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INTERIM GUIDELINES FOR ALTERNATIVE ASSESSMENT
OF THE WEATHER CRITERION

1   The Maritime Safety Committee, at its eighty-first session (10 to 19 May 2006), approved Interim Guidelines for alternative assessment of the weather criterion, aiming at providing the industry with alternative means (in particular, model experiments) for the assessment of severe wind and rolling criterion (weather criterion), as contained in the Code on Intact Stability for All Types of Ships covered by IMO Instruments (resolution A.749(18)).   The Interim Guidelines should be applied when the wind heeling lever and/or the angle of roll (as defined in paragraphs 3.2.2.1.1 and 3.2.2.1.2 of the Code) need to be determined by means of model experiments.

2   Member Governments are invited to bring the Interim Guidelines to the attention of interested parties as they deem appropriate.

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ANNEX

**INTERIM GUIDELINES FOR ALTERNATIVE
ASSESSMENT OF THE WEATHER CRITERION**

1   INTRODUCTION

1.1   The purpose of these Guidelines is to provide alternative means for the assessment of severe wind and rolling criterion (weather criterion) as reported in paragraph 3.2 of the Code on Intact Stability for All Types of Ships covered by IMO Instruments (resolution A.749(18)). In the following guidelines, the angle of roll is referred as ϕ, while in the Code the angle of roll is referred as θ.

1.3   The Guidelines provide procedures for the determination of the wind heeling lever l_{w1}, as defined in paragraph 3.2.2.1.1 of the Code, by means of direct measurements.

1.4   In addition, the Guidelines are given for the experimental determination of the angle of roll ϕ_1 as defined in paragraph 3.2.2.1.2 of the Code.

1.5   For quantities used but not defined in the following, the definitions of the Code apply.

2   APPLICATION

2.1   The tables and formulae described in paragraph 3.2.2.3 of the Code are based on data from ships having:

.1   *B/d* smaller than 3.5;
.2   *OG/d* between -0.3 and 0.5;
.3   *T* smaller than 20 s.

2.2   For ships with parameters outside the above limits, the angle of roll (ϕ_1) may be determined with model experiments of a subject ship, following the procedure described in the Guidelines as the alternative. In addition, the Administration may accept such alternative determinations for any ship if deemed appropriate.

2.3   The alternative means for determining the wind heeling lever (l_{w1}) may be accepted, to the satisfaction of the Administration, as an equivalent to calculation in paragraph 3.2.2.2 of the Code. When such alternative tests are carried out, reference should be made to the relevant part of the Guidelines. The wind speed used in the tests should be 26 m/s in full scale with uniform velocity profile. The value of wind speed used for ships in restricted services may be reduced to the satisfaction of the Administration.

2.4   The test programme should be approved by Administration in advance.

2.5   Tests should be documented by means of a report and a video or other visual records containing all relevant information on the model, the procedure and the test results, which should be approved by the Administration.

2.6   Any procedure different from those provided in the Guidelines should be subject to the approval of the Administration.

3 GUIDELINES FOR EXPERIMENTAL DETERMINATION OF THE WIND HEELING LEVER L_{W1}

3.1 Objectives and definitions

3.1.1   The purpose of the tests addressed in this section is to ensure uniform applicability of model tests for the determination of the steady wind heeling lever, l_{w_1} (paragraph 3.2.2.2 of the Code). It is allowed by this procedure to consider the steady wind heeling lever as dependent on the heeling angle (see figure 3.1.1).
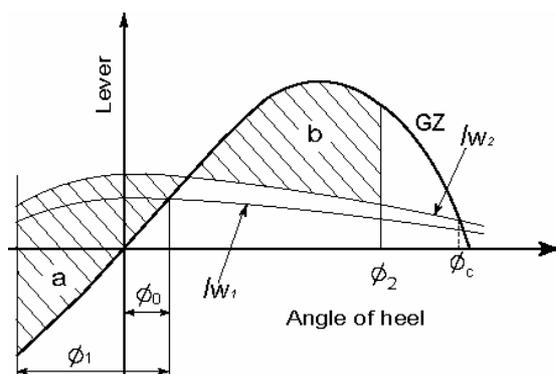
Figure 3.1.1: Weather criterion when the wind heeling lever is dependent on the heeling angle

3.1.2   The standard model test procedure consists of two parts. The first part is a procedure for estimating the heeling moment M_{wind} due to steady wind in a wind tunnel. A blower may be used as an alternative as long as the uniformity of wind speed is comparable. The second part addresses the estimation of the heeling moment M_{water} due to steady drifting in a towing tank.

