Probabilistic Assessment of Resonant Instability

N. Themelis, *National Technical University of Athens*

K.J. Spyrou, *National Technical University of Athens*

ABSTRACT

Near regularity of excitation is conducive to large amplitude responses. Moreover, higher waves tend to appear in groups (Draper 1971). These observations are the drivers of our approach for the probabilistic assessment of intact stability. The intention is to maintain the rigour and breadth of the deterministic approach while taking fully into account the probabilistic character of the seaway. Critical wave groups are specified on the basis of deterministic analysis. A procedure is put forward for calculating the probability of encountering these wave groups. A Ro-Ro ship's tendency for instability due to resonant behaviour in beam seas is used as the showcase for demonstrating the feasibility of the approach.

Keywords: *ship stability, wave group, probabilistic assessment*

1. INTRODUCTION

The mechanics that govern extreme ship behaviour and could host loss of intact stability have been studied for several years in a primarily deterministic context. This analysis has improved our understanding of the various types of ship instability, some times supplying also simple criteria to guide design. However, none could disregard that potentially destabilizing environmental excitations are of a probabilistic nature.

A method to interface the deterministic analyses of ship dynamics with wind/wave models and statistics has been proposed recently, exploiting the groupiness characteristic of high waves and the idea that the probability of occurrence of a certain instability could be assumed as equal to the probability of encountering the critical (or "worse") wave groups that generate the instability (Spyrou, 2005, Spyrou & Themelis, 2005). The method builds upon certain ideas that have been around in the field of ship stability for a number of years: Tikka & Paulling (1990) for example, discussed the calculation of the probability of encountering a high run of waves in astern seas and determined combinations of ship's speed and heading that could favour such an encounter. DeKat (1994) pointed out the importance of considering wave groups and he referred to the use of joint distributions of wave length and steepness in order to determine such wave groups, given a significant wave height and period. Along the same lines, Myrhaug et al. (1999) investigated synchronous rolling using joint distributions of successive wave periods, targeting essentially the encounter of a wave group with critical period.

In the current paper our objective is to demonstrate the feasibility of our method of stability assessment, through detailed application to a specific ship, of Ro-Ro ferry type. A popular route in the Mediterranean Sea is selected and probabilities of "instability" due to beam-sea resonance (in format of critical time as percentage of the duration of the voyage) are calculated. Two, conceptually different, cases of assessment are presented.

2. THE PROPOSED METHODOLOGY

Given a ship, the methodology can be deployed for "short" or "long-term" assessments, depending on the intended period of exposure to the weather. In the current context, as "short-term" is meant an assessment gauging safety during a single trip. It is thus fed by the "few hours" forecast of weather parameters. Such an assessment could serve as a decision-making tool in connection with a system of departure control like the one used in Greece for passenger ships (Spyrou et al. 2004); or with other operational measures like weather routing. On the other hand, long-term assessments could be performed for a variety reasons. Probabilities of instability on a seasonal or annual basis for reference routes can be determined with obvious utility at corporal and national administration levels. Moreover, by projecting the annual statistics to the ship's life-span, a long-term assessment could be tied to ensuring a satisfactory safety level by design[1]. In long-term assessments, the anticipated service profile should be specified beforehand. A restricted service, referring to specific routes, should lead to a different assessment result, compared to one of unrestricted service that sets no narrow limits to the navigational area (e.g. North Atlantic).

Different ship types are prone to instabilities of a different nature. In a general sense, an effective portfolio of criteria should cover against resonance phenomena (beam-sea resonance and parametric rolling in longitudinal seas); pure - loss of stability on a wave crest in following seas; instability due to breaking waves from abeam and "water-on-deck"; and finally broaching, including the so-called cumulative type. To become these criteria meaningful, norms of unsafe behaviour should be adhered to each one of them. The setting of warning and failure levels per criterion and ship type has been proposed, on the basis of threshold angular and linear displacements and accelerations, referring respectively to the safety of the ship and her cargo (Spyrou & Themelis 2005). The setting of warning level should play a cautionary role and its exceedence could be allowed with a controlled probability.

The probability of occurrence of dangerous ship motion, loosely referred-to from here on as "instability", could be assumed as equal to the probability of encounter of the critical (or worse) wave group that gives rise to this instability. Certain instabilities entail some regularity in the excitation, i.e. the amplitude is built up gradually; whereas others represent the outcome of the encounter of a single critical wave that can 'kick' the system out of its (safe) potential well. One might think therefore to disassemble the problem into two parts: one deterministic, for deducing the specification of the critical wave group (represented by the height, period and run-length) focused purely on ship motion dynamics; and one probabilistic centered upon seaway statistics, in order to determine the probability of encounter of such a wave group. For the specification of critical wave groups, advantage could be taken of the strengths of deterministic analyses: numerical simulation tools based on detailed models; and analytical techniques capturing key system dynamics (growth of amplitude per cycle, Melnikov's method etc.) represent the two ends of the spectrum, each having particular strengths and weaknesses. However it should be remarked that, by disassembling (methodologically) the ship dynamics part from the probabilistic seaway, an informed decision based on more than one tools is allowed; i.e. results from different simulation codes or combinations of simulation with independent stability analysis techniques can be utilised. A flow-chart of the above described methodology is presented in Figure 1.

