TOWARDS A FULL RISK-BASED ASSESSMENT OF SHIP STABILITY

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SUMMARY

A novel and practical method is put forward for calculating the probability of ship instability per capsize mode. The method, developed during the SAFEDOR project, is computationally efficient irrespectively of the level of complexity of the mathematical model that is adopted for predicting extreme motions. Application is included for a modern a Ro/Ro ferry that is assessed on a seasonal basis ("long-term" assessment) for winter operation across the Mediterranean Sea. Weather statistics relevant to the defined ship route, supplied by project partners, were effectively utilised. Limiting values of roll amplitude and acceleration were defined in an objective manner. The characteristics of wave groups that give rise to dynamic responses exceeding the limiting values are established. Probabilities of encountering these critical wave groups in the region of ship operation are subsequently calculated. A new type of diagram for probabilistic stability assessment is proposed.

1. INTRODUCTION

With innovative designs entering the Market with a quick pace, there is a feeling that customary methods of ship safety assessment are in necessity of fundamental upgrading in order to cope with the emerging new requirements and the potential of unexpected types of behaviour that could set in danger lives, the environment and properties. The existing framework of intact ship stability assessment has been developed basically in the '50s when some probabilistic elements were adjoined to a basic treatment of ship roll dynamics. At least at concept level, this framework remains intact till our days. As a consequence, current stability criteria reflect little of the state-or-the-art in ship dynamics as well as in the representation of the character of sea wave effects.

A method that combines the advanced deterministic analyses of ship dynamics with state-of-the-art wind/wave models and statistics has been developed during the SAFEDOR project, exploiting the groupiness of high waves and the idea that the probability of occurrence of a certain type of instability could be assumed as equal to the probability of encountering the critical (or "worse") wave groups that generate this instability Spyrou & Themelis [1-2]. A worthwhile feature of this new methodology is that it produces the spatial variation of the probability figure along a ship route, thus establishing a solid basis for considering alternative routes, whenever this becomes necessary. Furthermore, by distinguishing the probabilities of individual capsize modes, focused measures towards risk mitigation can be taken.

The proposed methodology brings together some ideas that have been heard in the field of ship stability for a number of years: Tikka & Paulling [3] had 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 [4] 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. [5] investigated synchronous rolling using joint distributions of successive wave periods, targeting essentially the encounter of a wave group with critical period.

A requirement in SAFEDOR was, not only to develop a novel method of stability assessment, but also to demonstrate practicality through detailed implementation. To this end, two popular ship types have been selected, a ROPAX ferry assumed to operate from Piraeus to Barcelona in the Mediterranean Sea; and a post-panamax containership set on the Hamburg-to-New York route in the North-Atlantic. Essential data about these two ships have been supplied by Navantia (ROPAX) and by GL on behalf of the shipyard Aker Yards (containership). Weather data befitting to the geographical regions of interest were supplied by project partners: NTUA [6] offered long-term statistics on the basis of a dense grid spanning the Mediterranean Sea. As for the North-Atlantic, project partner GKSS [7] offered access to short-term data, produced through a hindcast study performed. Whilst the assessment of the ROPAX has been already completed, that of the containership is still in progress and it will be reported in a future publication.

The presented method shows promise for direct application to a number of areas, including ship design, operability investigations and on-board decision support. Furthermore, by incorporating a suitable model for quantifying the consequences of the born instability, it can be transformed into a full "risk-based" framework of ship stability assessment.

2. OUTLINE OFASSESSMENT METHODOLOGY

Details about the theoretical basis can be found in [1]. The methodology could be deployed for "short" or "long-term" assessments, depending on the intended period of exposure to the weather. Essentially all types of instability can be treated, under the condition that they represent phenomena of known nature whose manifestation, in a numerical context, could be targeted in a rational manner. Admissible values of roll motion are based on threshold angular and linear displacements and accelerations, referring respectively to the safety of the ship and her cargo. Critical wave group encounters that could give rise to exceedence of these limiting values are then specified on the basis of deterministic dynamical analysis which however might not necessarily rely on a single numerical tool. Wave groups are parameterised by their run length, zero upcrossing period and height.