3.1.3   The steady wind heeling lever, l_{w_1}, is obtained by means of the following equation:

$$l_{w1}(\phi) = \frac{M_w(\phi)}{\Delta} = \frac{M_{wind}(\phi) + M_{water}(\phi)}{\Delta} \qquad (3.1.3)$$

where:

$M_w(\phi)$ is the total heeling moment (N*m) when the ship is drifting laterally due to beam steady wind (90° heading angle) with an angle of heel ϕ;

Δ is the displacement (N) of the ship; and

The drifting force is assumed to be equal to the horizontal force F_{wind} due to steady wind.

The equation 3.1.3 assumes that the wind force and the drifting force work as a couple. In that case the heeling moment M_w is independent on the point of reduction of the system of forces. However, due to the unavoidable unbalancing of vertical forces arising from direct measurements, the total heeling moment M_w may depend on the point of reduction. For practical purposes, it is considered sufficient to calculate all moments with respect to the point O given by the intersection of the ship centreplane and the waterplane.

3.1.4 F_{wind} is related to the wind drag coefficient C_D by means of the following equation:

$$F_{wind}(\phi) = \frac{1}{2} \cdot \rho_{air} \cdot U^2 \cdot A_L \cdot C_D(\phi) \qquad (3.1.4)$$

where:

ρ_{air} is the air density (1.222 kg/m^3 for full scale prediction);

U is the wind speed (m/s); and

A_L (m^2) is the lateral projected area of the ship exposed to wind in upright position.

3.1.5 M_{wind} is obtained at full scale by appropriate scaling of results from wind tests carried out as indicated in paragraph 3.3. M_{water} is obtained at full scale by appropriate scaling of results from drifting tests carried out as indicated in paragraph 3.4.

3.2   Model set-up

3.2.1   *Ship model used for wind tests*

The model should copy the above-waterline shape of the actual ship and should comply with the following:

.1   the overall length should be at least 1.25 m;

.2   all sharp corners in the actual ship should be sharp in the model to simulate separated flow;

.3   main fittings on the exposed decks and superstructures, e.g. cranes, masts, bulwarks, should be modelled and fitted properly;

.4   the size of the model should be determined to make the blockage ratio to the wind tunnel less than 5%, where the blockage ratio is defined as the ratio between the lateral projected area of the model above the waterline divided by the area of the test section of the wind tunnel; and

.5   when a blower is used the ship should be within the area of uniform wind speed.

3.2.2   *Ship model used for drifting tests*

The model should copy the under-waterline shape of the actual ship and should comply with the following:

.1   the size of the model should comply with paragraph 4.3.2;

.2   not only underwater fittings (e.g. bilge keels, rudders, etc.) but also potential underwater part when the ship heels (e.g. bulwarks, freeing ports, etc.) should be modelled and fitted properly.

3.3   Wind tests

3.3.1   *Wind characteristics*

The wind speed should comply with the following:

.1   The minimum wind speed to perform tests should be over the critical Reynolds' number, after which C_D is constant.

.2   The wind speed profile should be as uniform as reasonably possible. Except for the boundary layer in the vicinity of the end plate (figure 3.3.1), spatial deviation[1] of the wind speed should be less than 1%.

.3   The effects of end plate (due to its shape, size, roughness, etc.) and of the gap between end plate and model should be minimized.
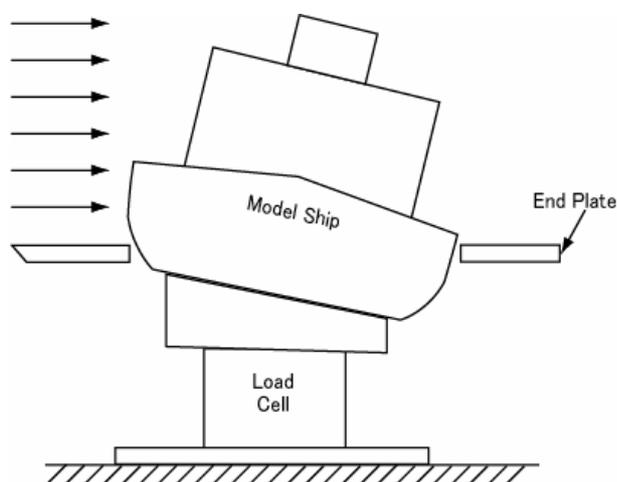
Figure 3.3.1: Example of an arrangement for tests in wind

3.3.2   *Complete test procedure*

The lateral horizontal force F_{wind} (and corresponding drag coefficient C_D) and the heeling moment due to wind M_{wind} with respect to O are obtained by a wind tunnel test or in wind from a blower. In calculating C_D according to equation (3.1.4), the actual value of air density during tests should be used. An example of model test arrangement is shown in figure 3.3.1. Model tests should be carried out in compliance with the following:

.1   Before tests are carried out, the vertical and horizontal distribution of the wind speed at the model position should be verified.