The groupiness characteristic of high waves coupled with the magnification of safety threats due to near regularity of the excitation, allow therefore the conceptual bridging of the deterministic and probabilistic viewpoints. Given a distribution of "weather nodes" (along the route of in a wider navigational area), individual probabilities per node are calculated.

[1] Some concern is necessary here for the observed slow drift of environmental parameters and the tendency for extremer seas as time progresses.

In summing up these probabilities, the duration of ship stay in the influence area of each node, as well as the principal direction of wave field encounter, are taken into account (Figure 2).

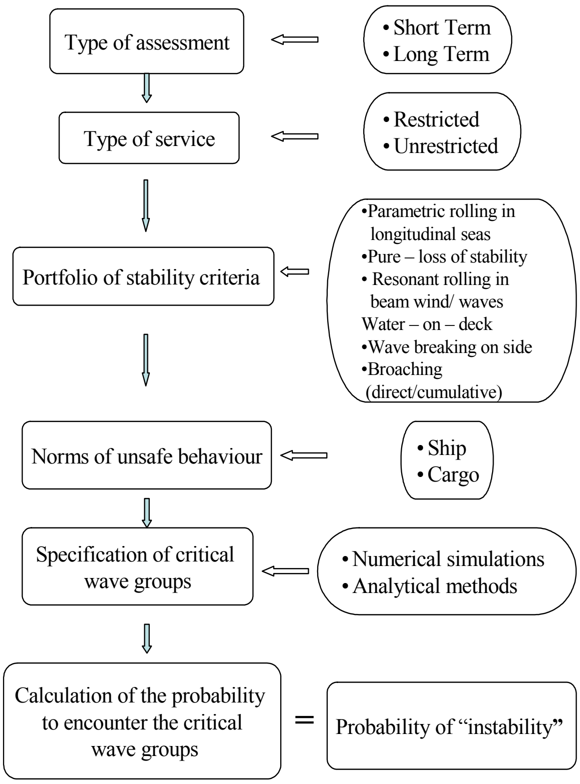


Figure 1 Flow chart of proposed methodology.

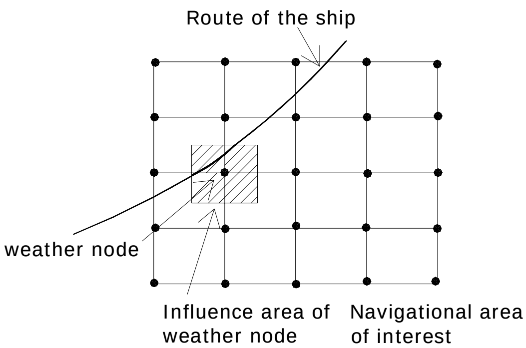


Figure 2 Weather nodes with their areas of influence.

To facilitate decision-making, the probabilistic treatment should be embedded upon a risk-based platform of assessment. In implementing this however, a scale for quantifying the consequences needs to be established.

3. PROBABILITY OF WAVE GROUPS

For a brief introduction to wave groups see for example Medina & Hudspeth (1990) and Masson & Chandler (1993). Application of the proposed methodology entails calculation of the probability of encounter of wave groups with successive periods in the critical range (related to the ship's roll natural period), given run length; and heights consistently above the critical height as determined from the deterministic analysis. A variety of parametric models might be useful in this respect. Bivariate distributions of wave height and period have been proposed by Longuet – Higgins (1975 & 1983); Cavanié et al. (1976); Tayfun 1993; and others. The probability density function (pdf) proposed by Tayfun (1993) is:

$$f\left(h,\tau\right)=C_T\, h\left(1+\frac{1-\kappa^2}{32\,\kappa h^2}\right) e^{-\frac{1}{2}\left[\frac{4h^4}{1+\kappa}+\left(\frac{\tau-\mu_{\tau/h}}{\sigma_{\tau/h}}\right)^2\right]} \tag{1}$$

where:

$$\mu_{\tau/h}=1+\nu^2(1+\nu^2)^{-3/2} \tag{2}$$

$$\sigma_{\tau/h}=\frac{2\nu}{\sqrt{8}h(1+\nu^2)} \tag{3}$$

$$C_T=\frac{2\sqrt{2}}{2\sqrt{4\pi\kappa(1+\kappa)}\sigma_{\tau/h}} \tag{4}$$

$\mu_{\tau/h}$ and $\sigma_{\tau/h}$ are the conditional mean and standard deviation, C_T a normalizing factor, $h=\frac{H}{H_{rms}},\ \tau=\frac{T}{T_m}$ the dimensionless wave height and period, $T_m=2\pi\frac{m_0}{m_1}$ the mean spectral period, m_j the j th ordinary moment of wave spectrum. According to Longuet – Higgins (1975) the spectral bandwidth ν is given by:

$$v = \sqrt{\frac{m_2 m_0}{m_1{}^2} - 1} \tag{5}$$

The parameter κ depends on T_m and the frequency spectrum. According to (Stansell et al, 2002) is calculated:

$$\kappa^2 = \frac{1}{m_0} \left| \int_0^\infty S(\omega) e^{i\omega t} d\omega \right|, \quad t = T_m \tag{6}$$

Tayfun (1993) approximated the conditional distribution of successive wave periods given the wave height on the basis of the Gaussian distribution for one wave period. Wist et al. (2004) noted that, for three wave periods at least, the multivariate Gaussian distribution is a satisfactory model of the conditional distribution. Their conditional pdf of p successive wave periods $\mathbf{T} = \left[T_1, ..., T_p\right]^T$, given that each wave height in the group exceeds the threshold H_{cr}, is given by equation (7). A general formula for variable threshold $H_{cr,i}$ per crest in the group could also be derived.