The most laborious part of the application of the methodology, which however due to its algorithmic nature is easily programmed, is the calculation of the probabilities to encounter the critical wave groups. Appropriate multivariate and joint conditional probability distribution functions for successive wave periods and heights are used. Principal background works that we have relied upon were those of Tayfun [8] and Wist et al [9]. Very briefly, the underlying theory is based on a variant of Kimura's [10] approach for the probabilistic analysis of wave groups, developed by Battjes & Van Vledder [11]. Assumption of the Markov chain property is made for the successive waves in the group. Adding to the versatility of the methodology, necessary probability calculations exploit spectral information of the wave field; i.e. there is no need of using direct time-series results.

3. THE INVESTIGATED ROPAX FERRY

This ship selected for application is an existing ROPAX that is currently operating in the Western Mediterranean Sea. Here however, an alternative, considerably lengthier, service across Mediterranean will be examined. Basic particulars of the ship are summarised in Table 1. Furthermore, in Figure 1 are shown rendered views of her hull-form from two different angles (stern and bow).

Table 1: Basic particulars of ROPAX ferry

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 to upper deck)	9.2 m	b_{BK}, l_{BK} (breadth, length of bilge keels)	0.26 m, 60.9 m
T_d (mean draught)	6.2 m	KG (vertical position of the center of gravity above keel)	12.72 m
C_b (block coeff.)	0.626	Trailers	99
V_S (speed)	22.5 kn	Cars	166

To confine the length of the paper, presented calculations refer to a single draft corresponding to the "full-load departure" condition. Also, the service speed is considered throughout, neglecting speed reduction due to weather. In general however, a (probabilistic) loading profile should be taken into account as well as a model of speed reduction.

Figure 1: The hull-form of the examined ROPAX ferry.

4. SHIP ROUTE AND WEATHER DATA

As said in the Introduction, stability performance on the route Barcelona to Piraeus has been investigated. The one-way travel distance between these two ports is calculated to be 1209.30 nautical miles. According to the assumed service speed, it should be covered in a nominal time of 53.75 hours. Wave statistics of the Mediterranean Sea have been accounted through placement of "weather nodes" along this route. Each node "carries" a square influence area. In order to achieve sufficient resolution, a grid with density 1^0 x 1^0 has been built that surrounds the route. In total, 23 nodes have been cast. Figure 2 shows the route as well as the placed weather nodes together with their areas of influence. Background maps were taken from Google Earth. It is remarked that Wave statistics (per node) were contributed by Athanassoulis et al [6] who were another NTUA team participating in the project. Figure 3 to Figure 5 present the mean values of H_S , T_P and Θ_M for winter season along the route. Preliminary comparison between respective parameters on a seasonal basis has confirmed that the most extreme wave conditions arise in winter.

Judging from the fact that the most probable peak periods that the ship will encounter where found to lie quite far away from ship's natural roll period (i.e. this ships is very suitable for operation in this geographical area), we examined also two presumptuous cases where peak periods and significant wave heights were considerably higher than the available mean values. This sort of parametric study could bear out the sensitivity of probabilities to peak period and wave height.

The time of exposure to the specific weather represented by some arbitrary node along the route depends on the length inside the corresponding "influence" rectangle (obtained with a simple geometrical calculation) and the speed sustained by the ship in that part of the journey. As already said, it was decided to assume a constant speed throughout, neglecting any voluntary or involuntary speed change incurred. Under this assumption, in Figure 6 is shown the percentage of exposure time to beam, head and following seas per node scaled with the whole duration of the voyage. This was deduced by taking into account the heading of the ship (according to the defined route) and the distribution of mean direction of the local wave field around each node. For example, given the density of the mean wave direction in the vicinity of an arbitrary weather node, the probability of exposure to head seas will be estimated by the area between the limiting angles that define the "head-seas" encounter. This is schematically demonstrated in Figure 7 where the adopted convention concerning the angle of encounter is also explained. Summing up the percentages of exposure to beam, head and following seas of each weather node the ratios were found to be 35%, 20% and 45% respectively.