.2   Tests should be carried out in upright condition and at some heeling angles with appropriate increment to lee and wind side covering a sufficient range of heeling angles to the satisfaction of the Administration.

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[1]   Spatial deviation is the variation of wind speed in longitudinal direction referring to the main flow and should be measured for the test section without the model.

.3   In heeled conditions the model shape exposed to wind should be the same as the above-water shape when the ship is floating freely. The change of trim due to heel can be neglected.

3.3.3 *Simplified test procedure*

As an alternative simplified procedure, the lateral horizontal force F_{wind} (and corresponding drag coefficient C_D) and the heeling moment due to wind M_{wind} with respect to O can be obtained for the upright condition only and considered as constants (not depending by heeling angle).

3.4   Drifting tests

3.4.1 *Complete test procedure*

The heeling moment M_{water} due to drift with respect to O is obtained by means of towing tank tests. An example of experimental set-up is shown in figure 3.4.1. Model tests should be carried out in compliance with the following:

.1   the ship model should be attached to a guidance system, which allows the model's free sinkage (an example of experimental arrangement is shown in figure 3.4.1);

.2   towing direction is to be at right angle to the longitudinal direction of the model (heading angle 90°);

.3   the towing speed should ensure that the measured drift horizontal force is equal to F_{wind} scaled with the appropriate scaling law. F_{wind} should be calculated by equation (3.1.4) using the measured drag coefficient in paragraph 3.3 and the assumed wind speed as prescribed in paragraph 2.3; and

.4   tests should be carried out in upright condition, and at some heeling angles with appropriate increment to lee and wind side covering a sufficient range of heeling angles to the satisfaction of the Administration.
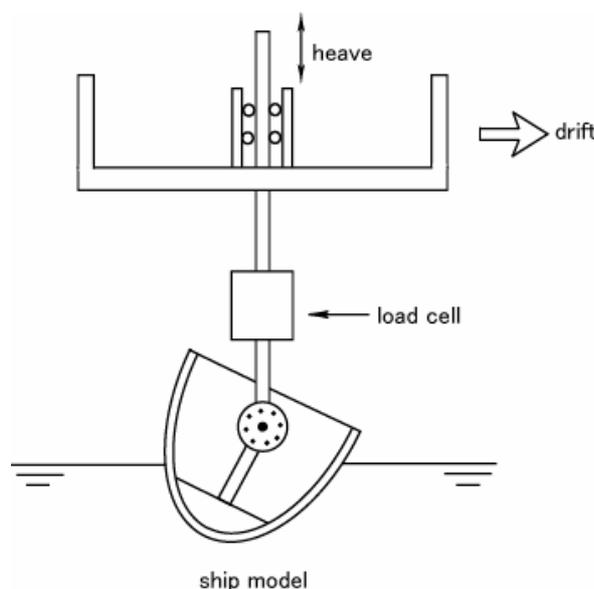
Figure 3.4.1: Example of an arrangement for drifting tests

3.4.2 *Simplified test procedure*

As an alternative simplified procedure, the moment M_{water} due to drift can be considered as given by a force equal and opposite to $F_{wind}(\phi)$ (as following from paragraph 3.3.2 or 3.3.3) acting at a depth below waterline equal to 0.5 d (where d is the ship draught in upright position).

3.5 Combined use of simplified and complete procedures

The combination of complete procedures and simplified procedures can be used.

3.6 Additional considerations

The steady wind heeling lever, l_{w_1}, is evaluated by means of equation (3.1.3). When extrapolation is needed outside the tested range of heeling angles, such extrapolation should be carried out to the satisfaction of the Administration.

4 GUIDELINES FOR EXPERIMENTAL DETERMINATION OF THE ANGLE ϕ_1

4.1 Objectives and definitions

4.1.1 The objective of the tests addressed in this chapter is the determination of ϕ_1 (paragraph 3.2.2.3 of the Code). The "angle of roll to windward due to wave action" ϕ_1 is defined, according to weather criterion, as follows:

$$\phi_1 = 0.7 \cdot \phi_{1r} \qquad (4.1.1)$$

where ϕ_{1r} is "regular waves roll-back angle", that is the resonant roll amplitude in beam regular waves (heading 90°) having steepness defined in the following sections. The reduction factor 0.7 takes into account the actual irregular nature of the sea.

4.1.2 The standard procedure for the determination of ϕ_{1r} is that by means of tests in regular waves. The use of alternative procedures is permitted. Sufficient justification should be provided to the Administration regarding the selected procedure.