$$f_{\mathbf{T/H}}\left(\boldsymbol{\tau}/h_i > h_{cr}\right) = \frac{e^{-\frac{1}{2}\left(\boldsymbol{\tau} - \boldsymbol{\mu}_{\tau/h_{cr}}\right)^T \Sigma^{-1}_{\tau/h_{cr}} \left(\boldsymbol{\tau} - \boldsymbol{\mu}_{\tau/h_{cr}}\right)}}{\left(2\pi\right)^{p/2} \left|\Sigma_{\tau/h_{cr}}\right|^{1/2}} \tag{7}$$

where the covariance matrix is given by:

$$\Sigma_{\tau/h_{cr}} = \begin{bmatrix} \sigma^2_{\tau/h_{cr}} & \mathrm{Cov}\left[T_1, T_2/H_{cr}\right] & \mathrm{Cov}\left[T_1, T_p/H_{cr}\right] \\ & \cdots & \\ \mathrm{Cov}\left[T_1, T_p/H_{cr}\right] & \cdots & \sigma^2_{\tau/h_{cr}} \end{bmatrix} \tag{8}$$

and $\mathrm{Cov}\left[T_i, T_j/H_{cr}\right] = \rho_{ij}\sigma^2_{\tau/h_{cr}}$. The mean values $\boldsymbol{\mu}_{\tau/h_{cr}}$ and the standard deviations $\sigma_{\tau/hcr}$ are calculated from equations (2) and (3). Assuming the Markov chain property for the waves, the correlation coefficients ρ_{ij} is:

$$\rho_{1j} = \rho_{12}^{j-1} \tag{9}$$

The correlation coefficient ρ_{12} of two successive wave heights is calculated as follows (Stansell et al, 2002):

$$\rho_{12} = \frac{E(\kappa) - \left(1 - \kappa^2\right)\frac{K(\kappa)}{2} - \frac{\pi}{4}}{1 - \frac{\pi}{4}} \approx$$
$$\approx \frac{\pi}{16 - 4\pi}\left(\kappa^2 + \frac{\kappa^4}{16} + \frac{\kappa^6}{64}\right) \tag{10}$$

where $E(\ )$, $K(\ )$ are complete elliptic integrals of the first and second kind, respectively.
The above, rather lengthy, procedure is essential because for resonance phenomena, one needs to determine the probability, a specified number of successive wave periods to lie in some narrow interval $\left[\tau_1, \tau_2\right]$, given that the corresponding wave heights exceed the critical level h_{cr}.

4. MATHEMATICAL MODEL OF COUPLED ROLL IN BEAM SEAS

A mathematical model has been developed that could be used for analysing coupled rolling motion in beam seas. This model is outlined briefly in the following: For more details see Themelis & Spyrou (2005). From kinematics and in accordance to Fig. 3, the equations of motion in heave, sway and roll are written as follows:

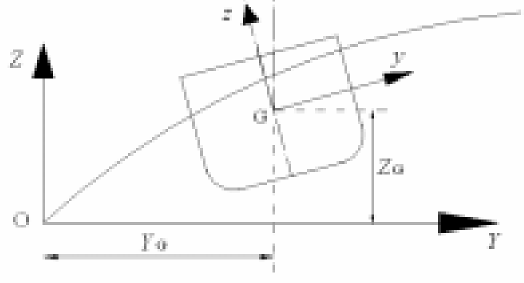


Figure 3 The inertial (OYZ) and body fixed (Gyz) coordinate systems.

$$m(\dot{v}-\dot{\phi}w)=\sum F_y \quad (11)$$

$$m(\dot{w}+\dot{\phi}v)=\sum F_z \quad (12)$$

$$I_G\ddot{\phi}=\sum M_G \quad (13)$$

where v, w are the sway and heave velocity of the ship's centre of gravity and $\dot{\phi}$ is the roll angular velocity, m and I_G are, mass and mass moment of inertia around x. The well-known transformation between the inertial and body fixed coordinate systems is applied.

The two forces and the moment that appear at the right-hand-side of (11)-(13) can be decomposed as follows:

$$\sum F = F_{Hs}+F_W{}^{FK}+F_R+F_V \quad (14)$$

F_{Hs} is hydrostatic, F_W^{FK} is Froude – Krylov, F_R is radiation and F_V is the viscous force.

Calculation of excitations In linear wave theory, the total wave velocity potential is the sum of the potentials of incident wave, diffraction and radiation. The hydrostatic and Froude – Krylov (hydrodynamic) forces are estimated by the integration of the incident wave pressure (static and dynamic respectively) over the wetted surface of the ship. For regular waves, the incident wave potential is calculated from:

$$\Phi_I=\frac{Ag}{\omega_w}e^{kZ^*}\sin(kY-\omega_w t) \quad (15)$$

$$Z^*=Z-A\cos(kY-\omega_w t) \quad (16)$$

The hydrostatic and Froude - Krylov forces are repetitively:

$$F_{HSi}(t)=-\rho g\iint_{S(t)} Z^*\vec{n}_i ds,\ \text{for } i=2, 3, 4 \quad (17)$$

$$F_W^{FK}(t)=-\iint_{S(t)}\rho\frac{\partial\Phi_I}{\partial t}\vec{n}_i ds,\ \text{for } i=2, 3, 4 \quad (18)$$

where i = 2, 3, 4 correspond to sway, heave and roll motion, ρ is seawater density and $S(t)$ is the instantaneous wetted surface. We should mention that the integration is performed over the instantaneous wetted surface and pressures are calculated from the exact wave elevation. As a matter of fact, the nonlinear part of the forces is taken into account, which is important for the accurate simulation of the large motions of the ship.