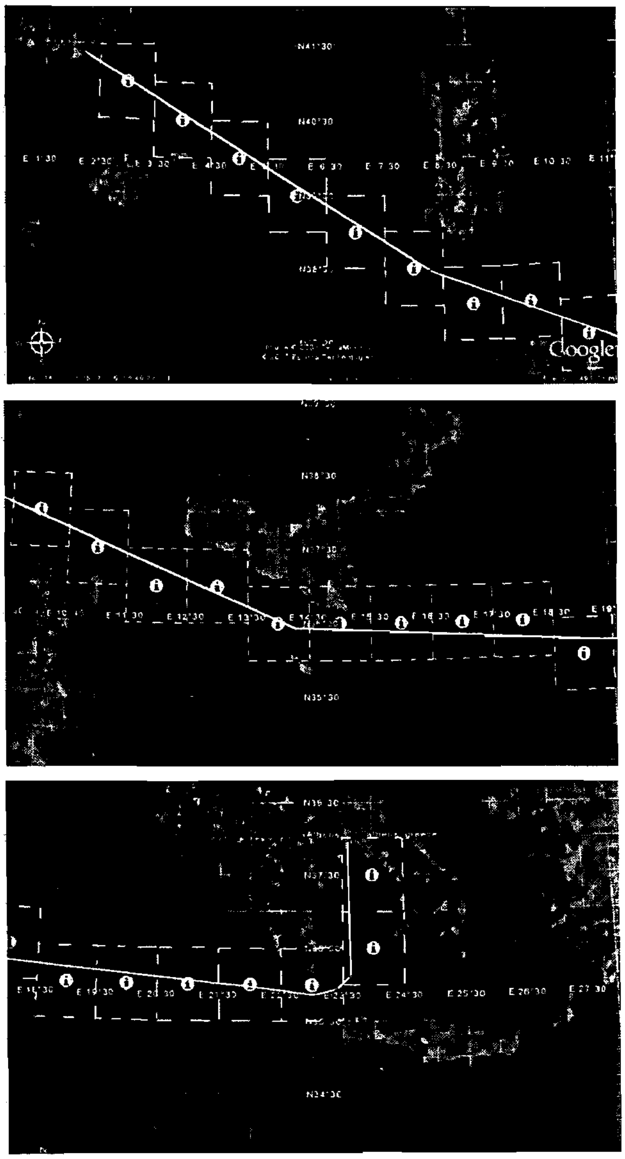

Figure 2: The selected route, placed weather nodes and their areas of influence.

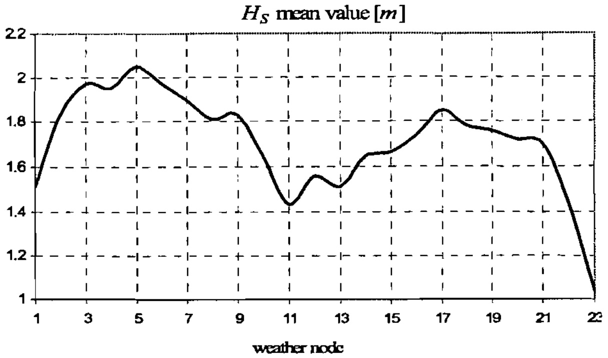

Figure 3: Variation of mean H_S along route (winter).

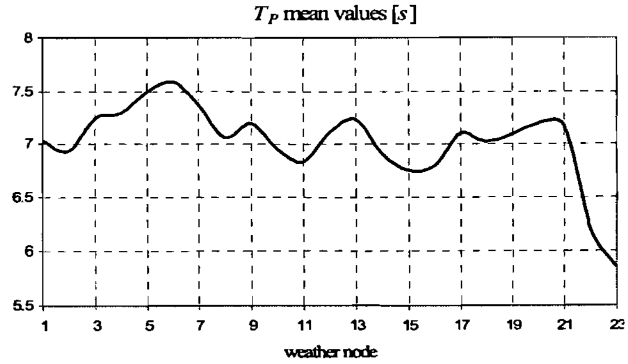

Figure 4: Variation of mean T_P, as above.

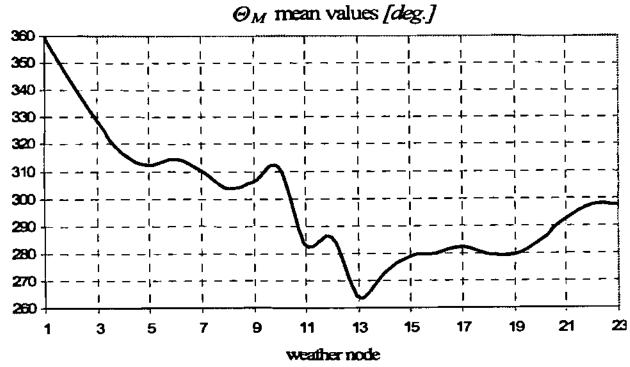

Figure 5: Variation of mean Θ_M (0^0 North, 90^0 East).

