WEATHER CRITERION – QUESTIONS AND ANSWERS

Dracos Vassalos[1], Andrzej Jasionowski[2], Jakub Cichowicz[1]
[1] The Ship Stability Research Centre, Department of Naval Architecture and Marine Engineering,
Universities of Glasgow and Strathclyde,
[2] Safety At Sea Ltd

Abstract

Following the reopening of the Intact Stability Code by the International Maritime Organisation (IMO), a number of questions are being raised concerning the practical applicability of Resolution A.562 known as the *Weather Criterion* on modern passenger ships and answers sought on a way forward by way of either re-examining and suitably tuning the criterion to reflect current (and emerging) ship particulars or adopting merging approaches/philosophies to assessing ship safety, using first-principles performance assessment tools. This paper attempts to provide pertinent answers to these questions.

1. INTRODUCTION

Notwithstanding minor changes as a result of global warming, the weather and its effect on ships has been present since the beginning of time and ships and, in the main, undesirable. Amazingly, however, the effect of waves on ship safety was considered explicitly for the first time as part of Resolution 14 of the 1995 IMO SOLAS Convention whilst prior to this various attempts to account for this effect culminated to considering explicitly only the effect of beam wind in what is known as the Weather Criterion adopted by the IMO Assembly Resolution A.562 in 1985. Earlier attempts to consider environmental influences on ship safety followed normally a statistical approach of dubious nature, reflected at the Rahola-inspired intact stability criteria of A.167 of 1969. The reasons for this pace of development and for the current state of affairs are many, but mostly deriving from the complex socio-political, techno-economic and emotional nature of safety, giving rise to inertia in devising and implementing meaningful criteria commensurate with state-of-the-art. However, recent well-published disasters of Ro-Ro/passenger ships (Herald of Free Enterprise 1987, Scandinavian Star 1990, Estonia 1994, Express Samina 2000), linked to intolerable consequences with respect to human life, triggered a chain of events that raised safety awareness among the whole maritime community and the wider public alike. Even more recent civil catastrophes of cosmic proportion (the September 11 2001 events in the USA) have brought all safety-driving forces (political, socio-economic, and technological) in alignment, pushing safety issues to the forefront of societal problems. This progressively acquired realisation that the marine industry is a “risk industry” is catching up with the maritime profession, necessitating changes in people’s attitude and the adoption of holistic risk-based approaches to maritime safety capable of striking a balance between all the many facets of safety cost-effectively and throughout the life cycle of the vessel.

Coupling these to rapidly changing trends and to intensifying competition particularly with respect to knowledge-intensive safety critical vessels (e.g. cruise liners) has closed the gap between knowledge and application on ship safety to the point that, rather worryingly, front-end research tools and findings are used to build and sustain competitive advantage. In this respect, vigilance and caution on the use of immature new technology to assessing safety at sea must now be exercised to its maximum.

With this in mind, this paper describes yet another visit on the issue of weather criteria using all the arsenal of tools currently at the disposal of a Naval Architect, to scrutinise the simplifying assumptions inherent in these criteria and to use the derived results as a basis to make suitable recommendations on a way forward.

WEATHER CRITERION BY MODERN PREDICTION TECHNIQUES

2.1. IMO weather criterion

Basics of the criterion

The stability standard known as Weather Criterion, adopted by IMO as Resolution A.562, is based on a number of simplifying assumptions as described next:

a) The ship attains a stationary angle of heel θ_0 due to side wind loading represented by a lever l_{w1}, which is not dependent on the heel angle and is the result of a 26 m/s wind, [2].
b) Around this angle the ship is assumed to perform resonant rolling motion due to side wave action, as a result of which it reaches a momentary maximum angle θ_1 on the weather side.
c) As at this position the ship is most vulnerable in terms of weather-side excitations, it is further assumed that the ship is acted upon by a gust wind represented by a lever $l_{w2} = 1.5 \cdot l_{w1}$. This is translated into an $\sqrt{1.5} = 1.2247$ increase of the wind velocity, assumed to affect the ship for a short period of time but at least equal with half of the natural period under the assumption of resonant ship response.
d) The requirement for stability is formulated as follows: should the ship roll freely from the off-equilibrium position θ_1 with zero angular velocity, the limiting angle θ_2 to the lee-side calculated on the basis of the condition $b > a$ (Figure 1) should not be exceeded during the ensuing half-cycle. This limiting angle is either the angle where significant openings are down-flooded, the vanishing angle θ_v, or the angle of 50 deg, which can be assumed as an explicit safety limit, whichever of the three is the lowest. Expressed as an energy balance, the work done by the wind excitation as the ship rolls from the weather-side to the lee-side should not exceed the potential energy at the limiting angle θ_2.

