The Development of a Standardized Experimental Approach to the Assessment of Ship Stability in the Frame of Weather Criterion

Gabriele Bulian (*), Alberto Francescutto(*), Andrea Serra(**) and Naoya Umeda(***)

(*) Dept. Naval Architecture, Ocean and Environmental Engineering, Trieste University, Italy, gbulian@units.it, francesc@units.it

(**) Fincantieri SpA, Design Office, Trieste, Italy, andrea.serra@fincantieri.it

(***) Dept. Naval Architecture and Ocean Engineering, Osaka university, Japan, umeda@naoe.eng.osaka-u.ac.jp

Abstract

This paper is a response to the decision of the IMO Sub-Committee on Stability, Load Lines and Fishing Vessels Stability taken at its 45th Session in 2002, concerning the revision of the Intact Stability Code, for which the possibility to conduct a direct assessment based on analytical, numerical, experimental or combined approaches should be opened aimed also at the development of other means, including scale model testing and full-scale trials, of demonstrating compliance with the requirements of any part of the future revised Code. This new trend requires the implementation of standardized procedures for experimental testing. The possibilities and difficulties offered by present experimental testing methodologies are presented on the basis of the results of a thorough experimental programme recently performed.

1 Introduction

The IMO Sub-Committee on Stability, Load Lines and Fishing Vessels Stability at its 45th Session in 2002, starting a revision of the Intact Stability Code, decided that “the scope of the revision exercise should include the preparation of instructions for the ship’s crew on matters addressed by the Code, as well as the possibility to conduct a direct assessment based on analytical, numerical, experimental or combined approaches and agreed that due attention should be given to dangerous phenomena, such as parametric rolling” and that “other means of demonstrating compliance with the requirements of any part of the future revised Code might be accepted, provided that the method chosen be shown to provide an equivalent level of safety. Such methods might include: mathematical simulation of dynamic behaviour, scale model testing and full-scale trials” [1,2].

On the other hand, the revision process started with the analysis of the applicability of present Weather Criterion to modern ship typologies and in particular to the very small [3] and to the large passenger ships [4]. Preliminary results, based on theoretical and experimental approaches show that the effective wave slope coefficient “r” cannot be greater than unity [5,7] and this result was, on a provisional basis, incorporated in the revision together with a more realistic behaviour of the wave steepness curve as a function of roll period [1]. Further on, also one of the roll damping parameters, X_1, was proposed for a reduction in the high values B/T range [8].

It was at this point observed that Weather Criterion was intended to be an approach to ship stability safety to be applied in its entirety, so that it cannot be subjected to partial modifications without risking an unpredictable variation of the implied level of safety.

To this end, an international research is in progress, aimed at the following complementary aspects:

- —analysis of the implied level of safety of the original formulation for different ship typologies [9,10];
- —development of procedures for experimental evaluation of the most critical parts of the Weather Criterion calculation procedure, with particular attention to the roll-back angle and to the wind heeling moment [11,13];
- —development of probability based approaches which, although preserving the global features of present Weather Criterion, take into account in a proper way the stochastic nature of wind and waves [14,15].

These studies will in any case be of importance to the newly adopted philosophy which is oriented to "identifying the possibility of developing a physical description of phenomena and scenarios as a means to improve upon a prescriptive approach for developing performance-based criteria".

The development of reliable procedures for experimental evaluation of the relevant parameters to be used in the stability assessment under Weather Criterion as substitutive to the original formulas is currently under development in cooperation between Italian and Japanese delegations at IMO, also taking into account the experience gained in the European Project Safenvship [7]. The main results are the subject of this paper.