The radiation forces are frequency dependent. Using the impulse response function, obtained as the Fourier transform of the frequency dependent radiation transfer function, the radiation forces will be (Cummins, 1962):

$$F_{Rj}(t)=-a_{jk}(\infty)\ddot{s}_k-\int_0^{+\infty}K_{jk}(\tau)\dot{s}_k(t-\tau)d\tau \quad (19)$$

$$K_{jk}(\tau)=\frac{2}{\pi}\int_0^{\infty}b_{jk}(\omega_e)\cos(\omega_e\tau)d\omega \quad (20)$$

for j, k=2, 3, 4.

The convolution integral is the well-known memory effect. a_{jk}, b_{jk} are the added mass and damping coefficients. $\dot{s}_k, \ddot{s}_k$ are velocity and acceleration of the ship in the k direction of motion and ω_e is the encounter frequency. In our model we use a state-space approximation of the radiation force in order to maintain the mathematical model in the form of a system of o.d.e.s which enables easier consideration of nonlinear dynamics.

Our model calculates also the sway drag force, roll damping, and cross coupling forces between sway, heave and roll. For example, the drag force due to bilge keels is calculated as follows (see also Fig. 4):

$$F_{BY} = \frac{1}{2}\rho(\dot{Y}_G - r_A\dot{\phi}\cos(\theta) - u_2) * \left|\dot{Y}_G - r_A\dot{\phi}\cos(\theta) - u_2\right| C_D A_{BK} \quad (21)$$

$$F_{BZ} = \frac{1}{2}\rho(\dot{Z}_G - r_A\dot{\phi}\sin(\theta) - u_3) * \left|\dot{Z}_G - r_A\dot{\phi}\sin(\theta) - u_3\right| C_D A_{BK} \quad (22)$$

$$M_B = -r_A\,[F_{SZ}\cos(\theta_1) + F_{SY}\sin(\theta_1)] \quad (23)$$

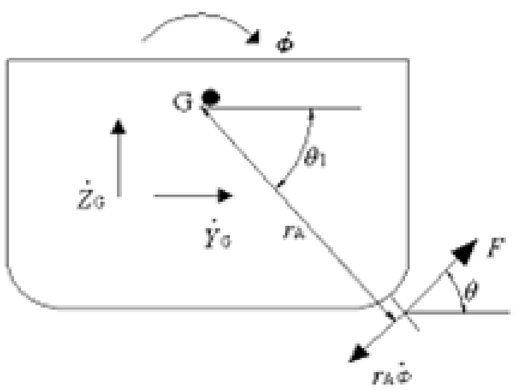


Figure 4 Bilge keel damping forces

C_D is the drag coefficient and A_{BK} the total bilge keel area. Other symbols are explained in Fig. 4. The method takes into account the local relative velocities along the hull, using the sway, heave and roll velocities ($\dot{Y}_G, \dot{Z}_G, \dot{\phi}$), the wave particle velocities u_2 and u_3 as well as the detailed geometry of the hull.

The numerical model is programmed completely in a Mathematica environment. Input data are, concerning the ship: the hull geometry, her mass and the distribution of mass; and for the incident wave, its height and frequency. The code creates panels over the hull whereon the static and dynamic pressures are calculated at successive time steps, as well as the angle between the horizontal plane and the normal vector of the panel.

5. APPLICATION

A ferry that operates in the Mediterranean has been investigated. Her basic particulars are presented in Table 1. The potential instability scenario targeted was resonant instability in beam seas. However, there is no indication of this ship being prone to such instability. A single draft, at “full-load departure”, was examined.

Table 1 Basic Particulars

L_{bp} (length)	157 *m*	GM (metacentric height, corrected)	2.08 *m*
B (beam)	26.2 *m*	T_0 (natural roll period)	15.26 *s*
D (depth, main deck)	9.20 *m*	b_{BK}, l_{BK} (breadth, length of bilge keels)	0.26 *m* 60.9 *m*
T (mean draft)	6.20 *m*	KG (vertical position of centre of gravity above keel)	12.724 *m*
C_b (block coef.)	0.626	Trailers	99
Vs	23 *kn*	Cars	166

A popular ferry route in the Mediterranean is Patra – Bari (Figure 5). Statistical data of wave period and height relevant to this route, on a monthly, seasonal and annual basis, can be found, for example, in Metadlas (Athanassoulis et al, 2004) that provides information for wind and wave statistics of the Mediterranean Sea. The probability of beam-sea resonance along this route on the basis of the winter season wind/wave data will be determined. Three “weather nodes” along this route have been used. For each node, the mean winter values of significant wave height H_S, mean peak period T_P and dominant wave direction Θ_{wave} are known (Table 2).