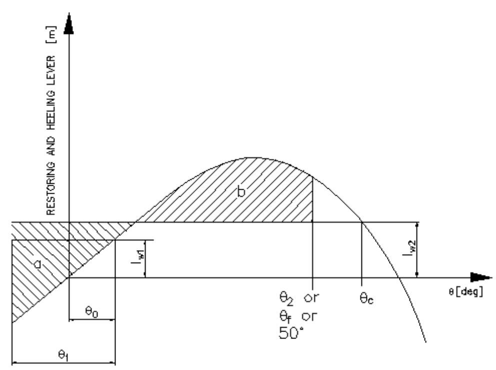

Figure 1: Weather Criterion

The heeling lever l_{w1} is calculated from the following formula:

$$l_{w1} = \frac{P \cdot A \cdot z}{1000 \cdot g \cdot \Delta} \qquad (1)$$

Where:

P	steady wind pressure P = 504 N/m^2
A	projected lateral area of the ship and deck cargo above the waterline [m^2]
z	vertical displacement between centre of the A area and centre of underwater lateral area (or approximately to a point at one half the draught) [m]
Δ	ship displacement [t]
g	gravitational acceleration 9.81 [m/s^2]

The maximum roll angle should be calculated from the following formulae:

$$\theta_1 = 109 \cdot k \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s} \qquad (2)$$

where k is a coefficient dependent on the relative area of bilge keels, X_1 depends on the beam to draught ratio, X_2 is a function of the block coefficient C_B, and s is a function of the roll period T_φ, which can in turn be estimated from the expression

$$T_\varphi = \frac{2 \cdot C \cdot B}{\sqrt{GM_T}} \qquad (3)$$

where:

$$C = 0.373 + 0.023 \cdot \frac{B}{T} - 0.043 \cdot \frac{L_w}{100}$$

T	ship draught
L_w	length of waterline
B	moulded breadth
GM_T	metacentric height corrected for free surface effect

$$r = 0.73 \pm 0.6 \cdot \frac{OG}{T}$$

OG	distance between the centre of gravity and waterline ("+" if CG is above the waterline and "-" if CG is below)

Problems with the criterion

Deriving from he simplifying assumptions described in the foregoing, the following problems could be listed with particular emphasis on large vessels (the list is not intended to be exhaustive):

- The choice of wave direction is the least "risky"
- The selected values of the various parameters of the weather criterion are inappropriate for modern (large) passenger ships [14], the key reason for IMO to embark into establishing an IS Code Working Group to tune these parameters accordingly as an interim measure, prior to considering alternative criteria or approaches in the longer term.
- The dynamic model considered describes only one degree of freedom, it considers explicitly only potential effects (it could be argued that the calculation of θ_1 takes explicitly into account the effect of waves and roll damping, even though the effect of waves on the restoring moment and the effect of wind bias in these calculations are altogether ignored).
- Additional "weather" effects such as wave and wind drift and unsteady wind gusting as well as "peculiar" motion effects such as parametric rolling and oscillatory yawing in beam seas have not received any attenytion or even a mention.

Typical result with modern (large) passenger ships

The results of application of the weather criterion to a sample vessel of a cruise liner, shown in Figure 2 with main particulars given in Table 1, are presented in . Clearly the vessel fails to satisfy the weather criterion.

Table 1: Main particulars of the sample vessel

Length between perpendiculars	Lpp [m]	272.0
Length of waterline	Lw [m]	281.23
Displacement	D [t]	41350
Breadth	B [m]	32.2
Draught	T [m]	7.5
Block coefficient	C_B [-]	0.613
Lateral area above waterline	A_{LAW} [m2]	10197.5
Lateral area below waterline	A_{LBW} [m2]	2095.4
Area of appendages (bilge keels)	A_{APP} [m2]	163.2
Transverse Metacentric Height	GM_T [m]	2.132

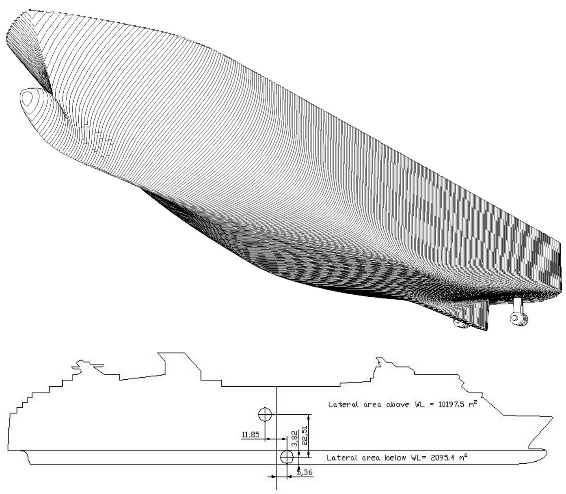

Figure 2: Sample vessel

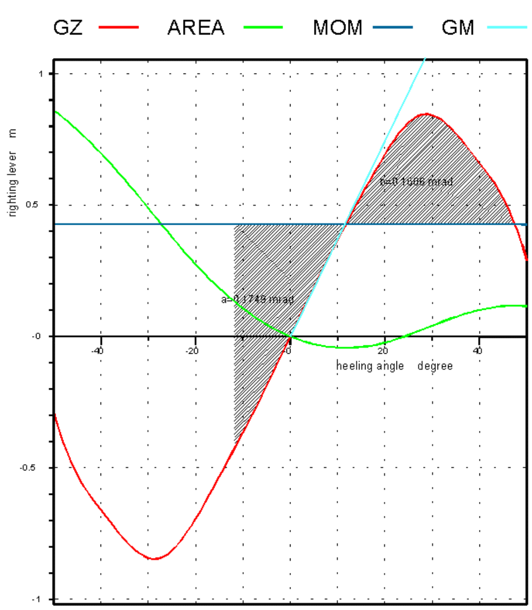

Figure 3: Weather criterion for the sample vessel.

