Systematic Experimental Tests for the IMO Weather Criterion Requirements and Further Development Towards a Probabilistic Intact Stability Approach

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ABSTRACT

A systematic wind tunnel and model basin tests campaign within SAFENVSHIP PROJECT, was performed at the Vienna Model Basin. A series of 12 model scale 1/100 and 2 model scale 1/40 and 1/35 of Large Passenger Vessels (LPS) have been studied. The wind tunnel tests were performed with upright and heeled ship. The tests in model basin concerned roll decay, forced roll tests in regular beam waves and with roll moment generator. The project was developed with the aim of:

- studying the roll motion of large passenger ships (LPS: Lbp>200 m)
- identifying the relevant parameters of the mathematical modelling of roll motion;
- obtaining experimentally the roll-back angle ϕ_1 (we follow in this paper the international standard notation instead of θ_1) in beam waves;
- obtaining the relevant parameters needed for the computation of the roll back angle;
- obtaining experimentally the relevant parameters needed for the computation of the effect of constant beam wind;
- developing a procedure for the execution of the experiments described above;
- develop an approach to the action of beam wind and waves taking into account the statistical distribution of both and compute the survival probability of a given ship.

In this paper, preliminary results of this project are presented.

1. Tested ship models

Large scale (λ=35 for C6075 and λ=40 for C6050) of two LPS and 12 small scale (λ=100) models of LPS (4 basic ship with three systematic variations of relevant parameters B/T and C_B each) have been tested (or are under testing) in 3 loading conditions each. The small scale models include the large scale typologies, so that scale effects will be clearly identified (this part is in progress). The tests have been conducted at Vienna Ship Model Basin SVA.
The main dimensions of the tested ships are given in Table. 1.

Model	C6050	C6075	C5989	C6052
Lbp (m)	242.2	254	256	205.54
B (m)	36-33.51	33.65-31.32	33.43-31.12	33.65-31.32
d (m)	8-8.60	7.48-8.03	7.43-7.98	7.48-8.03
B/d	4.5-3.9			
C_B	0.67	0.65	0.626	0.598
T (s)	14.45-36.44	12.91-44.94	14.08-43.03	15.34-36.84

Table.1. Main dimensions of the scale 1/100 tested models.

The relevant data ranges of the tested models are given in Fig. 1 compared with the range on which original Weather Criterion (in present format) was developed.
Due to the impossibility of generating the required waves in a towing tank, the large scale models were tested by means of a gyro roll exciter (Roll Moment Generator - RMG). The small scale models were tested both in regular beam waves and with a small RMG. The RMGs have been specially designed for these tests.
The tests in regular waves were conducted at three wave steepness values: 1/100, 1/50 and the value supplied by present IMO Weather Criterion at the known value of roll period (from a reliable finite element calculation performed on the complete ship structure taking into account all the weights in the considered loading condition, while the added mass was evaluated on the base of a Seakeeping Code).

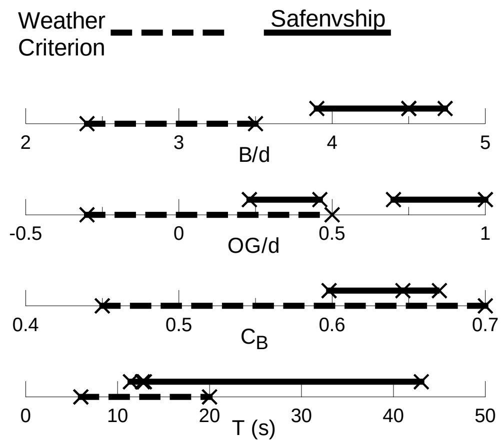

Fig. 1. Values of relevant parameters of tested ships as compared with the ranges used for the same parameters in the original formulation of Weather Criterion

All models were tested in roll decay, the large models with and without bilge keels and/or appendages at large scale, and with and without bilge keels for some small models. In a second phase, tests will be conducted on small models in irregular waves. In the following the results will be reported synthetically.

2. Parameter identification procedure to analyze the experimental data

A Parameter Identification Procedure (PIT) was employed to obtain the coefficients of a nonlinear mathematical model of roll motion in regular beam waves. The general model employed was a single degree of freedom:

$$I'\ddot{\phi} + D(\phi, \dot{\phi}) + R(\phi) = F(t)$$

with obvious meaning of the terms. By dividing by the virtual moment of inertia, the following equation is obtained:

$$\ddot{\phi} + d(\phi, \dot{\phi}) + \omega_0^2 \frac{\overline{GZ}(\phi)}{\overline{GM}} = f(t)$$

The following representations were assumed for the different contributions:

- Damping $d(\phi, \dot{\phi}) = 2\mu\dot{\phi} + \beta|\dot{\phi}|\dot{\phi} + \delta\dot{\phi}^3$
- Restoring $\omega_0^2\phi + \alpha_3\phi^3 + \alpha_5\phi^5 + ...$
- Forcing $\pi s_w \omega_0^2 \xi(\omega)\cos(\omega t)$ in the case of beam waves. A different formulation was used for the RMG.

