwanted bottom effects. For example, it is desirable for realising broaching-related phenomena that the basin length should be greater than or equal to 25 times the model length and the basin width should be larger than the tactical diameter of the model. For parametric rolling tests a longer tank maybe required, particularly for irregular seas. For the tank-wall effects, refer to ITTC Recommended Procedures and Guidelines 7.5-02-07-02.1 “Sea Keeping Experiments”. The model basin should be able to generate waves in accordance with Section 3.4. To accurately reproduce deep water waves, the basin depth should be larger than the half of the maximum wavelength.

For realising broaching, deck diving or extreme roll coupled with yaw, self-propelled model should be used in wider basin as specified before. For identifying threshold and magnitude of parametric rolling, free-running model with autopilot in wider basin is desirable but, alternatively, a model towed by a carriage could be used in a towing tank. For model test without forward velocity, such as stability under a dead ship condition or rolling in beam waves, a conventional towing tank as well as a wider basin can be used. Models tested without forward velocity should be allowed to freely drift for sufficient time.

3. DESCRIPTION OF PROCEDURE

3.1 Model Design and Construction

The model should be built to scale and should be large enough to contain the necessary instrumentation for propulsion, steering, measurement, telemetry and ballast adjustment and be sufficiently rigid with a smooth finish. The model should be ballasted to the displacement and the longitudinal position of the centre of gravity corresponding to the subject ship. This should be confirmed by draught reading by using draught gauges or draught marks on the outer skin.

Weights should be adjusted to achieve the vertical position of the centre of gravity ($\overline{KG}$) and radii of gyration in the transverse and longitudinal directions corresponding to the data on the full scale ship. The method of doing this and the values of dry radii of gyration in roll, pitch and yaw should be included in the report. In the absence of more accurate knowledge, a value of $0.35B$ to $0.45B$ for the roll radius of gyration depending on the ship type, and $0.25L$ for both the pitch and yaw radii of gyration are recommended. Inclining test and free roll test should be carried out to confirm that the metacentric height ($\overline{GM}$) and the natural roll period of the model are equal to those of the subject ship within 2% error.

Particularly for parametric rolling and beam sea tests, the model should be of such a scale that viscous roll damping effects are properly modelled and bilge keel effects are accurately accounted for. A minimum length of 2 metres is recommended, scaled according to Froude’s law, to account for modelling important viscous effects. For free running models the flow over the hull and appendages should be turbulent. For monohull vessels without bilge keels or sharp chines, a model length of greater than 2m may be required to capture viscous roll damping effects. Model scale must be chosen to ensure that the bilge keel height is at least 7mm. For small vessels, typically less than 50 m in length, smaller model lengths can be allowed if the above requirements are satisfied. For free-running models, special light materials are often required if the model mass is smaller than 100 kg.

Appendages related to ship motion should be fitted and rudders and fins should have turbulent stimulation if required to ensure representative realistic full-scale flows. The report should state which appendages were fitted and describe the turbulence stimulation method, if any.

3.1.1 Watertight Boundary Considerations

In all cases where there is possibility for capsizing of the vessel or for water on deck or superstructures, the model should be complete up to the weather deck including forecastle and bulwarks. The whole model should be watertight to be consistent with the requirements of the extreme motions and capsizing being tested, having regard to the relevant regulations in terms of freeboard and water-tightness. As an indication, the model should be watertight up to the downflooding point. If certain tiers of superstructures of the subject ship can be considered efficient at restricting water ingress, the superstructure may be modelled up to the specified tiers. The *GZ* curve of the experimental model should be consistent with the above and should be provided in the report.

3.1.2 Testing in Wind Considerations

If wind forces need to be included in the model tests, the superstructure should be added to the model. The amount of detail in modelling the superstructure does not need to be very high, but the projected areas need to be correct (Umeda et al. 2023).

3.1.3 Control System Considerations

The use of autopilot is in general recommended for free-running model experiments in order to facilitate mutual comparisons among different ships or operational conditions. The presence of a simple PID autopilot, where the rudder deflection is proportional to the course deviation (yaw), results in the model having a yaw natural frequency due to autopilot feedback, which, for a fixed autopilot gain, changes with model speed. Thus, it is likely, that at some speed the yaw natural frequency will correspond to the roll natural frequency, resulting in significant autopilot contributions to model roll, possibly even capsize. Therefore, the autopilot gains should be carefully selected such that the yaw natural period is greater than the roll period, a factor of 3 is suggested, and these gains should be varied with model speed, decreasing as one over the model speed squared. The characteristics of the autopilot and the steering system (including rate of turn of the rudder(s)) are to be clearly stated in the report.

3.1.4 Propulsion and Power Considerations

It is necessary for the free running model to have a main propulsion system, including speed and direction control and a power supply system. Propulsor characteristics and its control law, such as constant revolution or torque, should be stated in the report.