To calculate the time spent in the rectangle around a node (Table 3) a constant speed of $V_S = 23\ kn$ has been assumed throughout. Nonetheless, for a real application the speed should normally be reduced, depending on the local weather. Also, the ship heading and the direction of the local wave field determine the time spent in beam, head and following seas

(Figure 6). The adopted convention concerning the type of encounter is explained in Figure 7. The time has been scaled against the duration of the voyage (Table 4).

Figure 5 The examined Patra – Bari route superimposed on a map taken from Google Earth. Available nodes of wave data are also shown.

Table 2 Mean wave values for winter.

	$H_s(m)$	$T_p(sec)$	$\Theta_{wave}(deg)$
Weather node 1 (39^0N, 20^0E)	1.293	6.897	224.02
Weather node 2 (40^0N, 19^0E)	1.167	6.586	209.83
Weather node 3 (41^0 N, 18^0E)	1.077	5.936	189.70

Table 3 Time spent in each grid sub area.

	Distance(*nm*)	Time(*hr*)	%
Weather node 1	138.77	6.03	46.2
Weather node 2	73.39	3.19	24.4
Weather node 3	87.48	3.80	29.1
Total	299.98	13.04	100.0

Table 4 Percentage of time spent in beam, head and following seas

	Beam seas	Head seas	Following seas
Weather node 1	19.70%	16.50%	10.27%
Weather node 2	5.58%	7.59%	11.28%
Weather node 3	9.37%	9.86%	9.85%
Average	34.66%	33.96%	31.42%

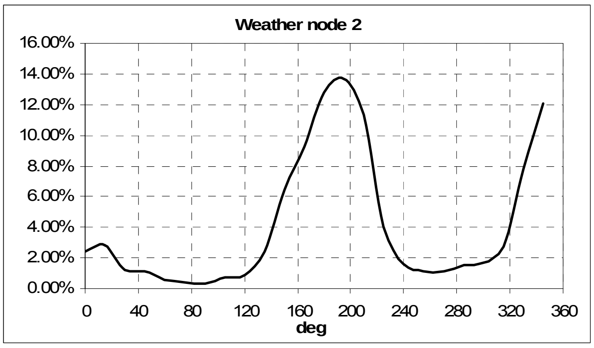


Figure 6 Wave direction characterization for operation near node 2.

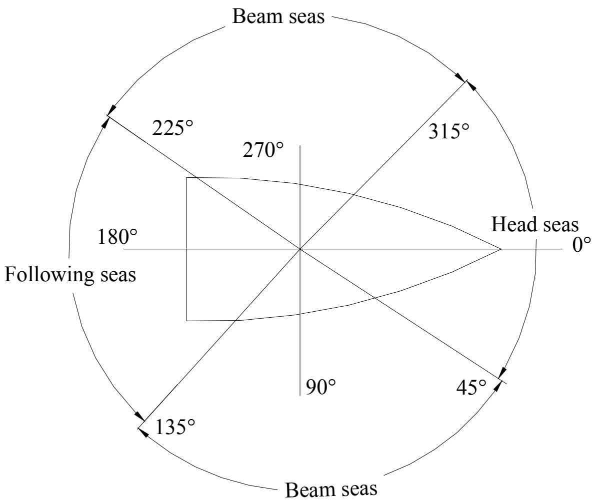


Figure 7 Convention for wave direction (0^0 waves coming from North, 90^0 East).

<u>Norms of unsafe response for ship and cargo</u> Norms of failure specific to the ship and her cargo were set. Concerning the ship, the principle of the weather criterion was adopted in order to determine the critical roll amplitude. For the investigated Ro-Ro ferry it meant that the critical roll angle should be the minor of: the angle of vanishing stability $\theta_c = 1.1$ rad; the down-flooding angle $\theta_f = 0.612$ rad; and $\theta_a = 0.8726$ rad (50 deg). Thus the critical roll angle should be $\phi_f = 0.612$ rad or 35 deg.

Turning to the cargo, the acceleration due to beam-sea rolling that could endanger the lashing of the remotest trailer was targeted as the critical response.

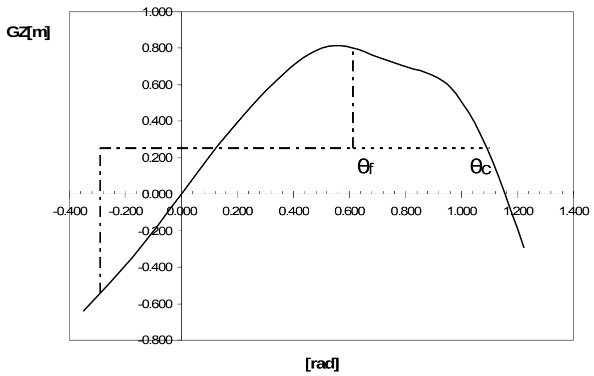


Figure 8 Application of the Weather Criterion.

The tendency of the trailer for transverse sliding and tipping was checked for three different lashing arrangements. Parameters and coefficients that are essential for the analysis are shown in Table 5. The Maximum Securing Load (MSL) is the least required strength of the lashings according to IMO. The most critical transverse acceleration was found corresponding to transverse sliding and a vertical securing angle of 60^0 (Figure 10). The critical acceleration is $a_y = 8$ m/s^2.