The frequency function $\xi(\omega)$ accounts for the effectiveness of the waves in dependence of the frequency (or better of the ratio wavelength/ship breadth). Typical expressions used were:

$$\xi(\omega) = \alpha_0 - \alpha_2 \frac{\omega^2}{\omega_0^2} \quad , \quad \xi(\omega) = \alpha_0 / \left(1 + \alpha_2 \frac{\omega^2}{\omega_0^2}\right) \quad \text{or} \quad \xi(\omega) = \alpha_0 + \alpha_1 \frac{\omega}{\omega_0}$$

In the case of waves, it is: $r = \xi(\omega_0)$, whereas this parameter cannot be obtained from the tests with RMG.

The coefficients indicated in the above equations were obtained by fitting the mathematical roll motion model to the experimental data (with the exception of the nonlinear restoring coefficients which in some cases were obtained from the hydrostatic calculations).

3. Results and discussion

3.1 Fitting capability

The single degree of freedom mathematical model exhibited good representation capability in all the tested cases, although the high values of the vertical centre of gravity KG with respect to ship draft would indicate a great importance of the coupling roll/sway. Moreover, the same set of coefficients allowed to fit all the steepness values tested for the same loading condition, as for example in Fig. 2:

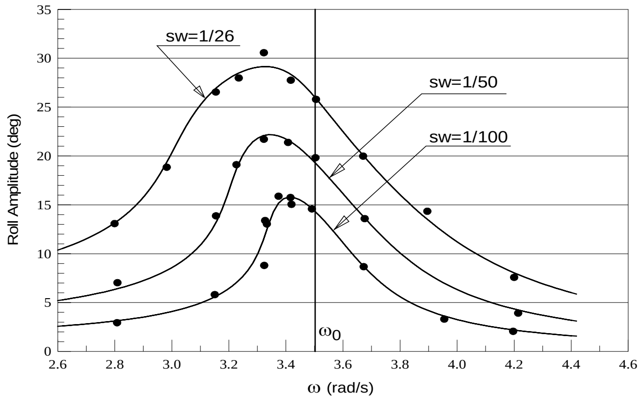

Fig. 2. Experimental results and fitting with mathematical model for model C6075 (small scale) tested in three wave steepness (sw) conditions.

The mathematical model implied in the present Weather Criterion (purely quadratic damping, excitation independent on frequency and irrelevance of nonlinear restoring) does not look very effective in simulating the experimental results due to the nonlinearity of restoring moment, the composition of damping and of the excitation. Anyway, an equivalent quadratic damping and an equivalent r factor can be obtained easily from any fitting.

When used as fitting parameters, the coefficients of GZ allowed to reconstruct reasonably the hydrostatic results. It was not possible to decide on experimental basis if the ship was rolling with a restoring arm closer to the fix- or free-trim condition since the two curves go very close each other in the tested range.

3.2 The factor "r" from the forced rolling tests in beam waves

It is now a clear conclusion that the IMO formula for the evaluation of factor r is not effective in these cases, as it was already discussed in connection with the change accepted in SLF 45 (point 6.18 in document SLF45/14). This is evidenced in Fig. 3 where the obtained values are represented by the diamond points:

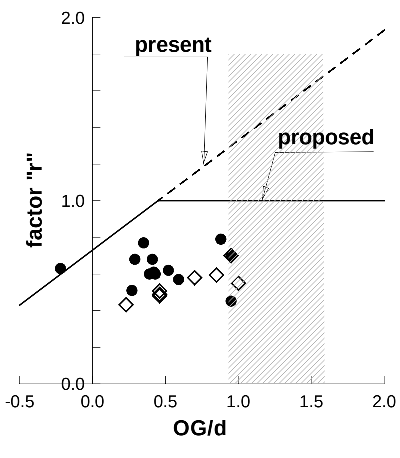

Fig. 3 – Effective wave slope coefficient r as in the original formulation, in the version as approved at SLF45. For comparison sake, the values estimated from present experiments are reported together with some previous values.

3.3 The damping coefficients X_1 and X_2

The damping was identified from the forced rolling in waves on small models, from roll decays and forced rolling with RMG both in small and large models. As it was correctly pointed out, the coefficients in present formulation of

Weather Criterion are strictly interrelated. The damping coefficient, the product $X_1 \cdot X_2$ in the absence of bilge keels, also results consistently increased (reduced damping) in the experiments. The research is in progress to identify reliable values of this product, of the individual coefficients, of the scale effects in damping evaluation and on the effect of the testing mode.