4.1.3 As a reference in selecting the more suitable procedure it should be noted that:

.1 The direct measurement of ϕ_{1r} (see paragraph 4.5) can lead to the need of generating very steep waves close to the breaking limit if the ship roll period is very short (see table 4.5.1). Generation of waves with such steepness and sufficient quality can be sometimes difficult due to breaking close to the wavemaker. In addition, in carrying out roll tests, care should be taken during the transient ship behaviour before steady state is reached, because possible large heeling angles (sometimes eventually leading to capsize) can occur. It should be underlined that ϕ_{1r} is the steady state maximum roll angle, for this reason capsize during initial transient phase of the test does not necessarily lead to not fulfilment of the criterion. It should be underlined that the methodology does not allow for corrections for scale effects on roll damping, and for this reason large models should be preferred when direct measurements are carried out.

.2 The there-step procedure (see paragraph 4.6.1) is the simplest among the two proposed alternative procedures. This method was adopted when original weather criterion was developed. The procedure is sensitive to the quality of execution and analysis of roll decay tests. The procedure allows to execute tests for the determination of the effective wave slope coefficient r, with reasonably small steepnesses, leading to rather simple tests. The methodology allows, in principle, corrections for scale effects on roll damping.

.3 The parameter identification technique (PIT) (see paragraph 4.6.2) is a procedure with a large degree of flexibility, that allows to take into account nonlinearities of both damping and restoring, and that provides means for allowing frequency dependence of the "effective wave slope function". The methodology allows, in principle, corrections for scale effects on roll damping. When used with only one series of tests for one single wave steepness, the number of free parameters should be reduced to guarantee robustness of the methodology. The method can take great advantages (regarding robustness and accuracy) from the execution of more than one series of tests at different wave steepness: for this reason the use of at least two different wave steepnesses is strongly recommended. To guarantee correct application of the method, a sufficient basic training of personnel on the theoretical background on which the method is based is needed.

4.2   Model basin

The facilities of the model basin should be such as to avoid wave reflections and shallow water effects. The breadth of the basin should be larger than the over all length of the model plus 2 m. The quality of the basin should be subject to the satisfaction of the Administration.

4.3   Model set-up

4.3.1 *Construction*

4.3.1.1 The model should be built geometrically scaled up to the upper weather deck including forecastle and bulwarks and be sufficiently rigid with a smooth finish. The whole model (excluding free flooded spaces) should be watertight in order to guarantee hydrostatic properties.

4.3.1.2 All superstructures included in stability calculations or that are submerged during the tests should be reproduced to scale to ensure the model has the correct righting arm curve. Superstructures that do not submerge during the tests described below can be omitted.

4.3.1.3 Appendages such as bilge keels or rudder should be fitted, properly scaled and the report should state which appendages were fitted during the tests.

4.3.2 *Scale*

To avoid scale effect on roll damping, the model overall length should be at least 2 m. However, the model should be scaled up, if necessary, to make the breadth of the bilge keels greater

than 7 mm. For monohull ships having neither bilge keels nor sharp bilges[2], however, the model overall length should be at least 4 m unless frictional effect on roll damping is corrected with theoretical methods described later, but in any case not less than 2 m or a scale 1:75, whichever is greater.

4.3.3 *Ballast and weight distribution*

4.3.3.1   The model should be ballasted to the appropriate displacement and loading condition for the ship. To ensure correct displacement and attitude, draught marks or suitable gauges should be used. Weights should be adjusted to achieve the correct position of the centre of gravity.

4.3.3.2   Weight distribution should be such as to guarantee reasonable radius of gyration for pitch. Unsymmetrical weights distribution should be avoided as far as practicable.

4.3.3.3   Inclining tests should be carried out to verify that the value of ship's metacentric height GM corresponds to that of the actual ship within an error of 2% or 1 mm at model scale, whichever is larger.

4.3.3.4   In addition, depending on the information provided to the model basin, natural roll period $T\phi$ in water or roll radius of gyration in air, should be checked to correspond to that provided within an error of 2%.

4.3.4 *Roll period $T\phi$ to be tested*

The ship natural roll period should be used for tests. In case a sufficiently accurate estimation of $T\phi$ is not available at the time of tests, they should be carried out for a series of at least 3 different roll periods, from which the results can be finally interpolated for the actual ship roll period.

4.4   **General** e**xperimental** s**et-**u**p**

4.4.1 *Instrumentation*

The instrumentation system should be appropriate to the model and type of test carried out. The use of non-intrusive measurement systems is recommended when feasible.   If it becomes necessary to attach cables to the model then care should be taken to minimize interference.