The purpose of these guidelines is to provide IMO member organisations, intending to undertake intact stability model tests in waves in the frame of the interim measures for Weather Criterion, with a sound basis for carrying out these tests and in particular to ensure uniformity in model tests for the determination of the angle of roll, ϕ_1 as an alternative to the formula shown in 3.2.2.1 of the Intact Stability Code as amended in [16]:

$$\phi_1 = 109 \cdot k \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s} \qquad (1)$$

The fundamental objectives of these tests are to quantify the behaviour of a ship in moderate sea conditions and to determine reliable values for relevant quantities of IMO Weather Criterion.

These guidelines are based on those presented to the 23rd ITTC, upgraded based on experience gained from Safenvship Project. Although they concern experiments to be used as alternative route for Intact Stability Assessment they do not concern directly "extreme motions and capsizing".

2 The Need of Updating the Existing Assessment Procedure and Related Problems

Several problems have been identified in the existing procedure for Stability Assessment in the frame of the Intact Stability Weather Criterion [3,4]:

overestimation of r (effective wave slope coefficient) connected with ships having large values of OG/T;

truncation of the damping factor X_1 to low values of B/T;

overestimation of the wave steepness to be assumed in the calculations for ships having high rolling period (20 s or more);

frequent underestimation of roll period through the adopted formula;

unclear basis for the 30% roll amplitude reduction for "stochasticity".

In spite of all these drawbacks, the formula for the calculation of the roll-back angle ϕ_1 is often surprisingly good. This means that an incorrect separation of effects (damping, forcing, restoring, stochasticity) was done on experimental results of ship rolling quite reliable for the ship typologies existing at the time of the original formulation of the weather criterion [17]. At the same time, the large residual value of the wave steepness assumed to hold at very large roll periods, which is the factor having the most important effect limiting the vertical centre of gravity on modern ship typologies like the large passenger vessels, is connected with scarce knowledge of the phenomenon and should absolutely be updated (this point was indeed put in the agenda for SLF46 [1]).

The results of the Safenvship Project [7] allow now a better quantification of these problems. At the same time, an extensive campaign of tests on scale models highlighted a series of problems connected with experimental tests:

scale effects, especially for ship models without bilge keels;

modelling problems connected with the structure of damping (quadratic only following Bertin, or linear-plus-quadratic/cubic) and with the separability of different contributions;

modelling of restoring, which was assumed linear;

modelling of excitation, which was assumed frequency-independent in the original formulation;

impossibility to test in waves for large full scale roll periods;

differences observed in the estimation of roll damping made with different methods (roll decay in calm water, roll decay after forced test conducted with RMG-Roll Moment Generator, forced roll tests in waves, forced roll tests by means of RMG);

difficulty in defining appropriate tests to measure the reduction due to the irregularity of the waves (stochasticity factor);

definition of the roll-back angle (roll response at the natural frequency, maximum roll response at constant steepness);

dependence of parameters on the tested wave steepness.

The authors understand that the current Weather Criterion has some difficulties for new ship types that did not exist when the Weather Criterion was developed. This is mainly because some coefficients are requested to be estimated with empirical formulae or tables. On the other hand, it is not so easy to revise these empirical methods by keeping the safety level of the conventional ships. Therefore, it is desirable to keep the framework of the weather criterion for experimentally determining coefficients as much as possible but extend applicability to new ship types. At the same time, the action of environment, i.e. wind and waves, and the consideration of the dead ship condition are considered in any case of great importance in the medium term with a look to develop different, modular, approaches of which the mentioned is just one of the possible scenarios.

In the following, therefore, after some general requirements for model set-up, we present two methodologies for the analysis of experimental results of roll motion in addition to direct measurement of roll-back angle. The first one is more traditional and allows the estimation of roll-back angle through the relevant parameters to compute it by using the Intact Stability formula, whereas the second one is an open one that can be used to estimate the relevant parameters of any mathematical model adopted for the description of roll motion (linear or nonlinear and, provided the relevant degrees of freedom are measured, even coupled with other motions or related to stochastic aspects of the environmental action).