l_{w1}	0.285 m
l_{w2}	0.427 m
θ_0	8.1 deg
θ_1	19.4 deg
θ_2	47 deg
T_φ	15.35 s (0.409 rad/s)

2.2. Scrutiny of weather criterion by state-of-the-art-simulations of ship dynamics

To test the ship stability in the context of the above prescriptive criterion, a series of tests have been performed with the use of state–of-the-art numerical simulation tools, capable of predicting the "complete" dynamic behaviour of a ship in random beam wind and waves.

Mathematical model

Equations describing damaged ship behaviour are derived from fundamental motion principles: the law of conservation of linear and angular momentum, shown below as two vectors of a set of 6 scalar equations for linear and angular motions:

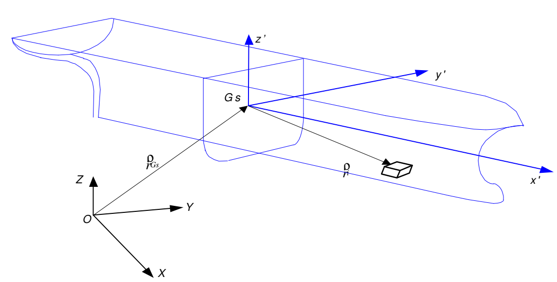

Figure 5: Coordinate system fixed to the centre of gravity of the intact vessel

$$(M_s)\cdot\frac{d}{dt}\vec{v}'_s+\vec{\omega}'\times(M_s)\cdot\vec{v}'_s=\vec{F}'$$
$$(I'_s)\cdot\frac{d}{dt}\vec{\omega}'+\vec{\omega}'\times[(I'_s)\cdot\vec{\omega}']=\vec{M}'_s \quad (4)$$

The right hand side of the equation, $\vec{M}'_s$ and $\vec{F}$ represent all the external forces and moments acting on the vessel expressed in a body-fixed system of reference, G_sxyz, located at the ship centre of mass. These forces/moments are predicted with conventional by today's standards Naval Architecture methods, [5]. The Froude-Krylov and restoring forces and moments are integrated up to the instantaneous wave elevation, the radiation and diffraction forces and moments are derived from linear potential flow theory and expressed in time domain using convolution and spectral techniques, [4], respectively. The second order drift forces, wind and current effects and other forces of viscous origin are also catered for, at present based on parametric formulations.

$$\vec{F},\vec{M}'_s=\vec{F}_{Gravity}+\vec{F}_{F-K,\mathrm{Re}storing}+\vec{F}_{Radiation}+\vec{F}_{Diffraction}+\vec{F}_{Manouvring,Rudder}+\vec{F}_{Drift,Current,\mathrm{Wind},Viscous}$$

where the various forces/moments are computed by:

$\vec{F}_{\mathrm{Re}storing}$ $\vec{F}_{F-K}$	direct integration of static pressures on actual geometry
$\vec{F}_{Radiation}$	convolution techniques
$\vec{F}_{Diffraction}$	spectral techniques
$\vec{F}_{Manoeuvring,Rudder}$	empirical formulae
$\vec{F}_{Drift,Current,\mathrm{Wind},Viscous}$	empirical formulae

A correction for viscous effects on roll motion is applied based on an established empirical method proposed in [6], where the viscous damping moment is divided into several components: friction, eddy shedding, lift, wave and bilge keel, and the total force is obtained by a superposition of all these components. However, the proposed method, representing the non-linear viscous damping as an equivalent linear coefficient at the roll natural frequency, remains a function of roll amplitude, which cannot be known *a priori* and hence not suitable for application to time-domain simulation in random seas. In this respect, an engineering approximation has been proposed in [7], whereby a discrete piece-wise constant treatment of the linearised coefficient is used with the coefficient evaluated at the wave spectrum peak frequency and for an amplitude corresponding to the amplitude of the last half-roll cycle. In this approach the viscous roll damping will vary with time, constantly adjusting to the current roll amplitude.

The relevant forces and moments exerted on the ship by wind excitation (acting along EX^E axis, see Figure 5Figure 5Figure) have been evaluated based on [1] and [8], with e.g. the roll moment derived as shown by equation (5):

$$F_{\varphi}=l_w\cdot\frac{1}{2}\cdot C_{wind}\cdot\rho_{air}\cdot(V_w(t))^2\cdot A \quad (5)$$

where:

$l_w=1.5\cdot z\cdot\left(0.3+0.7\cdot\cos^2(\varphi)\right)$ and

C_{wind} adjusted so as to match the wind heeling lever in (1).