4.4.2 *Calibration*

In order to ensure accurate operation of instrumentation, calibrations should be carried out and reported.

4.4.3 *Measurements*

Roll, and yaw if necessary, should be simultaneously measured and recorded as appropriate to the purpose of the test. Wave height measurements should be made for all tests with wave probes fixed in the tank.

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[2]   "Sharp bilges" used here means that bilge radius is smaller than 1% of the ship's breadth and the angle between piece-wise lines representing the bilge is smaller than 120°.

4.4.4 *Wave quality*

Wave generation quality should be assessed for the waves corresponding to the minimum and the maximum frequency used in the tests. The wave elevation should be measured by wave probes positioned at least 3 locations along the length of the basin, spanning the drift range of the model. This should be done without the model because the model can disturb incident waves. When the measured double amplitude of the wave elevation converges to a certain value, this value should be regarded as the wave height, H, for each position. Variations in wave height and wave period should be within $\pm 5\%$ among the different measured positions for the same signal.

4.5   Tests in regular waves

Tests in regular waves are the standard procedure for determining the "regular waves roll-back angle" ϕ_{1r}. In some cases the direct determination of ϕ_{1r} is not feasible, as, for example, in case of large models having long natural roll period $T\phi$. In such cases alternative procedures can be used as reported in paragraph 4.6.

4.5.1 *Test conditions*

The wave steepness (factor "s") should be selected from table 4.5.1.

Table 4.5.1: Wave steepness as a function of the full scale natural roll period

Ship roll period T_{ϕ} [s]	Wave steepness $s = H / \lambda$
<6	0.100
6	0.100
7	0.098
8	0.093
12	0.065
14	0.053
16	0.044
18	0.038
20	0.032
22	0.028
24	0.025
26	0.023
28	0.021
30	0.020
>30	0.020

4.5.2 *Direct measurement procedure*

4.5.2.1 Tests in regular waves can be used to directly obtain the "regular waves roll-back angle" ϕ_{1r}. ϕ_{1r} is the peak roll response of the ship in regular waves of steepness according to table 4.5.1. In order to determine ϕ_{1r}, the stationary roll motion amplitude should be measured for a sufficient number of frequencies around the natural roll frequency $\omega_0 = 2\pi/T_{\phi}$. The following minimum set

of test points is recommended ω/ω_0 = 0.8, 0.9, 0.95, 0.975, 1.0, 1.05, 1.2, with ω being the frequency of the regular wave in rad/s. Additional measurements in the proximity of the response peak might be necessary to allow for an accurate determination of ϕ_{1r} especially in case of strong influence of righting lever non-linearity.

4.5.2.2   During the tests the ship model should be positioned to be normal to the direction of the waves (90° heading angle). The heading angle of the model is either:

.1   fixed, with a guide attached to the towing carriage keeping the sway-heave-roll motion free from restraints. An example of experimental arrangement is shown in figure 4.5.2.2. The carriage should trace the drift motion of the model induced by the beam wave's action. Draught, GM and $T\phi$ should be adjusted taking into account the effect of the guide; or

.2   controlled by guide ropes which are fitted to the model on the centreline at the stem and stern, in a symmetrical fashion and at a vertical height between the waterline and the centre of gravity. These lines can be used to correct the model in yaw while allowing drift and sway, provided the heading during tests does not deviate from beam sea for more than 15°. However, whenever the yaw motion is corrected by means of the ropes, the corresponding part of the measured record should be neglected in the subsequent analysis, unless the effect of correction on the quantities of interest is clearly negligible.
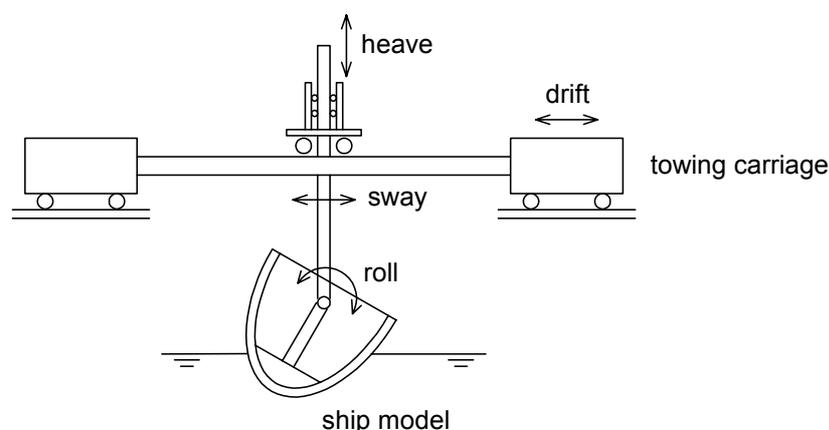
Figure 4.5.2.2: An example of the guide for roll test in beam waves

4.5.2.3   During the tests, care should be taken to use appropriate time windows for the measurements, so that the steady roll amplitude is measured without the influence of reflected waves between the model and the wave maker or the model and the beach.