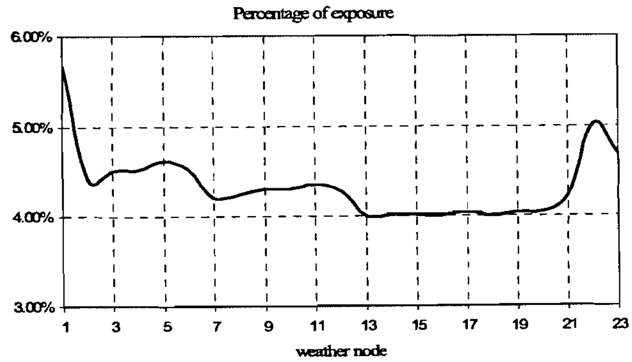

Figure 6: Local exposure to beam, head & following seas.

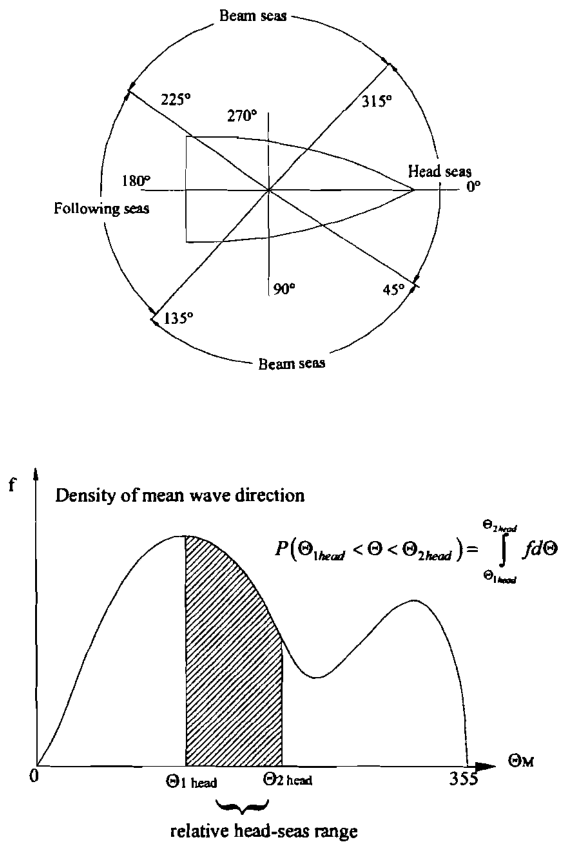

Figure 7: Convention for wave direction and example of probability of exposure time to head-seas.

5. NORMS OF UNSAFE RESPONSE FOR SHIP AND CARGO

Failure norms are formally establishing addressing the safety of the ship and of her cargo. These norms are expressed respectively through a critical roll angle for the ship and a critical acceleration for the cargo (in this case trailers) as explained next:

5.1 DIRECT CAPSIZE THRESHOLD

To determine a critical roll angle as a threshold of imminent "capsize", the principle of the weather criterion has been adopted (Figure 8). On the basis of hydrostatic calculation performed for the ROPAX it was concluded that, as ship capsize should be considered the exceedence of the minor of:

- the angle of vanishing stability determined as $\varphi_c = 63^0$;
- the flooding angle $\varphi_f = 35^0$;
- the ultimate angle of $\varphi_a = 50^0$ that is prescribed in the application of the weather criterion for balancing work against potential energy.

It accrues that 35^0 should be set as the critical roll angle.

5.2 SHIFT OF CARGO THRESHOLD

In terms of the cargo, the acceleration that could endanger the lashing of the remotest trailer was targeted as the critical response. The relevant calculating procedure follows closely IMO's cargo securing manual [12].