It appears that forced rolling tests (either in waves or with RMG) are much more reliable than roll decay tests and should therefore be recommended. There is, indeed some scatter in the extrapolation of roll damping using roll damping coefficients obtained from roll decays starting from small to moderate inclinations. On the other hand it is not easy to perform roll decays starting from very large angles and in these cases half roll amplitude or more is lost in the first swing which, depending on the technique used to incline the model, usually is the less reliable part of the data.

3.4 The effect of the bilge keels

This was obtained by means of roll decay experiments and forced roll experiment on the two large scale models with and without the bilge keels. The bilge keels area coefficient is $\frac{A_k \cdot 100}{L \cdot B} = 1.38$. Nevertheless the roll peak reduction was much more consistent than foreseeable from the present Weather Criterion Tables (0.96 multiplicative factor corresponding to a roll peak reduction of 4%), as evident from the RMG forced roll tests plotted in Fig. 4, where the comparison of forced rolling with two different values of RMG setting is reported. The same values for the RMG spinning rate have been used in both conditions with and without bilge keels):

There are other indications in literature [1] to support these results, connected with the extremely high position of centre of gravity.

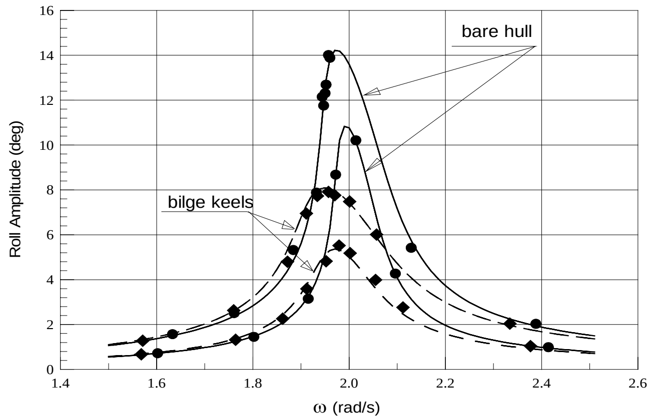

Fig. 4 Comparison of roll amplitude as a function of the excitation frequency for model C6075 (large scale) with and without bilge keels. Tests made in calm water with RMG.

4. Comparison of different testing procedures and different scale of models by means of simulation based on coefficients estimated from experiments

To compare the different results, some data have to be extrapolated to larger excitation intensity, due to the fact that the RMG for large models could not develop a roll moment sufficient to simulate moderate to severe conditions. The problem was solved by simulations based on the coefficients of the mathematical model obtained through experiments via the parameter identification procedure. In view of the results reported in Fig. 2, where it is clearly seen that the same set of coefficients can fit the three different wave excitation cases, it is expected that the adopted procedure is sufficiently reliable for the comparison exercise.

4.1 Comparison RMG-Waves in Bare Hull condition

As shown in the following Fig. 5 and Fig. 6, the tests executed in waves or with RMG on small scale models without bilge keels give comparable results.

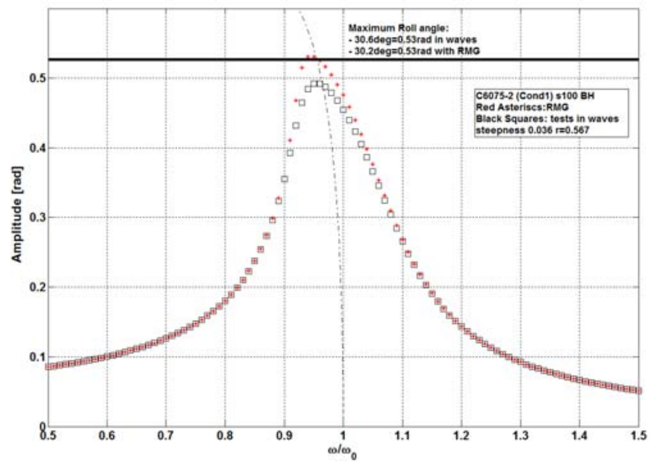

Fig. 5. Comparison between the tests made with RMG (stars) and in waves (squares) for model C6075 small without BK. As one can see, the agreement between the forecasts obtained with the two models is more than acceptable. The tests conducted with RMG however do not allow to obtain factor "r", which was obtained from tests in waves. Horizontal solid line indicates the maximum tested roll amplitude, i.e. the range within which the results do not constitute an extrapolation.