Turbulent wind velocity time series are commonly decomposed into a mean speed value and random fluctuations (turbulence) around it as in (6) below (see discussion in §1.1). In this study a Davenport wind spectrum is used as shown in (7) next:

$$V_w(t)=\overline{V}_w+\sum_{i=0}^{N-1}\sqrt{2\cdot S_w(\omega_i)\cdot d\omega_i}\cdot\cos(\omega_i\cdot t+\sigma_i) \quad (6)$$

$$S_w(\omega) = 4 \cdot K \cdot \frac{\overline{V}_w^2}{\omega} \cdot \frac{X_D^2}{\left(1 + X_D^2\right)^{\frac{4}{3}}} \qquad (7)$$

$$X_D = 600 \cdot \frac{\omega}{\pi \cdot \overline{V}_w}$$

$K = 0.003$

σ_i random phase angles, $0 - 2 \cdot \pi$

$\overline{V}_w = 26$ m/s, mean wind speed at 10m above the sea level

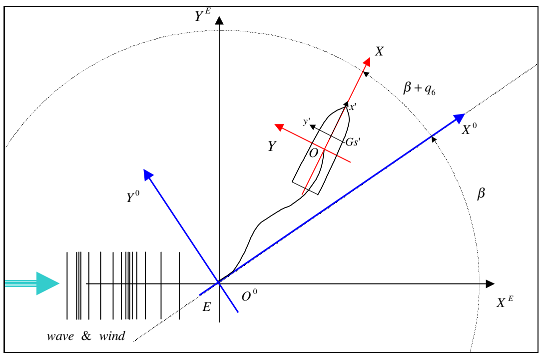

Figure 6: Conventions used for environment description [Coordinate systems: inertial earth fixed $EX^EY^EZ^E$, inertial initial $O^0X^0Y^0Z^0$, inertial moving with mean ship speed OXYZ, and non-inertial body-fixed Gsx'y 'z']

After re-arranging the whole system into a matrix form as a set of twelve differential equations of the first order, it is then solved for position in space of the centre of gravity of the intact ship $\vec{r}_{Gs} = \int \vec{v}_s \cdot dt$ and three rotations through a 4^{th} order Runge-Kutta-Feldberg integration scheme with variable step size.

Results of numerical simulations

As mentioned above, a series of numerical simulations were undertaken to systematically analyse the assumptions underlying the weather criterion. In particular the following objectives were targeted as of primary interest:

- To estimate the likelihood of a ship rolling around her equilibrium at θ_0, with angles exceeding the value θ_1, assumption (b) of §1.1
- To estimate the likelihood of wind gust events leading to wind heeling levers in excess of 50% above the average wind heeling lever and of duration half the vessel roll natural period, assumption (c) of §1.1
- To estimate the likelihood of ship response with potential capsize as a result of combined wind and waves excitation, assumption (d) of §1.1

In this respect, the sample vessel shown in Figure 2, was subjected to numerical simulations for a range of scenarios as described below, using the mathematical model described in §0.

The environment was considered using the combined effect of unsteady wind and corresponding random waves. The wind conditions are described by the Davenport wind-gust velocity variance spectrum (7). The sea state is modelled by the JONSWAP wave amplitude variance spectrum, with significant wave height of Hs=11m, deriving from the ITTC recommend relationship between wind speed (26m/s) and sea state, [13]. Both spectra are illustrated in Figure 7.

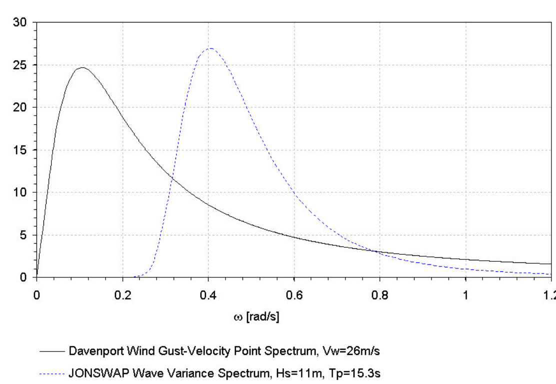

Figure 7: Variance spectra of wind gust-velocity and wave amplitude

The ship loading was assumed to be such as to match the natural period of approximately

15.3s, as estimated by (3). The relevant roll frequency response curve is shown in Figure 8. This represents the worst combination of wave excitation and ship loading from the point of view of vessel response in a random wave environment, in accordance with the Weather Criterion.

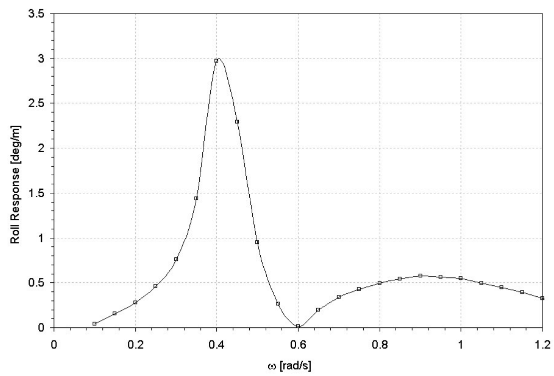

Figure 8: Sample vessel roll response curve

The sample time series of wind speed with the corresponding wind heeling lever, obtained from models (6) and (5), respectively, are shown from Figure 9 to Figure 11. The startling feature of the simulated heeling lever, emphasised in Figure 11, is the extremely high resultant wind excitation in excess of the vessel maximum restoring. More discussion on the likelihood of occurrence of such events is undertaken in §1.1 below.