4.5.2.4   Data to be recorded are model motions in all measured degree of freedom (DOF) and wave elevation.

4.6   Alternative procedures

When direct measurement of ϕ_{1r} is not feasible, alternative procedures can be used to calculate the angle of roll to windward due to wave action ϕ_1 at the steepness specified in 4.5.1, by means of data obtained from tests in regular waves with different steepnesses and/or other type of tests.

In view of the strict interrelation between the many elements constituting present weather criterion assessment, the evaluation of individual parameters relevant to the calculation formula of the angle of roll to windward due to wave action ϕ_1 is permitted only when they are all evaluated through experimental tests or appropriate calculation procedures. In the following, procedures are reported as alternatives to the direct measurement of ϕ_{1r} (refer to paragraph 4.5).

4.6.1 *Alternative procedure 1: Three-step procedure*

The procedure consists of the sequential evaluation of:

.1   roll damping (Bertin's coefficient N) from roll decay test in calm water;

.2   effective wave slope coefficient r from roll tests in beam waves; and

.3   the "regular waves roll-back angle" ϕ_{1r}.

4.6.1.1 Execution of roll decay tests

4.6.1.1.1 To obtain the roll damping characteristics of the ship, a series of roll decay tests for the scaled model in calm water should be carried out. The model is initially inclined up to a certain heel angle. This initial angle should be larger than about 25°. If the mean roll angle between the initial angle and the next peak angle is smaller than 20°, the initial angle should be increased to obtain a mean angle of 20° or over. When the initial roll angle is given to the model, additional sinkage and trim should be minimum. The model should be released from an initial angle with zero roll angular velocity. During this test, no disturbance including waves propagating in the longitudinal direction of the basin and reflected by its end should be given to the model. At least four tests with different initial angles are required. If the roll damping is very large, the number of tests should be increased to obtain sufficient number of peaks of the roll angle. Recording of the roll time history should start before the release of the model to confirm that no angular velocity is given when releasing. Recording should continue until the model has reached rolling angles smaller than 0.5°. This eventually requires that the length of the basin should be sufficiently large.

4.6.1.1.2 Full details of the experiments, including time histories, should be included in the report.

4.6.1.2   Determination of ϕ_{1r}

4.6.1.2.1 *First step*

The aim of this step is the determination of the Bertin's extinction coefficient curve and the roll period as a function of roll amplitude. Assuming that the absolute values of measured consecutive extremes (one maximum and following minimum or vice-versa) of roll angle during roll decay are $\phi_1, \phi_2, \ldots$ (deg), the mean roll angle $\phi_{m_i} = \dfrac{\phi_i + \phi_{i-1}}{2}$ and the decrement $\delta\phi_i = \phi_i - \phi_{i-1}$ are calculated. Bertin's extinction coefficient, N, as a function of ϕ_m is obtained by $N_i = N\!\left(\phi_{m_i}\right) = \dfrac{\delta\phi_i}{\left(\phi_{m_i}\right)^2}$. It should be noted that N depends on roll amplitude. The obtained raw data for $N\!\left(\phi_{m_i}\right)$ should be fitted by a smooth curve. In addition, periods from peaks to peaks should be calculated as a function of mean roll angle, which is necessary for step 2.

An equivalent linear damping coefficient $v_e(\phi)$ defined as:

$$v_e(\phi) = \frac{1}{\pi} \cdot N(\phi) \cdot \phi$$

where ϕ is in degrees, can be used as an alternative to the Bertin's coefficient. When the equivalent linear damping coefficient is used, all the formulae involving $N(\phi)$ should be modified accordingly.

In case frictional correction on roll damping is required in paragraph 4.3.2, the above value of N should be reduced by the value from the following formula, which represents the model-ship correlation on frictional damping:

$$\delta N = \frac{2.11 * S * r_S^2}{\phi_r * \Delta * GM * T_\phi^{1.5}} \qquad (4.6.1.2.1\text{-}1)$$

where:

$$S = L * (1.7 * d + C_B * B) \qquad (4.6.1.2.1\text{-}2)$$

$$r_S = \frac{1}{\pi}\{(0.877 + 0.145 * C_B)(1.7 * d + C_B * B) + 2 * (KG - d)\} \qquad (4.6.1.2.1\text{-}3).$$

All variables should be in model scale and the symbols in the above formulae are defined as follows:

L	= length of the ship at waterline (m)
B	= moulded breadth of the ship (m)
d	= mean moulded draught of the ship (m)
C_B	= block coefficient
GM	= metacentric height corrected for free surface effect (m)
Δ	= displacement (kg)
T_Φ	= roll period (s)
ϕ_r	= roll angle (degrees)

Alternatively a numerical calculation with unsteady boundary layer can be used to the satisfaction of the Administration.