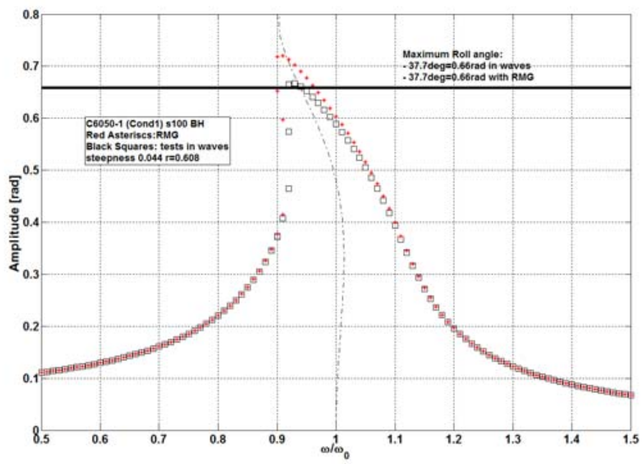

Fig. 6. Comparison between the tests made with RMG (stars) and in waves (squares) for model C6050 small without BK. As one can see, the agreement between the forecasts obtained with the two models is more than acceptable. The tests conducted with RMG however do not allow to obtain factor "r", which was obtained from tests in waves. Horizontal solid line indicates the maximum tested roll amplitude, i.e. the range within which the results do not constitute an extrapolation.

4.2 Comparison RMG-Waves with Bilge Keels

As shown in the following Fig. 7 and Fig. 8, also with bilge keels the tests executed on small scale models give comparable results.

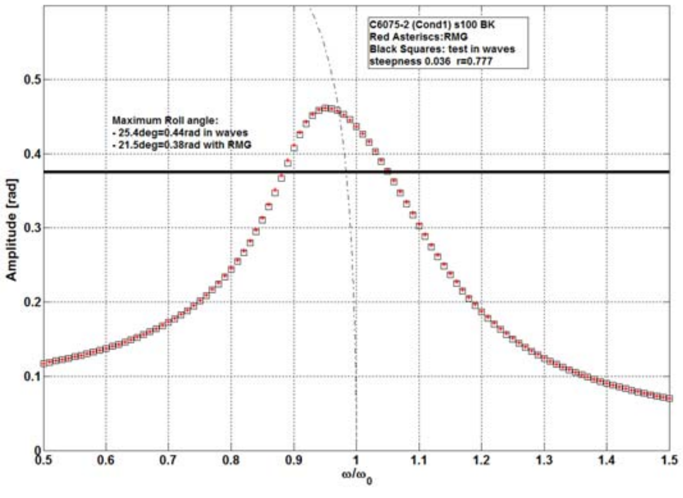

Fig. 7. Comparison between the tests made with RMG (stars) and in waves (squares) for model C6075 small with BK. As one can see, the agreement between the forecasts obtained with the two models is excellent. The tests conducted with RMG however do not allow to obtain factor "r", which was obtained from tests in waves. Horizontal solid line indicates the maximum tested roll amplitude, i.e. the range within which the results do not constitute an extrapolation.

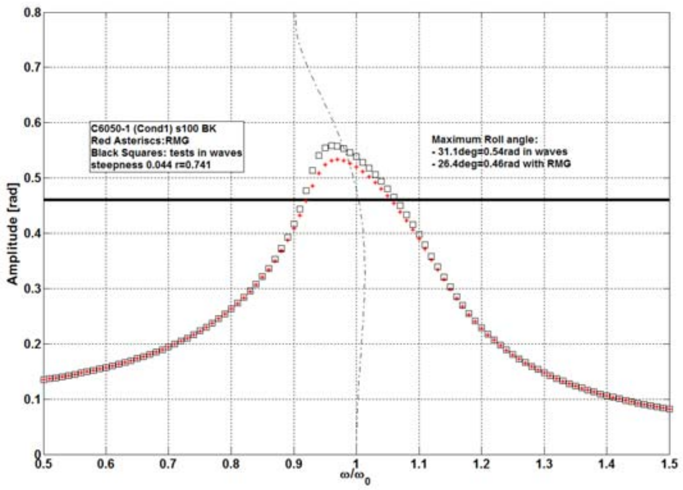

Fig. 8. Comparison between the tests made with RMG (stars) and in waves (squares) for model C6050 small with BK. As one can see, the agreement between the forecasts obtained with the two models is very good. The tests conducted with RMG however do not allow to obtain factor "r", which was obtained from tests in waves. Horizontal solid line indicates the maximum tested roll amplitude, i.e. the range within which the results do not constitute an extrapolation.