3 Requirements for Model Set-Up and Test Execution

3.1 Model Set-up

<u>Construction</u>

The model should be built to geometrically scaled up to the upper weather deck including forecastle and bulwark and be sufficiently rigid with a smooth finish. To avoid scale effect on roll damping, its over all length should be at least 2.5 metres for a ship with bilge keels or with hard chine. For other ships, their overall length should be at least [4] metres. Appendages relating to roll motion, such as bilge keels, should be fitted as they are in full scale but dynamically-controlled devices, such as fin stabilizers, if they can be accounted for, should be fixed. Superstructures that do not submerge during the tests described below can be omitted.

<u>Ballasting</u>

The model should be ballasted to the specified displacement and trim angle. Weights should be adjusted to achieve the position of the centre of gravity and radius of gyration in transverse direction corresponding to these data on the subject ship. Inclining test and roll test with this model should be carried out to confirm that the metacentric height ($\overline{GM}$) and the natural roll period in water (T_ϕ) of the model are equal to those of the subject ship within $\pm 2\%$. It is recommended to carry out the tests described below in a range of values of T_ϕ and $\overline{GM}$. Then it is possible to interpolate the results for the case of the exact set of T_ϕ and $\overline{GM}$, which can only be available after the hull construction.

Roll period T_ϕ and natural roll frequency ω_0 have to correspond to the scaled value of the full scale roll period (respectively natural frequency) in water. The approximate formula suggested in the original Weather Criterion has to be used with particular care and only when more accurate knowledge is not available.

<u>Model Basin and Instrumentation</u>

An indoor model basin having a wave maker, a wave absorbing beach and a towing carriage should be used. The depth of the basin should be larger than one half the maximum wavelength used in the tests. The breadth of the basin should be larger than the sum of the model over all length and 2 metres. The wave maker should be capable of operating generating stable and periodic waves for the range used in the test described below with digitally stored signals, which can guarantee repeatability of wave generation.

The instrumentation should be provided to measure wave elevation and roll angle as time histories with a sampling rate of at least 20 points per roll period. For measuring the wave elevation, the disturbance due to the probe should be minimum. For measuring the roll angle, optical sensors, a gyroscope or equivalent should be used. The period T_ϕ should be inside the effective frequency range of a wave probe and a roll sensor.

3.2 Typologies of tests

3.2.1 Tests in regular waves

Tests in regular waves can be used to obtain directly the "regular waves" roll-back angle ϕ_{1r} or quantities relevant to its evaluation (damping factors k, X_1, X_2 and effective wave slope coefficient r). Stationary roll motion amplitude has to be measured in a sufficient number of points with frequencies around the natural roll frequency to provide adequate data for a description of the roll resonance curve at constant wave steepness. If ω_0 (rad / s) is the natural roll frequency of small amplitude free rolling, 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], taking additional measurements in proximity of the response peak, especially if this is badly described due to peak bending caused by righting arm nonlinearity.

When the roll period is too large for a realistic wave generation, internal exciter systems, based on gyroscopic effects can be used (see below).

It is to be noticed that, usually, the peak of the roll response curve does not occur at the roll natural frequency ω_0, but at a frequency that is

- lower for softening $\overline{GZ}$ curve and...
- higher for hardening $\overline{GZ}$ curves.

Care should be taken in having a good description of the response curve in case of large nonlinear effects.

3.2.2 Wave steepness of regular waves

Table 1: Wave steepness as a function of the roll natural period. All data are given in full scale. For practical use, nonlinearity of water waves should be taken into account.