Power may be supplied from rechargeable batteries which reside in the model. Alternatively, power may be supplied to the model from a moving carriage via a non-intrusive umbilical cable. The propulsion system should have the capability to cover the full speed range of the ship.

3.1.5 Model Restraints

The model should preferably be unrestrained. When the model is towed, the towing point and the arrangement should be carefully selected to avoid undesirable effects on roll, pitch and yaw. The influence of any restraining system on ship behaviour should be examined and reported in detail.

3.2 Calibration

In order to ensure accurate operation of instrumentation, calibrations should be carried out and reported. Calibration diagrams, where the measured quantities (output values) are plotted versus the calibration units (input units), may be useful to check the calibration itself as well as the linearity and repeatability of the instruments. Calibration should generally be in accordance with ITTC Recommended Procedure and Guidelines 7.6-01-01 “Control of Inspection, Measuring and Test Equipment”.

The calibration of wave height meters should be carried out by changing their vertical positions from calm water level, which should be measured with a calibrated ruler. The calibration of gyroscopes and accelerometers should be carried out by changing their inclination, which should be measured by a calibrated inclinometer. The calibration of propeller revolution sensor, rudder angle sensor and optical tracking sensor should be carried out following the advice of the manufacturer.

For the calibration of the waves, the regular wave height, or significant wave height and modal period (or the first moments) of irregular waves should be measured (without the model) by wave probes at more than three locations along the length of the basin spanning the range of positions where the model will be operated. Variations in the regular wave height, or irregular wave significant wave height and modal period should be within 5% among the different measured positions but with the same wave maker input signal. If the regular wave height or significant wave height and modal period variation exceed this limit, the possibility of standing waves due to insufficient wave absorption could exist. In case of short-crested irregular waves, more than two wave probes or equivalent should be used for determining a directional wave spectrum. If wave breaking occurs the above wave calibration may be performed with a reduced regular wave height, or irregular wave significant wave height keeping the shape of the wave spectrum the same, to assure that the wave reflection is acceptable. However, the breaking regular wave height or breaking wave spectrum measured at more than three locations along the basin should be interpolated to determine the spatially varying wave height/spectrum in which the model is operating.

For the calibration of the deterministic breaking waves (or transient waves) at a target area where the ship encounters the wave train at a given time, wave profiles should be measured by 6 to 8 probes arranged on a straight line at the direction of wave propagation. For checking the nonlinear effect, all waves with different heights used in the test should be recorded. It is desirable to record wave profiles using a video camera to realize how it breaks accurately. Another optional method is to measure breaking waves by a scanning laser system that uses a sheet of laser light with orthogonally positioned video cameras and image processing software.

For modelling wind forces two options are available. The first one is to calibrate the wind velocity such that prescribed wind loads act on the model. During the calibration the model is moored by means of instrumented wires. The second option is to calibrate the wind velocity itself. The uniform wind velocity calibration is performed using Pitot tubes or windmill-type sensor. Wind velocity at various places in the wind field should be measured systematically to obtain the relationship between blower revolution and wind velocity as a function of location. For a floating (moored) model, the calibration of wind refers to ITTC Recommended Procedures and Guidelines 7.5- 02-07-03.1 "Floating Offshore Platform Experiments". For a model at forward speed, it is suggested to generate wind by an array of wind fans mounted at the carriage moving with the model, although the calibration of wind velocities or forces is difficult at forward speed.

3.3 Measured Quantities

For identifying the threshold of capsizing only, measurements of incident wave system, the model's weight and centre of gravity are crucial, while measurements of ship motion can be omitted. Whether capsize occurs or not can be judged without any sensor.

In order to determine the causality for capsizing, the following main items should be recorded, as applicable, at sufficient sampling frequency (Hz), which is at least 20 divided by the model natural roll period:

- model position relative to basin.
- propeller rate of revolutions.
- model velocity and heading relative to the waves.
- model motions in 6 degrees of freedom (surge, sway, heave, roll, pitch and yaw).
- rudder angle.
- wave elevation at the model position. In case of free running tests the wave elevation history at several points in the model basin could be acceptable.

If the test uses combined wind and waves the following are required:

- wind characteristics (speed, direction and gradient profile) at the model position.
- wind generator setting.

The use of non-contact measurement systems, such as gyroscope or optical tracking sensor, is essential for measuring ship motions.

Video documentation is highly desirable during capsize model testing.

It is recommended to determine the model position relative to incident wave system, so that the wave elevation amidships can be estimated.