4.3 Scale Effect in Bare Hull Condition

As shown in the following Fig. 9 and Fig. 10, there is a scale effect on damping in bare hull condition which at first glance seemed to be quite large [IMO]. A more accurate analysis reveled however that the difference was overestimated in the regression. The small model gives an overestimation of roll damping effect. As a consequence, experiments aimed at measuring roll damping cannot be reliably executed on small models.

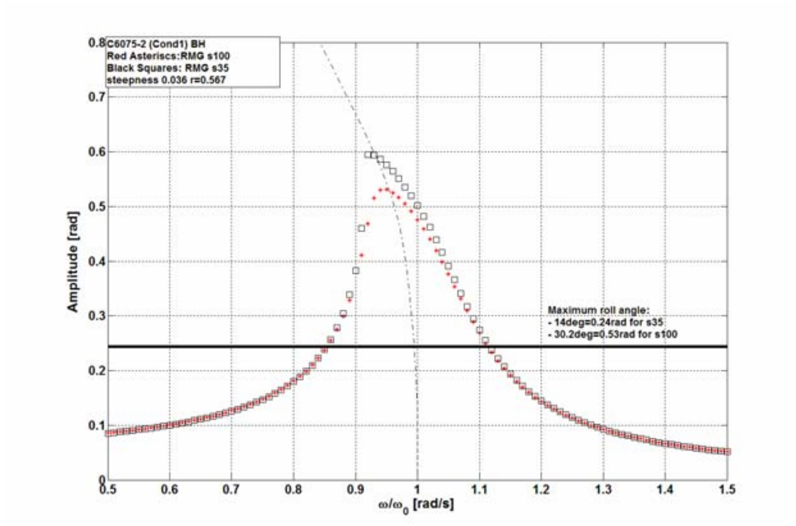

Fig. 9. Comparison between the tests made with RMG on small model (stars) and large model (squares) for model C6075 without BK. As one can see, the agreement between the forecasts obtained with the two models is not good. Horizontal solid line indicates the the maximum tested roll amplitude, i.e. the range within which the results do not constitute an extrapolation.

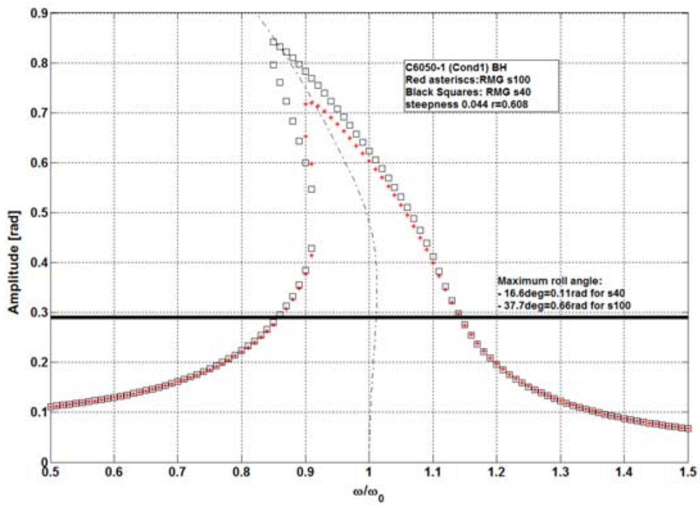

Fig. 10. Comparison between the tests made with RMG on small model (stars) and large model (squares) for model C6050 without BK. As one can see, the agreement between the forecasts obtained with the two models is not good. Horizontal solid line indicates the maximum tested roll amplitude, i.e. the range within which the results do not constitute an extrapolation.

4.4 Scale effect with Bilge Keels

As shown in the following Fig. 11 and Fig. 12, there is an acceptable scale effect on roll damping with bilge keels. Tests in waves with small models with bilge keels are thus reliable both for roll damping and effective wave slope estimation.