Roll Period T_ϕ [s]	Steepness s	Wave frequency ω [rad/s]	Wave frequency f [Hz]	Wave length λ [m]	Wave height H [m]
<6	0.100				
6	0.100	1.047	0.167	56.2	5.621
7	0.098	0.898	0.143	76.5	7.497
8	0.093	0.785	0.125	99.9	9.293
12	0.065	0.524	0.083	224.8	14.614
14	0.053	0.449	0.071	306.0	16.219
16	0.044	0.393	0.063	399.7	17.587
18	0.038	0.349	0.056	505.9	19.223
20	0.032	0.314	0.050	624.5	19.985
22	0.028	0.286	0.045	755.7	21.159
24	0.025	0.262	0.042	899.3	22.483
26	0.023	0.242	0.038	1055.4	24.275
28	0.021	0.224	0.036	1224.1	25.705
30	0.020	0.209	0.033	1405.2	28.104
>30	0.020	*(Ad Interim - SLF45 - Final Report)*			

The wave steepness s has to be selected from the Table 1 [to be defined: specification has to be made of the s values for $T > 30\,s$ pending as per decisions 6.18, 6.19 taken at SLF45/14]. An additional value is also recommended to have a more complete description of the roll motion modelling.

As it will be explained below, the "effective" roll-back angle ϕ_1 to be used in the present version of Weather Criterion can be obtained from ϕ_{1r} by considering a [30%] reduction for stochasticity. [Alternatively, the stochasticity reduction factor can be obtained by means of appropriate tests in irregular waves with significant wave height to be defined.]

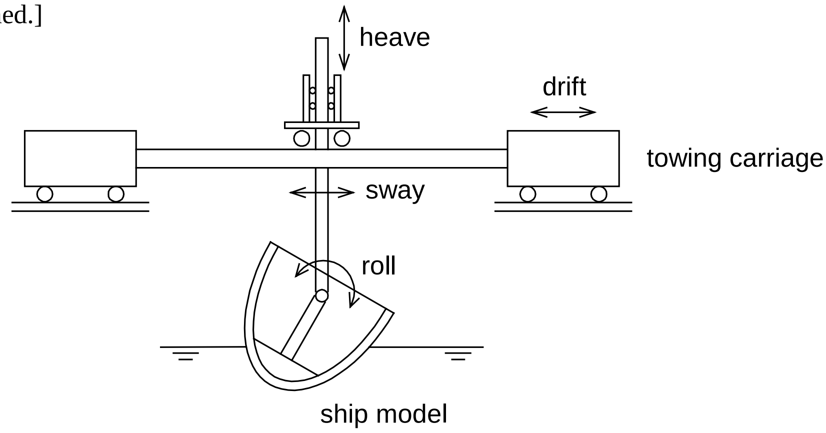

Figure 1 An example of the guide for roll test in beam waves.

In the model basin, the ship model should be positioned to be normal to the direction of the waves. The heading angle of the model is fixed with a guide attached to the towing carriage by keeping the sway-heave-roll motion free from restraints as shown in Figure 1. Here the towing carriage should trace the drift motion of the model and draught, $\overline{GM}$ and T should be adjusted with this guide. Alternatively, especially for large models, the use of ropes to restrain the model in yaw while allowing drift and sway, is allowed. Then the periodic waves defined above should be generated and the roll motion of the model should be measured. When the measured (single) roll amplitude converges to a certain value, this value should be regarded as the steady roll amplitude, ϕ_r (deg). If the steady roll amplitude cannot be determined, the wave steepness should be reduced. Even after the steady roll amplitude is found, multiple reflection between the model and the wave maker could change the roll amplitude. In such occasion, the measurement after the reflection should be ignored. Availability of time histories will allow an easy checking of the correct time window to be analysed. Indications on optimal measuring time interval are given in Ref. [12].