The tendency of the trailer for transverse sliding and tipping was checked for three different lashing arrangements regarding the vertical securing angle. The specific angles examined were $\left(30^0, 45^0, 60^0\right)$ which span the permissible range. The lashing arrangement contains three lashings symmetrically located on each side, assumed with 100 kN strength, which is the lower strength limit (DNV [13]). Trailer's mass, its centre of gravity above the deck as well as the friction coefficient between the deck and trailer's rubber are also involved [14]. The most critical transverse acceleration $\left(a_y = 6.04 \text{ m/s}^2\right)$ was found corresponding to transverse sliding and a vertical securing angle of 60^0.

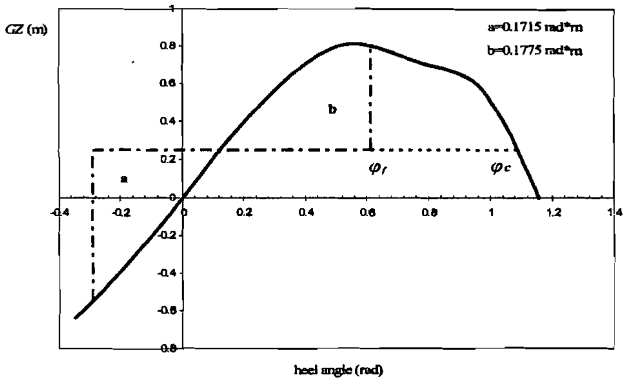

Figure 8: Application of the weather criterion.

6. CRITICAL WAVE GROUPS

In the context of the current application, critical wave groups have been identified for the following stability criteria: beam-sea resonance, parametric rolling in longitudinal seas and pure-loss of stability.

6.1 WAVE GROUPS LEADING TO BEAM-SEA RESONANCE

To determine the critical combinations of wave height, period and run length that could generate exceedence of norm, deterministic numerical simulation based on a mathematical model of coupled roll, heave and sway motions has been employed (see also Themelis & Spyrou [14]). The ship is assumed initially unbiased. Figure 9 and Figure 10 present the key characteristics of those thus identified critical wave groups, referring respectively to ship and trailer response. The practical range of wave periods has been covered. It is remarked that the wave breaking limit of Airy waves $(H/\lambda \,\square\, 1/7)$ restricts the identification of critical heights in the low period range (about $T_w < 8.5$ s).

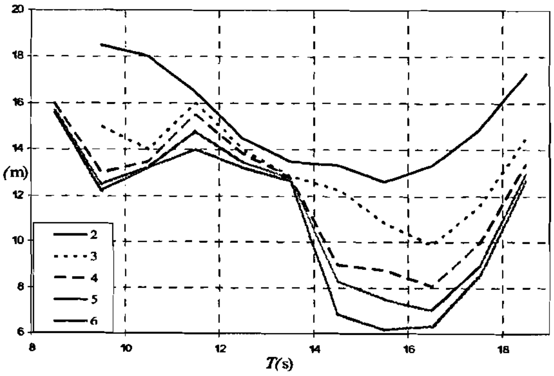

Figure 9: Critical wave groups with reference to the limiting roll angle (ship).

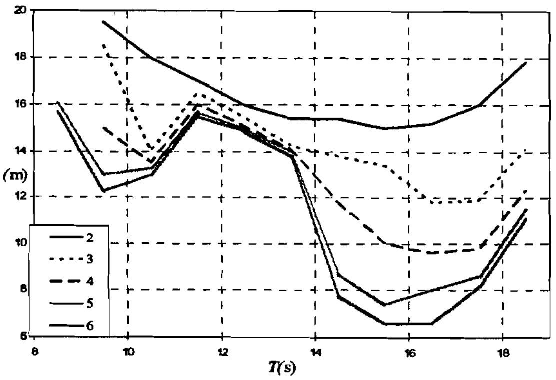

Figure 10: Critical wave groups with reference to the limiting transverse acceleration (cargo).