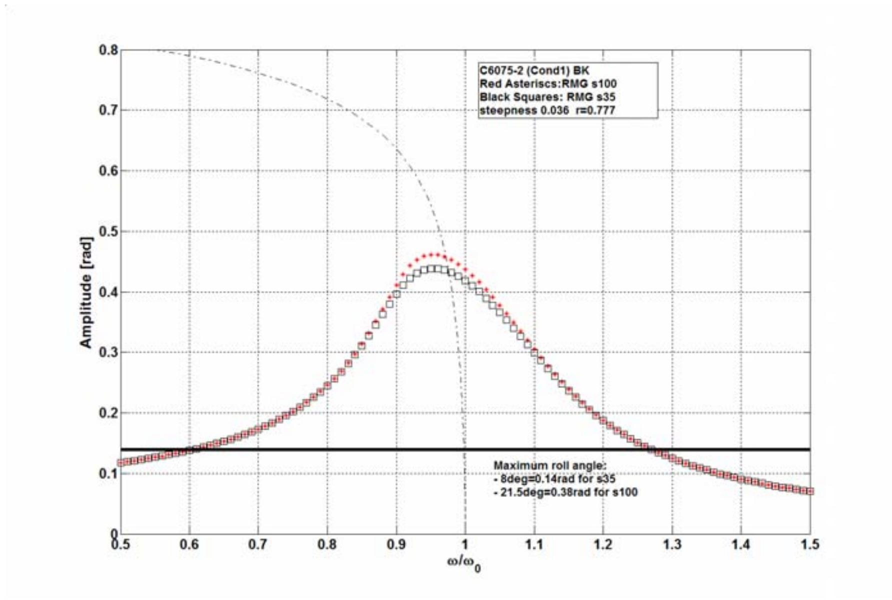

Fig. 11. Comparison between the tests made with RMG on small model (stars) and large model (squares) for model C6075 with BK. As one can see, the agreement between the forecasts obtained with the two models is excellent. Horizontal solid line indicates the maximum tested roll amplitude, i.e. the range within which the results do not constitute an extrapolation.

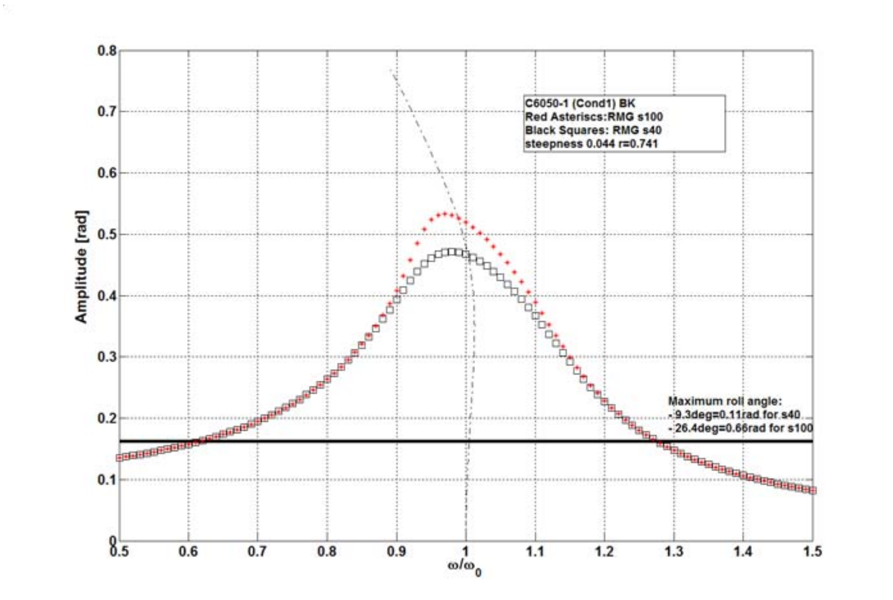

Fig. 12. Comparison between the tests made with RMG on small model (stars) and large model (squares) for model C6050 with BK. As one can see, the agreement between the forecasts obtained with the two models is acceptable. Horizontal solid line indicates the maximum tested roll amplitude, i.e. the range within which the results do not constitute an extrapolation. The difference between the two curves could in this case be consequence of non perfect nonlinear fitting.

4.5 Global capability of IMO formula for roll motion amplitude

As shown in the following Fig. 13 and Fig. 14, although the individual terms are wrongly estimated by present IMO Weather Criterion, the global capability of the formula for the evaluation of roll motion amplitude for this typology of ships, with bilge keels and using the true roll period, is acceptable.

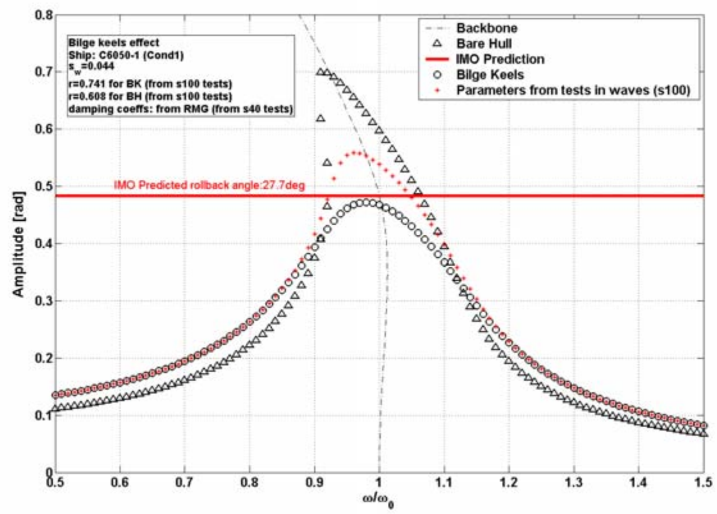

Fig. 13. Comparison of predictions made on experimental basis with computation based on present IMO formula [11] for roll motion amplitude for model C6050 in waves. Same nominal wave steepness (factor s) used.