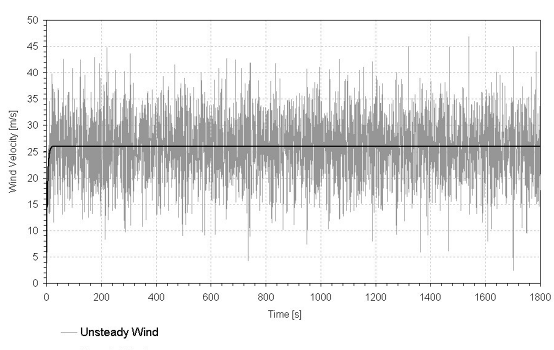

Figure 9: Time realisation of unsteady wind velocity

A number of hypothetical scenarios were simulated using a 1-DOF mathematical representation of vessel roll to assess qualitatively the vessel response under excitation of: (a) steady wind only; (b) unsteady wind without waves; (c) steady wind with co-linear random waves; (d) unsteady wind with random waves, as shown in Figure 12 to Figure 14, respectively.

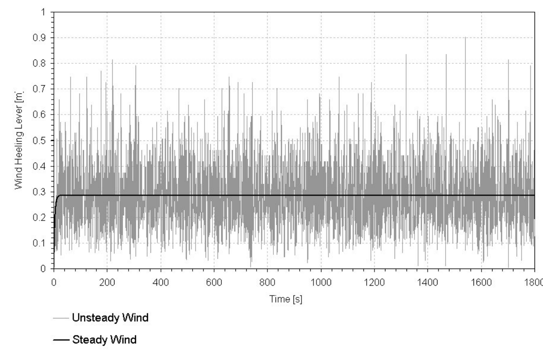

Figure 10: Time realisation of the heeling lever due to unsteady wind excitation

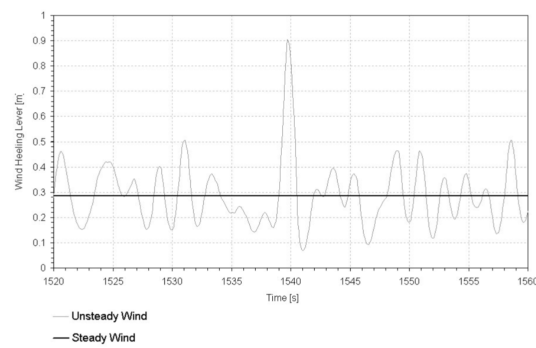

Figure 11: Time realisation of the heeling lever due to unsteady wind excitation (stretching a time segment of Figure 10)

It becomes clear from Figure 12 that despite the momentarily very high wind excitations, the net effect is of rather limited influence on roll response. This is likely a result of the rather short duration of the wind gusting, as shown in Figure 11, exciting the vessel away from resonance, and hence leading to small roll response.

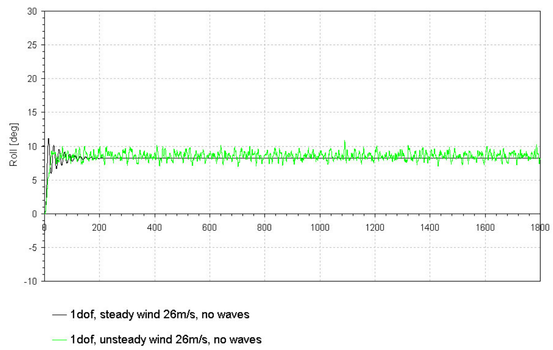

Figure 12: Time realisation of sample vessel roll response due to steady and unsteady wind excitation [1-DOF model]

The vessel roll response as a result of wave action is also rather moderate, as shown in Figure 13, with significant roll amplitude reaching approximately 6 deg. On first sight, this result contradicts the assumptions underlying the estimates of θ_1 in the weather criterion, in that it is highly unlikely for the roll angle to reach 19.4deg (estimate of θ_1) as a result of wave actions only. Closer examination, as Figure 14 demonstrates, shows that the combined wind and waves effect, which represents better the "weather", is likely to lead to much larger roll response (significant roll amplitudes ~12deg). It would appear therefore that the underlying assumption (b) of the weather criterion can be justified. It is only a question of level of likelihood. As pointed out by Rachmanin in his discussion of [15] the choice of θ_1 is based on a roll amplitude of 2% probability of exceedence whilst Yamagata's choice for θ_1 is 70% of the resonant roll amplitude in regular waves. These issues are further discussed in the context of the underlying statistics of extreme behaviour discussed in §1.1.