3.2.3 Wave measurements

Without the ship model, a periodic wave should be generated in the model basin. Here the signal for the wave maker should be sinusoidal and its period should be equal to the measured roll natural period of the model, T_ϕ. The wave elevation should be measured at a wave probe at more than three locations along the length of the basin, spanning the drift range of the model. When the measured (double) amplitude of the wave elevation converges to a certain value, this value should be regarded as the steady wave height, H (metres). Variations in the wave height and wave period should be within $\pm 5\%$ among the different measured positions but with the same signal. The wave length, λ, can be calculated as follows:

$$\lambda = \frac{gT_\phi^2}{2\pi} \tag{2}$$

where g indicates the gravitational acceleration of 9.81 (m/s^2). For generic wave tests, to be used in the procedures of *reconstruction* of ϕ_{1r}, the wave steepness $s = H/\lambda$ should be selected in the range 1/50-1/20. For direct measurement of ϕ_{1r}, the wave steepness should correspond to the tabular value as a function of the estimated roll period (Table 1).

3.2.5 Roll Decay Test

The roll decay test should be carried out initially to obtain/adjust the natural roll period T_ϕ .

To obtain the roll damping characteristics of the ship, a series of roll decay tests of the scale model in calm water could be carried out. The model is initially inclined up to a certain heel angle. This initial angle should be more than about 25 deg. If the mean roll angle of the initial angle and the next peak angle is smaller than 20 deg, the initial angle should be increased to obtain the mean angle of 20 deg 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 at initial stage. 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. More than four tests with different initial angles are required at least. If the roll damping is very large, the number of the 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 provided when releasing and continue until the model has reached rolling angles smaller than 0.5 degrees. This eventually requires that the length of the basin should be sufficiently large.

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

3.2.6 Forced roll by means of gyroscopic roll moment generator

Aim of this test is the estimation of the roll damping coefficients of the hull. The RMG should be of gyroscopic type. It should have been calibrated before performing the experiments in a range of spin rates and tumbling/rotating frequencies containing those tested for the model. However, before performing the forced roll tests, the moment generated by the RMG should be recorded with the model outside water and fixed. Spin rates to be tested should be those that will be used in the forced roll experiments. The tumbling/rotating frequency to be checked could be limited to the natural frequency of the model. Time histories of the generated moment should be saved and provided. A comparison between a numerical/analytical prediction and the measured generated moment should be performed, if possible, in order to disclose possible problems. For each test the recorded time histories should be provided. Moreover, aimed at calibration checking, the following data should be provided:

- Spin rate of each gyro
- Tumbling/rotating frequency

4 Data Analysis

Experimental results have to be properly analysed to obtain the relevant parameters.

Roll-back angle can be directly obtained only by means of tests in regular waves.

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 roll-back is permitted only when they are all evaluated through direct methods.

While the evaluation of the effective wave slope coefficient r is not sensitive to scale effects, so that even small models can be employed, particular care has to be used when analysing damping coefficients and the effect of appendages [7].

4.1 Direct measurement of roll-back angle

If the tank length and wave generator power allows, the roll-back angle can be obtained through a series of tests in regular beam waves at constant wave steepness selected following Table. 1. The drawing of the roll response curve versus frequency, using tentatively the frequencies indicated in §3.2.1, allows an easy determination of the maximum roll response at resonance (some problem can arise, connected with the selection of the proper steepness for highly nonlinear restoring curves) as it was done in [5-7]. Comparison with the results of Eq. 1 is easy. However, this method could result in non-harmonic roll motions or capsizing because of nonlinear restoring. If such phenomenon is observed, other procedures should be used.

4.2 Three step procedure

This is the typical procedure adopted up to now, consisting in the sequential evaluation of:

- roll damping (Bertin coefficient N) from roll decay;
- effective wave slope coefficient r from forced roll, once known the roll damping;

- the roll-back angle ϕ_1 from Eq. 1 allowing a 30% reduction for stochasticity.

First step: Assuming that the consecutive peaks of roll angle during roll decay are $\phi_1, \phi_2, ...$ (in deg), the mean roll angle $\phi_{m_i} = (\phi_i + \phi_{i-1})/2$ and the difference $\delta\phi_i = \phi_i - \phi_{i-1}$ between successive peaks of roll in the record are measured and be tabulated. Bertin's extinction coefficient, N, as a function of ϕ_m is obtained by $N_i = N(\phi_{m_i}) = \delta\phi_i / (\phi_{m_i})^2$. It should be noted that N depends on roll amplitude. Experiment has to be conducted with great care and tests starting with large amplitude repeated because usually there is a strong reduction of amplitude during first roll period.