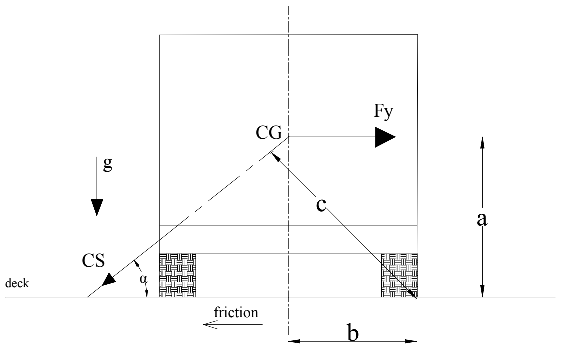


Figure 9 Forces acting on the trailer – lashing system (transverse section).

Table 5 Trailer and lashings characteristics.

cargo mass	$m = 40\ t$
Centre of gravity above deck	a = 2.753 *m*
lever-arm of tipping	b = 1.261 *m*
Coefficient of friction	Steel – rubber: μ = 0.3
Lashing arrangement	4 chains with MSL = 100 *kN* on each side, symmetrical vertical securing angle: α = 30°/45°/60°

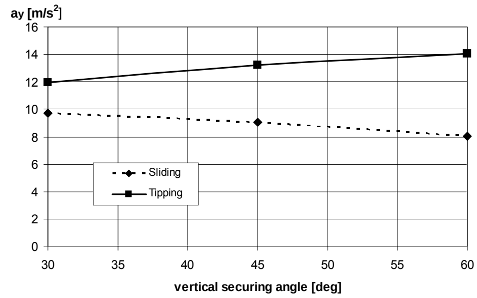


Figure 10 Critical transverse accelerations for sliding and tipping for the three lashing arrangements.

<u>Critical wave groups</u> The calculation of critical wave groups proceeds as follows: firstly, the range of wave periods (e.g. 4 – 19 sec) is discretised. Then, for each discrete period (representing however a narrow range around it) we set the desired number of successive waves (starting with $n = 2$) and we determine the minimum critical wave height H_{cr} that generates a response reaching the value of the severest norm (in this case roll angle, or acceleration at the remote trailer position). The calculation continues with $n = 3$ etc. Figures 11 and 12 summarise the key characteristics of the identified critical wave groups, respectively for ship and cargo.

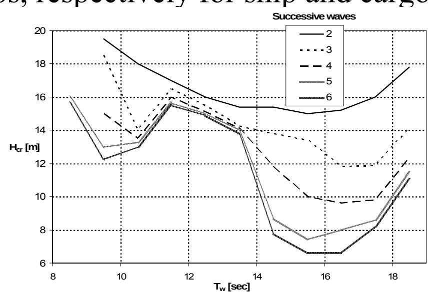


Figure 11 Critical wave groups with reference to the limiting roll angle (ship).

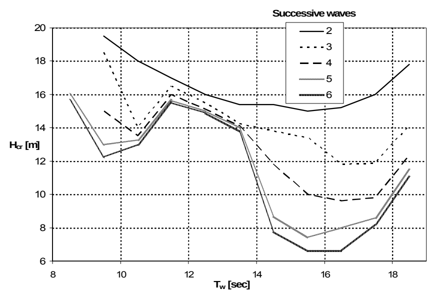


Figure 12 Critical wave groups for the limiting transverse acceleration (cargo).

Probability to encounter critical wave groups The JONSWAP frequency spectrum was used (Hasselmann, 1973). As is well-known, its spectral density function is:

$$S(\omega) = a g^2 \omega^{-5} \exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^4\right) \gamma^{\exp\left(-0.5\left(\frac{\omega-\omega_p}{\sigma\omega_p}\right)^2\right)} \tag{25}$$

where

$$a = \frac{5}{16}\left(\frac{H_S^2 \omega_p^4}{g^2}\right) A_\gamma \tag{26}$$

$$A_\gamma \cong 1 - 0.287 \ln(\gamma) \tag{27}$$

$$\begin{aligned} \sigma &= 0.07 \text{ if } \omega \le \omega_{\mathrm{p}} \\ &= 0.09 \text{ if } \omega > \omega_{\mathrm{p}} \end{aligned} \tag{28}$$

a is the generalized Philips' constant, A_γ a normalizing factor, γ the peakness parameter, σ the spectral width parameter and ω_p the angular spectral peak frequency. For the peakness parameter γ the following formulas can be used (DNV, 2002). For the calculation of probabilities P_i for each wave period partition around T_i, the values of H_S, T_P were taken from Table 2.

$$\begin{aligned} &\gamma = 5 \text{ for } \frac{T_P}{\sqrt{H_S}} \le 3.6 \\ &\gamma = e^{5.75 - 1.15\frac{T_P}{\sqrt{H_S}}} \text{ for } 3.6 \le \frac{T_P}{\sqrt{H_S}} \le 5 \\ &\gamma = 1 \text{ for } 5 \le \frac{T_P}{\sqrt{H_S}} \end{aligned} \tag{29}$$

It was preferred to express the probabilities as percentage of critical time scaled with regard to the duration of the voyage t_{tot}. This is done approximately with the following simple transformation:

$$\bar{t}_i = \frac{t_i}{t_{tot}} = P_i \frac{T_i}{T_m} \tag{30}$$

The contribution of each range of wave periods to the total probability can be deduced from Figures 14 and 15.