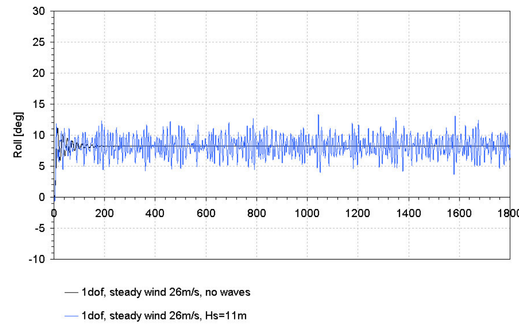

Figure 13: Time realisation of the sample vessel roll response due to steady wind and random wave excitation [1-DOF model]

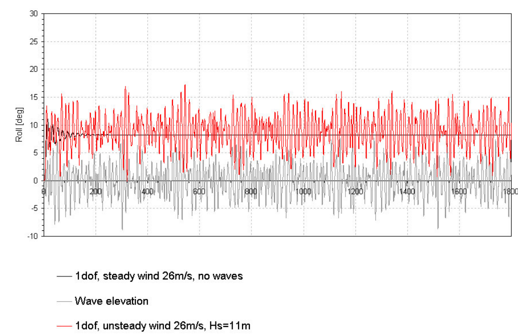

Figure 14: Time realisation of the sample vessel roll response due to unsteady wind and random wave excitation [1-DOF model]

Furthermore, the need to use additional degrees of freedom in calculating the response of the vessel even in beam seas is highlighted in Figure 15 and Figure 16. Significant roll reaches ~17deg in both cases, a combined effect of drift, coupling of roll with sway-heave (and yaw), and accounting now for non-linear wave excitation by direct wave pressure integration up to the instantaneous free surface.

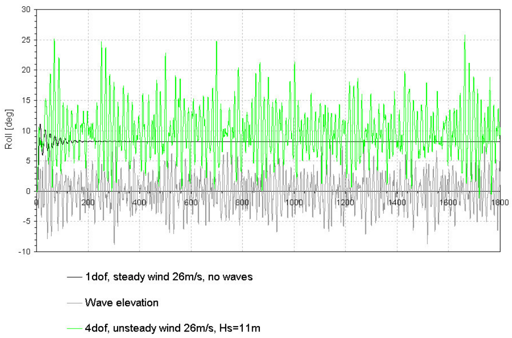

Figure 15: Time realisation of sample vessel roll response due to unsteady wind and random wave excitation [4-DOF model: sway-heave-roll-pitch]

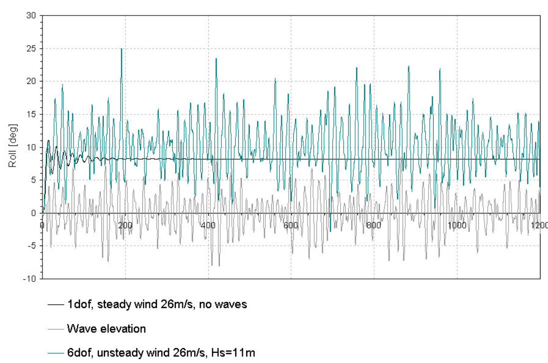

Figure 16: Time realisation of sample vessel roll response due to unsteady wind and random wave excitation [6-DOF model]

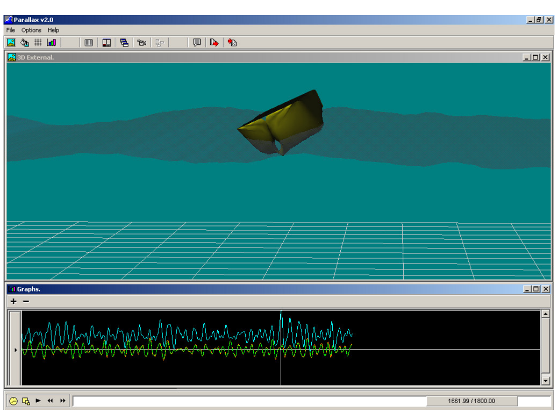

Figure 17: An animated display of the output of the numerical predictions of the sample vessel response

2.3. Deductions from the wind turbulence process

The wind in the atmospheric boundary layer is known to be distinctively turbulent and non-stationary, [11]. As a consequence, the wind speed varies rather randomly on many different time scales. These time scales range from long-term variations (years) to very short ones (minutes down to less than a second). The latter are commonly considered to correspond to small-scale (micro-scale) turbulence. These small-scale fluctuations are superimposed onto the mean velocity varying on daily or even larger scales. This distinction between a mean flow and superimposed intermittent small-scale turbulence with high probability of large velocity fluctuations (gusts for atmospheric winds) is justified by the existence of a spectral gap, shown in Figure 18, which means that there is only little wind speed variation on time scales between about 10 minutes and 10 hours. It is on this reasoning that model (6) is based.

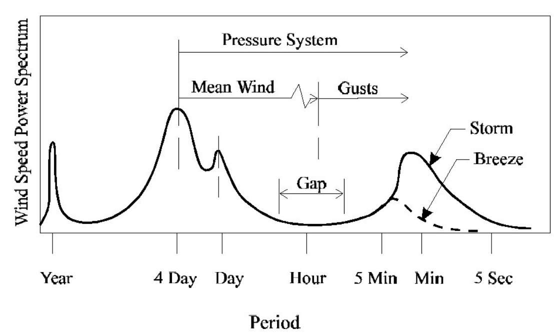

Figure 18: Distribution of wind fluctuations with period

The atmospheric turbulence is generally considered a stationary Gaussian random process, [12]. The assumption that turbulence is a Gaussian random process appears warranted by the approximately Gaussian character of the turbulent velocity fluctuations. The assumption of stationarity implies that the statistical characteristics of turbulence are invariant, necessitating consideration of a process in a given physical place over only limited time. In this respect, tt is suggested here, that the statistical characteristics of the stationary Gaussian random process, such as the joint probability density function of amplitude and period of gust velocity excursions, can be assessed using the method proposed by Ochi, [9]:

$$f(a,\tau)=\frac{\sqrt{2\cdot\pi}}{\nu}\cdot\frac{\sqrt{m_1}}{m_0}\cdot\left(1+\frac{\nu^2}{4}\right)\cdot\left(\frac{h}{\tau\cdot\sqrt{m_1}}\right)^2\cdot R \qquad (8)$$

$$R=\exp\left(-\frac{a^2}{2\cdot m_0}\cdot\left(1+\frac{1}{\nu^2}\cdot\left(1-\frac{2\cdot\pi}{\tau\cdot\sqrt{\frac{m_1}{m_0}}}\right)^2\right)\right)$$

$\nu=\sqrt{\frac{m_0\cdot m_2}{m_1^2}-1}$ spectral width parameter, spectrum narrow if ν<<1.0

m_i spectral moments of the random process in question

Applying the above to the wind gust Davenport spectrum, shown in Figure 7, reveals that the considered process is not narrow-banded, as indicated by the spectral width parameter ν, which is equal to 1.339 in this case, hence violating somewhat the assumptions underlying formulae (8).

However, considering the zero up-crossing period for the wind turbulence process shown in Figure 10 and Figure 11, of approximately 3s, it can be seen that this period approximates the most likely periods estimated by (8) and shown in Figure 19 below. It seems reasonable, therefore, to proceed with formulae (8) for a relative assessment of likelihood of occurrence of specific wind gust excursions.

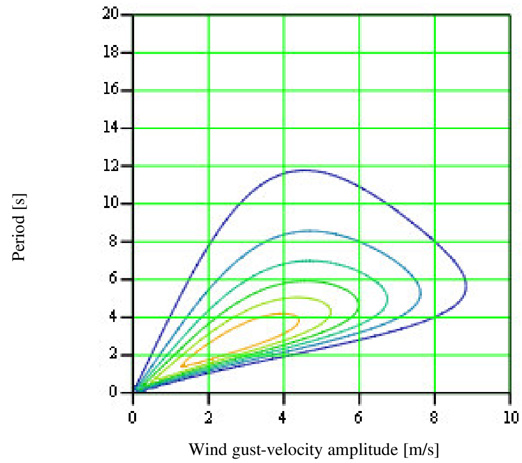

Figure 19: Joint probability density functions of gust-velocity and wave amplitudes with respective periods

Deriving from the above, it is estimated that the assumption of a wind gust excursion of 22.47% from the mean wind speed of 26m/s that leads to a 50% increase in the wind heeling lever from its mean, is a likely event with probability of being exceeded of

$$1-\int_0^{7.5s}\int_0^{5.82\frac{m}{s}} f(a,\tau)\cdot da\cdot d\tau = 44.1\%$$

Using this assumption as a basis for the weather criterion, as quoted in (c) of §1.1, is thus reasonable.

2.4. Deductions from the ship roll response

Unlike the wind turbulence process, roll response due to random excitation, can be considered a narrow-banded random process. This allows application of the well-known work of Michael Ochi on extreme value statistics, [10], for establishing likely extreme roll excursions due to wind and wave excitation, such as shown in Figure 15 and Figure 16. Ochi has derived a simplified method for the prediction of the extreme values of the maxima of a stationary and Gaussian random process defined by a random sample of size n. For a narrow-banded process it can be assumed that the probability density function of the excursions is a Rayleigh distribution. Thus, the probability distribution *f(x)* of amplitudes *x* of a response conforming to Gaussian random process of given spectral moment m_0, can be written as:

$$f(x)=\frac{x}{m_0}\cdot e^{-\frac{x^2}{2\cdot m_0}}$$

The corresponding cumulative distribution function is:

$$F(x)=1-e^{-\frac{x^2}{2\cdot m_0}}$$

The probability density function of extreme values of the distributed maxima can then be expressed as follows:

$$g(x)=n\cdot f(x)\cdot(F(x))^{n-1}$$

The number n of cycles encountered in a given time T can be estimated from

$$n=\frac{T}{T_R}$$

where T_R is the response reference period.