Alternatively, a forced roll test may be used to determine the $N(\phi)$ coefficient by using an internal or external roll motion generator.

The former requires measurement of roll angles and the latter does that of roll moment. The experimental procedure and the subsequent analysis of data should be subject to the satisfaction of the Administration. In order to decide on the suitability of experimental and analysis procedure, as a guide, a reasonable agreement between results from forced roll tests and $N(\phi)$ from roll decay tests, can be considered a good indication.

4.6.1.2.2 *Second step*

The aim of this step is the determination of the effective wave slope coefficient r. The following two methods are provided:

.1   The resonant roll amplitude in regular waves is determined according to the procedure described in paragraph 4.5.2 but using a wave steepness which should be smaller than 1/20. Regardless of the requirement in paragraph 4.5.2, a used wave period should be the same as the given natural roll period. Once the steady roll amplitude is obtained, the natural roll period for this amplitude should be estimated with the results of roll decay test. If this period is significantly different from the wave period, roll angle measurement should be repeated but by using the newly estimated period as the input to the wave maker. Then the effective wave slope coefficient, r, is determined as follows:

$$r = \frac{g \cdot T_{wave,r}^2 \cdot \phi_r^2 \cdot N(\phi_r)}{180\pi^2 \cdot H_r} \qquad (4.6.1.2.2\text{-}1)$$

where $T_{wave,r}$ and H_r are the wave period in seconds and the wave height in meters respectively used in the test, and g is the gravitational acceleration in m/s^2 In equation (4.6.1.2.2-1) the wave steepness is assumed to be related to wave height and wave period by $s = 2\pi \cdot H /(g \cdot T_{wave}^2)$. The effective wave slope is assumed to be independent on ϕ_r.

.2   Alternatively it is possible to directly measure the roll excitation moment M_{exc} by means of a dynamometer. The model should be connected to the carriage by means of a guide allowing drift, sway, heave and pitch motions but fixing surge, roll and yaw. The dynamometer should measure the moment with respect to centre of gravity between model and the carriage. The dynamometer should be designed to limit the interaction between the detected force components within 2% of the resultant ones. Coefficient r is then determined as follows:

$$r = \frac{M_{exc}}{\Delta \cdot GM \cdot \pi \cdot s} \qquad (4.6.1.2.2\text{-}2)$$

4.6.1.2.3 *Third step*

The aim of this step is the prediction of the peak of roll for the steepness specified in table 4.5.1. By using the curve for $N(\phi)$ and the estimated value for r from previous steps, and by using the wave steepness s obtained from table 4.5.1, the predicted angle of roll ϕ_{1r} can be calculated by the following formula:

$$\phi_{1_r} = \sqrt{\frac{90\pi r s}{N(\phi_{1_r})}} \quad (\deg rees) \qquad (4.6.1.2.3)$$

Since this formula includes ϕ_{1r} in both its right- and left- sides, the calculation should be carried out with the following iterative procedure:

.1 ϕ_{1r} is initially assumed to be 20°;

.2   the right-hand-side of this formula is calculated;

.3   the obtained ϕ_{1r} should be substituted into the right-hand-side; and

.4   when the value of ϕ_{1r} converges to a certain value, this should be regarded as the
          final value.

4.6.2   *Alternative procedure 2: Parameter identification technique (PIT)*

The parameter identification technique (PIT) approach is outlined below, taking into account
linear and nonlinear features of the mathematical model describing the roll motion in beam
waves, with other forcing sources or roll decays. The basic structure of the method consists in the
regression of the solution (exact or approximate, analytical or numerical) of the system of
differential equations describing the time evolution of the system under analysis, containing as
unknowns the characteristic parameters (coefficients of the mathematical model adopted to
describe damping, restoring, forcing terms). The regression is considered to the experimental
values of stationary roll amplitude versus frequency for forced roll. The basic idea on which the
PIT relies is thus as follows: the solution of equation (4.6.2.1.1), for any consistent set of
parameters and different wave frequencies allows to obtain a prediction for the roll response. The
parameters of the model are modified systematically by the minimization procedure in order to
obtain the best agreement between the predictions given by the model and measured
experimental data. The "optimum" set of parameters is then obtained and used in solving
equation (4.6.2.1.1) for the steepness required by table 4.5.1 and different wave frequencies, to
obtain, finally, the peak ϕ_{1r} of the roll response curve. The angle of roll to windward due to wave
action ϕ_1 is calculated according to paragraph 4.1.