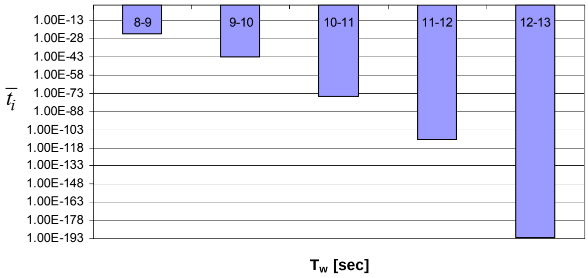


Figure 14 Critical time with reference to the roll angle (logarithmic scale).

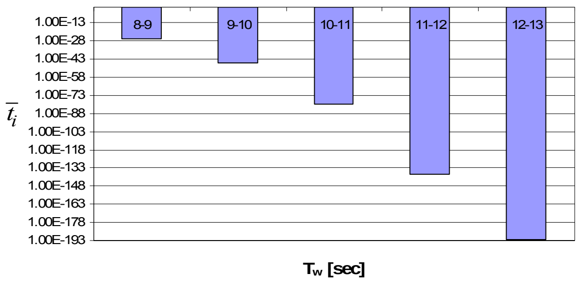


Figure 15 Critical time with reference to the transverse acceleration of trailer (logarithmic scale).

The probabilities are, in most cases, negligible, stemming of course from the fact that the range of wave periods which usually arise in the Ionian and Adriatic Sea are far below the Ro-Ro ferry's natural roll period. As a matter of fact, the probability of resonance should be extremely low. The critical time $\bar{t}_i$ for the entire voyage is summarized below with reference to the two considered norms of beam-sea resonance:

Ship: ($\phi > 35^0$)	1.161E-22
Cargo: ($a_y > 8$ m/s^2)	9.425E-25

In the above we have used H_S, T_P values that are the most probable for the winter season. The actual distribution of significant wave height H_S and peak period T_P for weather node 1 (winter season) is shown in figures 16 and 17 (exctracted from the

Metadlas of the Mediterranean, see Athanassoulis et al 2004).

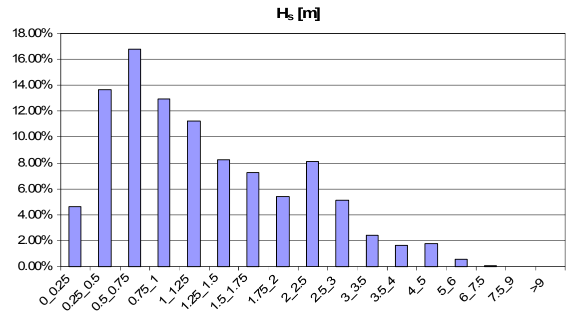


Figure 16 Distribution of significant wave height for winter (weather node 1).

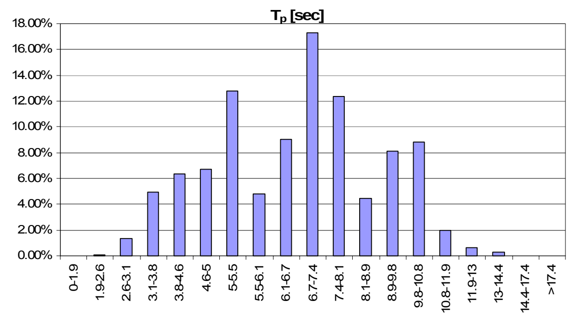
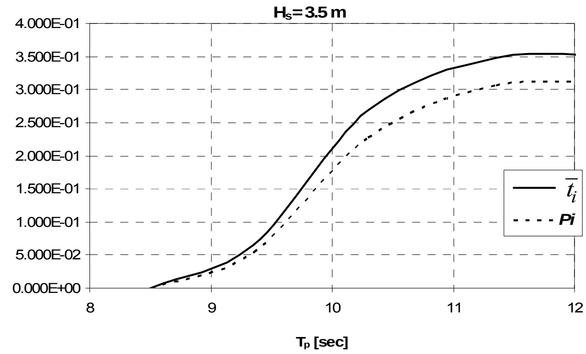


Figure 17 Distribution of peak period for winter (weather node 1).

As a next step, we examined the effect of combinations of H_s, T_P on the critical time $\bar{t}_i$, focusing on the requirement that the roll angle should not exceed 35^0. Such thinking could be relevant in the context of a short-term assessment, e.g. for assessing whether the ship should be allowed to sail, given the weather forecast. For simplicity we assumed uniform weather conditions throughout the journey (i.e. the data of a single weather node characterize the entire journey). We derived the critical time $\bar{t}_i$ as function of T_P for fixed H_S (Figure 18); and as function of H_S as function of T_P (Figures 19). For the rather extreme conditions that were deliberately examined, it is obvious that the exposure of the ship to critical weather is too high.

Figure 19 Critical times and probabilities as the period T_P is varied. H_S is fixed at a high value.



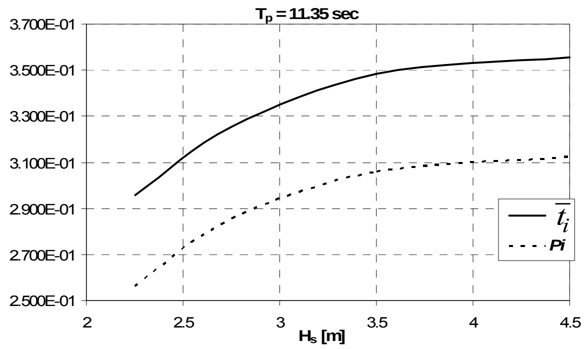


Figure 20 Critical times and probabilities as H_S is varied, for a fixed T_P.