Second step: When the peak ϕ_r of the roll response curve is obtained following the procedure reported in §3.2.1, the effective wave slope coefficient, r, can be determined as follows:

$$r = \frac{\phi_r^2 N(\phi = \phi_r)}{90\pi(H/\lambda)} \tag{3}$$

This coefficient is assumed to be independent on ϕ_r.

Alternatively, limiting our attention to the determination of factor r alone, it is possible to directly measure the roll exciting moment by a dynamometer with which the model and the towing carriage is connected with a guide for allowing the sway, heave and pitch motions of the model but fixing the surge, roll and yaw motions of the model. Here the dynamometer should be designed to limit the interaction between the detected force components within [2%] of the resultant ones.

Third step: By using the measured values of $N(\phi)$ and r as well as the wave steepness s obtained from the Table 3.2.2.4-4 of the Code (as eventually amended), the angle of roll ϕ_{1r}, in regular waves can be calculated by the following formula:

$$\phi_{1r}\,(\text{deg}) = \sqrt{\frac{90\pi rs}{N(\phi_{1r})}} \tag{4}$$

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

.1 ϕ_{1r} is initially assumed to be 20 deg;
.2 the right-hand-side of this formula is calculated;
.3 the obtained ϕ_{1r} should be substituted into the right-hand-side;
.4 if the value of ϕ_{1r} converges to a certain value, this should be regarded as the value for the weather criterion.

Finally the angle of roll ϕ_{1r} (in irregular waves) in 3.2.2.1 of the Code [18] is evaluated by setting:

$\phi_1(\text{deg}) = 0.7 \cdot \phi_{1r}(\text{deg})$

Here the value of 0.7 indicates the effect of randomness in ocean waves.

In this procedure, while the effect of nonlinear roll damping is taken into account, that of nonlinear roll restoring is ignored. Some existing procedures with nonlinear roll damping and nonlinear roll restoring taken into account could be incorporated here through sufficient practical experience in the near future. However, because at the peak the limiting effect is due to the damping, the assumption of linear restoring leads to an incorrect estimation of the frequency at which the roll peak occurs, but it does not largely influence the value of the predicted roll peak.

4.3 Parameter Identification Technique (PIT)

The use of a Parameter Identification Technique is recommended, taking into account all the linear and nonlinear features of the mathematical model describing the roll motion in beam waves. This allows obtaining the parameters of any mathematical model and can be used to provide values and models for future approaches. 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), to the:

- experimental values of stationary roll amplitude versus frequency in the case of forced roll (either in waves or with RMG);
- time history in the case of roll decay.

The method is fast and powerful, it allows an efficient separation of effects and is modular, so that it can be widely used *to test the goodness of a mathematical model by measuring the goodness of fit.*

The application to a campaign of experimental tests, on a series of hulls obtained by systematic variation of relevant form coefficients ($C_B, B/T, OG/T, ...$) allows to investigate the dependence of the parameters on the coefficients and thus develop simple algorithms to be used at design stage.

In case this technique is used for a regulatory purpose, more detailed guidelines are indispensable for selecting types of mathematical model of ship motions.

5 Conclusions

A methodology for the experimental testing alternative to the application of Eq. 1 to assess ship stability in the frame of Intact Stability Weather Criterion has been presented. Different methodologies for data analysis are discussed, aimed at Weather Criterion in its present form and beyond. The problem is still open as regards the evaluation of the stochasticity factor. We hope to have soon the results of a systematic series of test together with a deeper knowledge of the theory of wave generation by wind which was used in the original formulation to approach this problem in a more rational way.

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