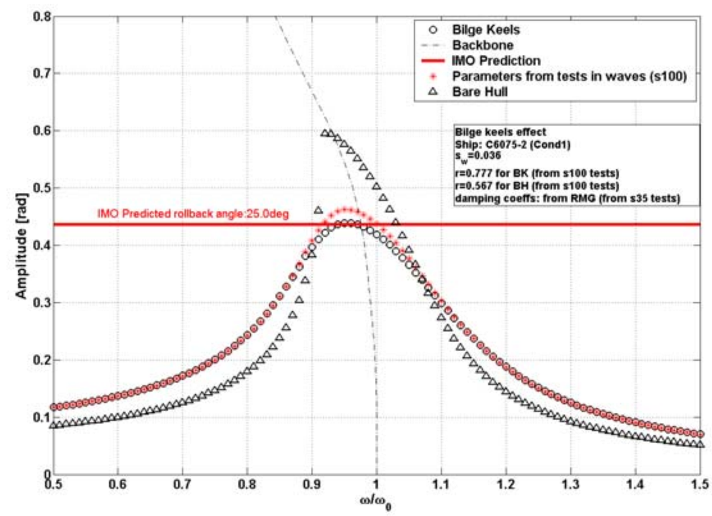

Fig. 14. Comparison of predictions made on experimental basis with computation based on present IMO formula for roll motion amplitude for model C6075 in waves. Same nominal wave steepness (factor s) used.

Further details on experimental results from Safenvship Project, including Wind Tunnel tests, can be found in Ref. [5-10].

5. Developments In Progress: a "Stochastic" modular approach to the action of wind and waves

Present "Weather Criterion" in IMO Intact Stability Code is a rule intended to prevent extreme roll motions of the ship due to the combined effect of wind and waves. Although the idea is physically sound, many of the assumptions on which the criterion is based are questionable and are being criticized during the discussions for the revision of the "Intact Stability Code" at IMO. The parameters used for the prediction of the rollback angle seem to be not realistic for certain types of ships when not fitted with bilge keels or when fitted with bilge keels of limited size. Regarding the effect of wind, the gustiness factor assumed by present rules does not take into account the actual dimension of the ship and imposes an heeling moment under gust action which is 50% larger than the mean heeling moment due to constant wind speed (assumed to be about 26m/s). The environment assumed by the present criterion is basically a deterministic one, with some correction for taking into account its actual stochastic nature. Moreover, the methodology used by the Criterion in the inherent estimation of the maximum roll angle after gust is not physical, because it assumes that, during the first swing after the gust, both the effects of waves and damping disappear, this leading to an energy balance approach. The Criterion is of the pass/fail type and no ranking is possible among different design proposal on the basis of this criterion.

Because of all these matters, the criterion is very difficult to be modified in limited parts even using experimental results: this means that the criterion should be used as a "black box", without possibilities for taking into account some important features of the ship under analysis. The determination of the "level of safety" inherent the criterion is also very difficult.

In order to overcome these problems, a methodology is under development for taking into account the combined effect of wind and waves in a realistic stochastic environment [12]. The aim of the proposed simplified methodology is to give an estimation of the roll motion of a ship at zero speed under the action of beam waves and wind. The ship is supposed restrained in yaw, in such a way that the encounter angle with waves and wind is constant and equal to 90deg, the speed of the ship is supposed to be zero (dead ship condition). The rolling ship is described as a 1-DOF system. Explicit coupling with other degrees of freedom is neglected. Forcing due to waves is calculated using the sea wave slope spectrum from which, by means of a transfer function (that in this context we can call "hydrodynamic admittance"), the spectrum of the roll moment due to waves is estimated. The effect of wind is split in two parts: the action of the mean wind speed and that of the wind speed fluctuations (the gustiness). The mean wind speed is used to calculate the mean heeling moment due to wind. In this case the hydrodynamic reaction due to steady drift motion is supposed to be fully developed, and thus an heeling lever for the wind force equal to the vertical distance between the hydrodynamic centre of pressure and the aerodynamic centre of pressure is used. When the effect of gustiness is of concern, due to the relatively fast time scale associated to this process, the hydrodynamic reaction due to sway is assumed to not have sufficient time to develop and is thus neglected, leading to an heeling lever for the wind force fluctuation equal to the vertical distance between the aerodynamic centre of pressure and the centre of mass of the ship. The effects of the spatial correlation of the wind turbulence field and of the departure from the quasi-steady theory are taken into account by means of the so called "aerodynamic admittance function". The effect of the instantaneous heeling angle on the wind moment is neglected in the analytical approach, but can be easily implemented in a time domain simulation, although in this work a constant wind heeling lever has been used in the numerical simulations. The damping moment takes into account linear, quadratic and cubic terms in the roll velocity. To tackle the problem using an approximate spectral technique instead of a Monte Carlo time domain approach, the roll motion equation is linearized in the vicinity of the static heeling angle due to mean wind speed using a simplified statistical linearization technique that takes into account the effect of nonlinear damping and nonlinear restoring first derivative.