6. CONCLUDING REMARKS

A survey of literature on probabilistic intact stability assessment would reveal that current methods are: either focusing narrowly on the problem (e.g. study of beam-sea resonance or parametric rolling only, with dubious assumptions regarding the nature of excitation and/or type of response); or, due to the rush for practicality, the widening of scope is accompanied by paying little attention to the true dynamical nature of the phenomena. Little confidence has been gained that stability standards could be based on the state-of-the-art of probabilistic approaches.

On the other hand, in the recent past, risk-based approaches have pervaded all facets of naval architecture and almost naturally, the question of a solid and yet practical probabilistic approach has been heard more loudly than ever.

An effort to fill this gap has been presented in the current paper. The developed method was applied at a very practical level, selecting a Ro-Ro ferry and setting it to operate on a specific popular route. The assessment produced results that are logical, although further elaborations are needed in order to standardise the calculation methods that are suitable for each stage of the assessment.

7. ACKNOWLEDGEMENT

Part of this research work (related to short-term assessment) has been supported by the the General Secretariat for Research and Technology of Greece (project ESPEN). The part related to long-term assessment has been carried out for the needs of the project SAFEDOR funded by the European Commission.

8. REFERENCES

Athanassoulis *et al,* 2004, "Metadlas: Wind and wave atlas of the Mediterranean Sea", WEAU (consortium: CS, NTUA, CNR/ISMAR, THETIS, Semantic, MeteoFrance), ISBN 2-11-095674-7.

Cavanié, A., Arhan, M. & Ezrtaty, R., 1976, "A statistical relationship between individual heights and periods of storm waves". Proceedings, Conference on Behaviour of Offshore Structures, Trondheim, pp. 354-360.

Cummins W. E., 1962, "The impulse response function and ship motions", Schiffstechnik, Vol. 9, pp. 101–109.

Det Norske Veritas, 2002, "DNV MaxWave", Report No. 2001 – 1491.

de Kat, J.O., 1994, "Irregular waves and their influence on extreme ship motions", Report No. 208883-OP1 – ONR'94.

Draper, L. 1971, "Severe wave conditions at sea", Journal of the Institute of Navigation, Vol. 24, 3, pp. 273-277

Hasselmann, K., 1073, "Measurements of wind - wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP)", Dt. Hydrogr. Z. Reihe A (8) 12.

IMO, 1991, Code of safe practice for cargo stowage and securing and amendments thereto. Resolution A.714 (with 1994/95 amendments, Annex 1-13).

Longuet-Higgins, M.S., 1975, "On the joint distribution of the periods and amplitudes of sea waves", Journal of Geophysical Research, Vol. 80, pp. 6778–6789.

Longuet-Higgins, M.S., 1983, "On the joint distribution of wave periods and amplitudes in a random wave field", Proceedings of the Royal Society, A 389, pp. 241–258.

Masson, D. & Chandler, P., 1993, "Wave groups: a closer look at spectral methods", Coastal Engineering, Vol. 20, pp. 249–275.

Medina, J.R. & Hudspeth, R.T., 1990, "A review of the analyses of ocean wave groups", Coastal Engineering, Vol. 14, pp. 515 – 542.

Myrhaug, D., Dahle, E.A., Rue, H. Slaattelid, O.H., 1999, "Statistics of successive wave periods with application to rolling of ships", International Shipbuilding Progress, Vol. 47, pp. 253-266.

Spyrou, K.J., 2005, "Design criteria for parametric rolling", Oceanic Engineering International, Vol. 9, pp. 11-27.

Spyrou, K.J., Politis, K., Loukakis, T., Grigoropoulos, G.., 2004, "Towards a risk – based system for the departure control of passengers ships in rough weather in Greece", Proceedings 2nd International Maritime Conference on Design for Safety, Sakai, Japan, Oct. 27 – 30, pp. 255 – 261.

Spyrou, K.J. & Themelis, N., 2005, "Probabilistic assessment of intact stability", Proceedings of 8th International Ship Stability Workshop, Istanbul, Oct. 6-7.

Stansell, P., Wolfram, J. & Linfoot, B., 2002, "Statistics of wave groups measured in the northern North Sea; comparisons between time series and spectral predictions", Applied Ocean Research, Vol. 24, pp. 91–106.

Tayfun, M.A., 1993, "Joint distributions of large wave heights and associated periods", Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 119, pp. 261–273.

Themelis, N. & Spyrou, K., 2005, " A coupled heave-sway-roll model for the analysis of large amplitude ship rolling and capsize of ships in beam seas on the basis of a nonlinear dynamics approach", Proceedings 16th International Conference on Hydrodynamics in Ship Design, Gdansk, Poland, Sept. 7 – 11.

Tikka, K.K & Paulling, J.R., 1990, "Prediction of critical wave conditions for extreme vessel response in random seas", Proceedings 4th International Conference on Stability of Ships and Ocean Vehicles STAB '90, Naples, Sept. 24 -28, pp. 386 – 394.

Wist, H. Myrhaug D. and Rue H., 2004, "Statistical properties of successive wave heights and successive wave periods", Applied Ocean Research, Vol. 26, pp. 114–
13