When PIT is used, at least two response curves obtained for two different wave steepness are
strongly recommended to be used.

4.6.2.1   Modelling of roll motion in beam sea and determination of model parameters

4.6.2.1.1   *Recommended model in beam sea*

The following differential equation is recommended as a suitable model for describing roll
behavior in regular beam sea:

$$\begin{cases} \ddot{\phi} + d(\dot{\phi}) + \omega_0^2 \cdot r(\phi) = \omega_0^2 \cdot \pi \cdot s \cdot \xi\left(\dfrac{\omega}{\omega_0}\right) \cdot \cos(\omega \cdot t) \\[2mm] d(\dot{\phi}) = 2\mu \cdot \dot{\phi} + \beta \cdot \dot{\phi}|\dot{\phi}| + \delta \cdot \dot{\phi}^3 \\[2mm] r(\phi) = \phi + \gamma_3 \cdot \phi^3 + \gamma_5 \cdot \phi^5 \\[2mm] \xi\left(\dfrac{\omega}{\omega_0}\right) = \alpha_0 + \alpha_1 \cdot \dfrac{\omega}{\omega_0} + \alpha_2 \cdot \left(\dfrac{\omega}{\omega_0}\right)^2 \end{cases} \qquad (4.6.2.1.1)$$

In the recommended model (4.6.2.1.1) the following parameters should, in principle, be
considered as to be determined by the PIT: $\omega_0, \mu, \beta, \delta, \gamma_3, \gamma_5, \alpha_0, \alpha_1, \alpha_2$. However, in certain cases,
some of these parameters can be considered as constant and/or equal to zero.

4.6.2.1.2   *Definition of χ^2*

4.6.2.1.2.1   From a series of experiments in beam waves according to paragraph 4.5.2 (apart from required wave steepness), a value of roll amplitude $C_{exp,ij}$ is obtained for each tested wave frequency ω_i and steepness s_j. It is recommended to determine the roll response curve for at least two different value of the wave steepness and a set of frequencies, for each wave steepness, as in paragraph 4.5.2. Given a tentative set of parameters $\{\omega_0,\mu,\beta,\delta,\gamma_3,\gamma_5,\alpha_0,\alpha_1,\alpha_2\}$, the value of roll amplitude $C_{mod,ij}$ can be obtained (by numerical integration or analytical solution) as predicted by the model in equation (4.6.2.1.1) for each tested wave frequency ω_i and steepness s_j.

4.6.2.1.2.2   The following function is used as a measure of the goodness of fit for the model:

$$\chi^2\left(\{\omega_0,\mu,\beta,\delta,\gamma_3,\gamma_5,\alpha_0,\alpha_1,\alpha_2\}\right)=\sum_{i,j}\left(C_{mod,ij}-C_{exp,ij}\right)^2 \qquad (4.6.2.1.2.2)$$

As can be seen from equation (4.6.2.1.2.2), χ^2 depends on the tentative values of the model parameters.

4.6.2.1.3   *Fitting of the model*

The scope of the PIT is to determine a set of "optimum" parameters $\{\omega_0,\mu,\beta,\delta,\gamma_3,\gamma_5,\alpha_0,\alpha_1,\alpha_2\}_{opt}$ such to minimize χ^2, that is:

$$\chi^2\left(\{\omega_0,\mu,\beta,\delta,\gamma_3,\gamma_5,\alpha_0,\alpha_1,\alpha_2\}_{opt}\right)=\min\left(\chi^2\right)$$

Any numerical or analytical minimization procedure can be used, to the satisfaction of the Administration.

4.6.2.1.4   *Calculation of roll response's peak ϕ_{1r}*

4.6.2.1.4.1   When the "optimum" set of parameters $\{\omega_0,\mu,\beta,\delta,\gamma_3,\gamma_5,\alpha_0,\alpha_1,\alpha_2\}_{opt}$ is determined by the minimization procedure, the response curve for the steepness required in table 4.5.1 can be obtained as follows.

4.6.2.1.4.2   Equation (4.6.2.1.1) is solved by means of standard numerical integration algorithms or analytical solution for different frequencies in order to obtain the roll response curve. The peak of such curve is ϕ_{1r}.

4.6.2.2   Additional comments

The framework of the methodology provided in paragraph 4.6.2.1 could be used, in principle, to obtain damping parameters from free roll decays or forced roll motion by means of roll moment generators (RMGs). Partially different modelling and/or definition of χ^2 could thus be needed and can be used to the satisfaction of the Administration.

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