3.4 Wave Generation

The model test may be carried out in regular, irregular, transient waves or specially designed wave packets. Tests in regular waves should provide adequate data for a range of wavelengths, steepness and headings appropriate to the capsize modes being investigated. For efficiently identifying capsizing boundaries, higher wave steepness should be used first. Wavelength to ship length ratios from 0.6 to 2.3 could be considered for the investigation of capsize modes related to the reduction of stability in astern waves. For parametric roll tests in head seas the ratio of wavelength to ship length typically should be considered over the range of 0.8 to 1.5, giving due consideration of the parametric resonance condition. The actual test conditions should be decided based on the expected environmental conditions and the worst conditions for the relevant dangerous phenomena. To determine wavelength from measured wave period, it is essential to use non-linear dispersion relation of water waves.

For tests in irregular waves, due attention should be paid to modelling correctly wave group characteristics, which is in principle governed by the shape of the wave spectrum. Deriving from ocean wave measurements, a maximum characteristic wave steepness of $H_{W1/3} /(gT_p^2/(2\pi)) = 0.05$ is recommended as a guide. In the absence of information on specific spectrum data, JONSWAP spectrum and ITTC (1978) spectrum should be used for fetch- limited waves and ocean waves, respectively. The wave signal used should not be repeated during a single test. It is important to guarantee uniformity of waves in space and time during the measurement by taking propagation of energy into account. For the signal of short-crested irregular waves, each element wave should have unique wave frequency and direction. Due to the possibility of non-ergodicity in parametric rolling, several realisations of shorter durations are more desirable than one realisation of long duration (refer to ITTC Recommended Procedures and Guidelines 7.5-02-07-04.3 "Predicting the Occurrence and Magnitude of Parametric Rolling").

Transient waves and wave packets may be generated at predetermined locations in the tank by superimposing elementary waves of varying amplitude, phase and frequency. As an interim indication, it is preferable to apply nonlinear wave theory combined with empirical modification. The statistical properties and meanings of the used transient waves or wave packets in the real sea states should be clearly stated.

3.5 Wind Generation

For capsizing investigations at forward speed the wind effects are normally not included since wind forces are difficult to model properly. At zero speed (drifting) wind forces can be important as they have a great effect on ship heading and drifting direction and therefore on heel angles. Present intact stability criteria consider the effect of beam wind in the case of the dead ship condition only (weather criterion). See interim guidelines for alternative assessment of the weather criterion contained in IMO documents MSC.1/Circ.1200 (IMO 2006) and MSC.1/Circ.1227 (IMO 2007). The guidelines describe how to determine wind forces in a wind tunnel and how to determine the mean heel angle during drifting, without considering waves.

For free drifting tests in wind and waves, a wind velocity field is generated by an array of wind fans mounted on the carriage following the model. The fan's rate of revolutions or effective area can be controlled in order to generate a variable wind velocity (gusts) satisfying a wind spectrum formulation.

3.6 Preparation

A roll decay test should be carried out to obtain the natural roll period and the damping characteristics of the model in the test condition at zero and forward speeds. The model should be released from an initial angle with zero roll angular velocity. An effort should be made to incline the model by a moment with minimum net vertical and horizontal forces. At zero speed, following the IMO MSC.1/Circ.1200 "Interim Guidelines for Alternative Assessment of the Weather Criterion" (IMO 2006), the initial roll angle should be larger than about 25 degrees, and the average of the initial roll angle and the next peak should be over 20 degrees. In the case of the test with forward speed, any steering effort including an autopilot should not be used. Full details of the experiment, including time histories, should be included in the report.

The roll decay test carefully performed by human handling can be sufficiently accurate (Hashimoto et al. 2019).

In case of a model with propulsion, the speed should be calibrated for smooth water as a function of propeller revolution.

If broaching is of concern then the turning characteristics as a function of speed and rudder angle should be measured with particular attention given to heel angle in turn.

3.7 Execution of Test

Prior to the start of the tests a datum for all instrumentation used should be established. This should be rechecked after completion of the tests. Particular attention has to be paid to start up transients and the details of the start up condition should be reported.

It should be noted that in the case of following and stern quartering seas, the model should be situated near the wave maker first. After the wave train propagates enough in the model basin, the model propeller revolutions should be increased to the specified value to achieve the required speed and the steering system activated. The model should be tested in fully developed wave realisation.

It is necessary to repeat runs starting the model with different initial conditions as far as practicable due to the nonlinearity and dependency on initial conditions of extreme motions. The number of runs and their details should be reported. In irregular waves attention should be paid to the characteristics of the waves that the model encountered.

When determining the threshold for the occurrence of parametric rolling and the resultant rolling amplitude, it should be noted that, under some conditions, encountering many waves might be necessary for roll motion to fully develop. It is desirable to carry out numerical simulation also for the systematically varied conditions and compare both experiment and simulation.