As final result from the application of the proposed method, the mean roll angle and the spectrum of the roll motion (assumed to be a gaussian process) are obtained. The probability of capsize (named here "capsize index" due the approximate nature of the methodology and the large number of simplifying assumptions) is estimated on the bases of the assumed gaussianity of the roll process and using the hypothesis that capsize is a Poisson process whose principal parameter (the mean time to capsize) is calculated as the inverse of the up-crossing frequency of the capsize angle. The capsize angle, depending on the particular case, could be the second intercept between the mean wind heeling lever and the $\overline{GZ}$ curve, or an arbitrary limiting angle, such as, e.g., the deck submergence angle or the progressive flooding angle. In Fig. a diagram is shown to give a picture of the different components of the methodology. As can be seen from the picture, the approach is modular, this means that each component (environmental condition, transfer function for the roll moment, damping coefficients, etc.) can be easily updated and tuned on the particular ship under analysis, without changing the final analytical or time domain analysis. This peculiarity, combined with the relatively easy approximate analytical solution to the problem and the few data needed for the implementation, makes the methodology suitable for an analysis in the early stage of the design process and, thus, makes the method, in principle, suitable from a regulatory point of view.

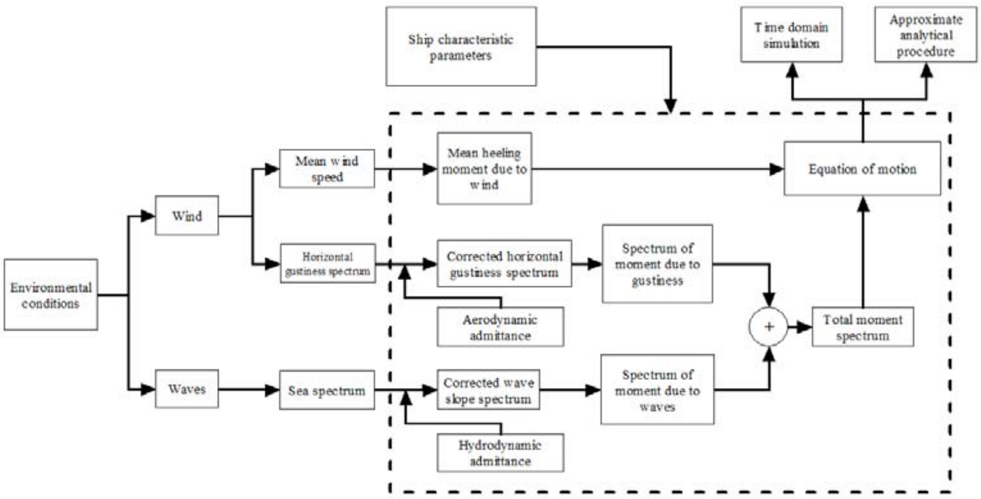

Fig. 15. Scheme of the methodology.

6. Conclusions

1. The reduction effect due to bilge keels (factor “k”) is much larger than presently accounted in IMO Weather Criterion;
2. The tests conducted both with RMG and in waves on small models, with and without bilge keels, give comparable results;
3. The scale effect in the absence of bilge keels is non negligible in some cases;
4. The scale effect in the tests with bilge keels is negligible, so that small models can be reliably employed;
5. The tests conducted with RMG do not provide information on factor “r”;
6. The roll decay tests have to be used with caution when large amplitude roll damping is sought for;
7. The effective wave slope coefficient (factor “r”) estimated from experiments is much lower than that computed on the basis of present Weather Criterion formulae;
8. In spite of the badly incorrect evaluation of individual pieces, the present IMO formula for the evaluation of roll motion amplitude is acceptable for the tested ship models with bilge keels and using the true roll period;
9. Roll period appears to be roughly underestimated at large rolling periods. Consequently the wave steepness “s” is overestimated;
10. Wave steepness from the table “s” versus “T” appears still to be roughly overestimated at large roll periods.

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