The corresponding extreme value statistics are estimated as follows:

$$a_{63}=\sqrt{m_0}\cdot\sqrt{2\cdot\ln n}$$ most probable extreme value

$$a_1=\sqrt{m_0}\cdot\sqrt{2\cdot\ln\frac{n}{0.01}}$$ extreme value corresponding to risk of being exceeded of 1%

Considering the roll response derived in either Figure 15 or Figure 16, with significant value of about 17deg, the following extreme amplitude occurrences can be predicted in 48 hours duration sea conditions with wind of 26m/s and waves of Hs=11m:

$T=48$ hours, $T_R=15$ s, $m_0=18$

$a_{63}=21.3$ deg $\quad$ $a_1=24.9$ deg

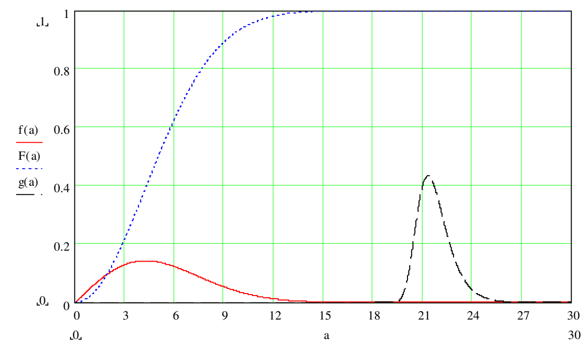

Figure 20: Probability functions of the ship roll motion with corresponding likely extreme values

As can be seen, either of these values exceeds the roll angle $\theta_1=19.4\,\text{deg}$, estimated according to the weather criterion discussed in (b) of §1.1, and it is well beyond the 2% probability of exceedence indicated by Rachmanin. These findings provide a quantitative indication in support of the underlying assumption concenring the ship roll response to the the leeside with the vessel subjected to excessive wave and wind excitation.

However, considering that the equilibrium angle for the sample vessel is approximately 8deg, it can be inferred that the most extreme roll towards the leeside within 48 hours will not be greater than approximately **33deg**, at which angle, the vessel has still a considerable stability margin, see Figure 3. This would suggest that the assumption (d) concerning the vessel response is the weakest element of the weather criterion, in need of further revision and study, possibly along the lines discussed in this paper. This weakness seem to derive from the relatively low joint probability of occurrence of the critical conditions, namely extreme roll to the weather side together with gust wind velocity of large enough value and duration, occurring simultaneously at the very instant of the extreme roll.

3. CONCLUDING REMARKS

The results from the study reported in this paper tend to indicate that even though the underlying assumptions inherent in the weather criterion can be justified in so far as the individual parameters comprising the scenario postulated by it are probable. However, the probability of the scenario itself occurring is low enough to be taken seriously as a criterion for judging the fate of a large passenger ship in beam wind and waves.

It is, therefore, recommended that the criterion as a whole be revisited and reanalysed using modern tools and current understanding of the perceived or actual intact ship stability risks in a seaway.

Pertinent questions to be asked and answers sought for, concern the likelihood of:

(a) the vessel encountering relevant storms
(b) the vessel having a certain (worst) loading condition (GM, I_{xx})
(c) the vessel finding hereself in beam seas heading without any control
(d) the vessel being excited by a specific gust force
(e) the vessel surviving a given (relevant/worst) scenario in the conditions considered.

Considering the above, the question of acceptability conserning the ensuing risk would still remain to be considered and rhis is an altogether different (and more difficult) problem.

4. REFERENCES

[1] Ishewood, R.M., *“Wind Resistance of Merchant Ships”*, The Royal Institution of Naval Architects, 1972.

[2] Spyrou, K.J. ‘Total Ship Safety”, CPD Course lecture notes, SSRC, Glasgow, June 2003.

[3] Denis St., M., Pierson, W.J., *“On the motion of Ships in Confused Seas”*, Trans. SNAME, Vol. 61, 1953.

[4] Cummins W.E., *“The impulse response function and ship motions”*, Schiffstechnik Bd. 9 – 1962.

[5] Salvesen, N., Tuck, E.O. and Faltinsen, O.,: *“Ship Motions and Sea Loads”,* SNAME, Vol. 78, 1970.

[6] Himeno Y., *“Prediction of ship roll damping – state of the art”*, Report No 239, University of Michigan, College of Engineering, September 1981.

[7] Jasionowski, A., *“An integrated approach to damage ship survivability assessment”*, PhD dissertation, February 2001, University of Strathclyde.

[8] Vassalos, D. and Letizia, L., *"Formulation of a non-linear mathematical model for a damaged ship subject to flooding"*, Sevastianov Symposium, Kalinigrand1995.

[9] Ochi, M.K., *“Ocean Waves”*, Cambridge, Ocean Technology, Series 6, 1998.

[10] Ochi, M.K., *“On prediction of extreme values”*, SNAME, March 1973

[11] Boettcher, F., Renner, C., Waldl, H.P. and Peinke, J., *"On the statistics of wind gusts"*, Department of Physics, University of Oldenburg, August 20, 2002.

[12] Press, H., Meadows, T. and Hadlock, I.,*"A re -evaluation of data on atmospheric turbulence and airplane gust loads for application in spectral calculations"*, Report 1272, National advisory committee, NACA technical notes, 1955.

[13] The Loads and Responses Committee, 22nd ITTC Conference, 1999.

[14] Francescutto, A., Serra, A. and Scarpa, S. "*A Critical Analysis of WheatherCriterion for Intact Stability of Large Passenger Vessels"*, Proceedings, 20th International Conference on Offshore Mechanics and Archtic Engineering (OMAE), June 2001, Rio de Janeiro, Brazil.

[15] Vassalos, D., "*A Critical Look into the Development of Ship Stability Criteria based on Work/Energy Balance*", RINA Transactions, 1986, pp 217-234.