Parametric rolling occurs in various combinations of ship speed and wave frequency, typically when the resulting frequency of encounter is near to $(2/n)$ times the natural roll frequency, where n is any integer. The n=1 scenario ("principal resonance") is practically important. The occurrence of parametric rolling requires a threshold wave height. The minimum wave height is determined in principle by two factors: the degree of fluctuation of roll restoring lever due to wave passage, and the ship's roll damping which is speed dependent. It should be noted that a threshold maximum wave height may also exist. It is often observed that where head sea parametric rolling disappears when wave height increases.

3.8 Report

The test results should be presented as critical conditions of capsizing in regular waves or capsizing probability in irregular waves, and for parametric rolling thresholds for the occurrence and magnitude of the resultant rolling amplitude. They should be a function of the main ship characteristics, operational and environmental parameters.

The report should also contain the following (where applicable):

- A description of the extreme motions and capsizing modes identified.
- Model details including appendage details, turbulence stimulation.
- Model Conditioning information including GZ curves.
- Model steering system and autopilot details.
- Roll decay tests and time histories.
- Instrumentation calibration details.
- Required and actual wave spectrum and wave characteristics.
- Model initial conditions.
- Analysis of the time series records of wave elevation, model motion in 6 degrees of freedom, propeller revolutions, rudder angle and the model position relative to wave.
- All run details.

4. UNCERTAINTY ANALYSIS

Standard uncertainty analysis can be applied to all measured basic quantities and motions. Capsizing could be a different situation due to the extreme phenomenon involved. However, a properly designed experimental system is reproducible for strongly nonlinear phenomena (Matsuda et al. 2016).

When considering extreme behaviour in regular waves the test should be repeated once using the same initial conditions as far as practicable. However, it should be noted that capsizing boundary could be indeterminate because of chaotic behaviour due to nonlinearity of restoring moment. Here totally different outcomes could be observed with practically the same initial condition. This indicates that negligibly small error could result in opposite conclusion on safety against capsizing. Thus, it is desirable to carry out numerical simulation also for the systematically varied conditions and compare both experiment and simulation.

Considering extreme behaviour in irregular waves the number of model runs and their duration should be noted. The level of confidence of estimated capsizing probability should be calculated by using the formula of binomial probability distribution. A simple estimate of the capsizing probability, p_c, is a ratio of the number of capsizing events, N_c, to that of different realizations, N, as follows:

$$p_c = \frac{N_c}{N} \tag{1}$$

If p is the true capsizing probability, the confidence interval of capsizing probability can be calculated by the following equation:

$$\Delta p = \frac{2}{\sqrt{N}} \sqrt{p_c(1-p_c)}\, z_{1-\alpha'/2} \tag{2}$$

Here, $Z_{1-\alpha'/2}$ is the $\left(1-\frac{\alpha'}{2}\right)$-quantile of the standard normal distribution, which can be determined from the table of normal distribution and α' is the confidence level of predicted capsizing probability. Range of error tolerance of the capsizing probability can finally be determined as follows:

$$p_c - \frac{\Delta p}{2} \le p \le p_c + \frac{\Delta p}{2} \tag{3}$$

with probability of $1-\alpha'$. Because of possible non-ergodicity due to nonlinearity, several realizations of shorter durations are more desirable than one realization of long duration.

5. BENCHMARK TESTS FOR VALIDATION

The following benchmark tests can be used for validation:

- Capsizing Experiments associated with parametric rolling (23rd 2002, pp. 613-616, Table 2.4) A container ship model running in following and quartering waves

- Capsizing Experiments associated with broaching (23rd 2002, pp. 613-616, Table 2.5) A fishing vessel model running in following and quartering waves.

6. LIST OF SYMBOLS

B	Breadth,	m
g	Gravity acceleration,	m/s^2
$\overline{GM}$	Metacentric height, m	
$H_{W1/3}$	Significant wave height,	m
$\overline{KG}$	Vertical position of the centre of gravity,	m
L	Length,	m
N	Number of realizations	
N_c	Number of capsizing events	
p_c	Capsizing probability	
T_p	Spectral peak (modal) period,	s
Z	Quantile of standard normal distribution	
α'	Confidence level	
Δp	Width of confidence interval for an estimate of capsizing probability	

7. REFERENCES

IMO MSC.1/Circ.1200 Interim Guidelines for Alternative Assessment on the Weather Criterion. London, May 2006.

IMO MSC.1/Circ.1227 Explanatory Notes to the Interim Guidelines for Alternative Assessment on the Weather Criterion. London, January 2007.

Hashimoto, H., T. Omura, A. Matsuda, S. Yoneda, F. Stern, & Y. Tahara (2019) "Several remarks on EFD and CFD for ship roll decay", *Ocean Eng.*, Vol. 186, pp. 371-382.

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