6.2 WAVE GROUPS LEADING TO PARAMETRIC ROLLING

In theory, this ship might present a tendency for head sea parametric rolling at the principal region of instability for a speed of $V_S = 22.5$ kn and for a wavelength equal to 1.5 times the ship length. Of course, other combinations of speed and wave length could also give rise to parametric rolling. These critical combinations could be predicted by setting the frequency parameter $a = \frac{4\omega_0^2}{\omega_e^2}$ around to 1.0, where as usual, ω_0 is the natural roll frequency and ω_e is the encounter frequency. An analytical criterion targeting the transient part (growth) of parametric rolling has been used (Spyrou [16]. This criterion produces the critical magnitude of parametric excitation h_{cr} that is necessary for realising a q - fold increase of an initial roll disturbance, within p roll cycles. In this criterion, which was applied here for a rather for a wide range of a values ($a \in [0.7, 1.2]$), the parametric excitation h is linked exclusively to the fluctuation of GM, in accordance to the following formula: $h = \frac{GM_{trough} - GM_{crest}}{2GM_{mean}}$. As well known, roll damping plays a critical role for the inception of parametric rolling and its value should be obtained with care. The obtained value of roll damping divided by roll moment of inertia (mass plus hydrodynamic) according to the numerical code of beam-sea rolling referred-to earlier, [16], was $k = 0.01039$ s^{-1}.

The targeted q-fold increase can be presented as the ratio of the critical roll angle (35^0 or the amplitude of roll oscillation during which the critical acceleration $a_y = 6.04$ m/s^2 is realised) to an uncertain initial roll disturbance which may be assumed during operation in a rough sea by the ship. We have considered this disturbance as distributed in the range $\varphi_0 = 0^0$ - 6^0 with 3 deg discretisation step and equal probability for each sub-range. In Figure 11 is shown the obtained critical parametric amplitude, assuming initial roll angle in the range $\varphi_0 = 0^0$ - 3^0. If p parametric roll cycles were necessary for realising the targeted growth, these should result from about $2p$ critical waves of the encountered group.

Thereafter, the amplitudes of parametric excitation h_{cr} may be converted into respective critical wave heights, taking into account the ship form. This is depicted in Figure 12. It is worth to mention that, for small run lengths (less than 5 wave encounters), the required wave heights are quite excessive and it was opted not to include these in the respective diagram.

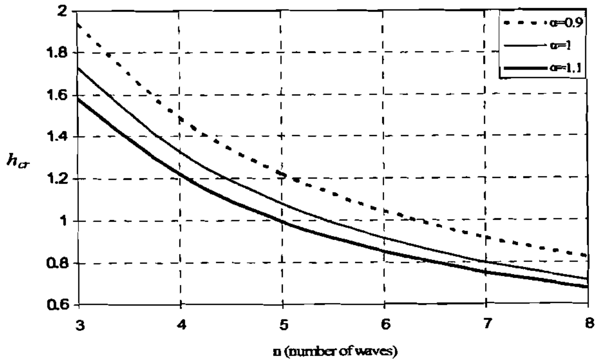

Figure 11: Critical parametric roll amplitudes assuming an initial roll angle in the range φ_0=0^0 - 3^0.

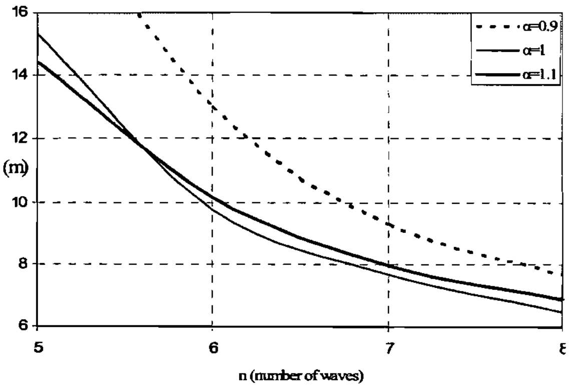

Figure 12: Required wave height for reaching the critical roll angle from an initial roll disturbance.

6.3 CRITICAL WAVE ENCOUNTERS FOR PURE - LOSS OF STABILITY

Pure-loss of stability in astern seas is based on the single encounter of a critical wave and in this respect this phenomenon can be treated separately from parametric rolling although both accrue from the fluctuating righting-arm. The procedure for the determination of the critical waves that could lead to pure-loss of stability is based on a procedure described in [17]. The key idea exploited is that the critical fluctuation of GZ can be identified on the basis of the following condition: the time of experiencing negative restoring in the vicinity of a crest should be, at least, equal with the time that is necessary for developing capsizal inclination, assuming an initial roll disturbance. Unlike a resonance phenomenon, this growth is relatively slow and the condition on the ship norm should prevail over the condition on the cargo.

In Figure 13 is shown the calculated h_{cr} for various values of λ/L. Its reflection in terms of wave height for the ROPAX ferry can be obtained from Figure 14.

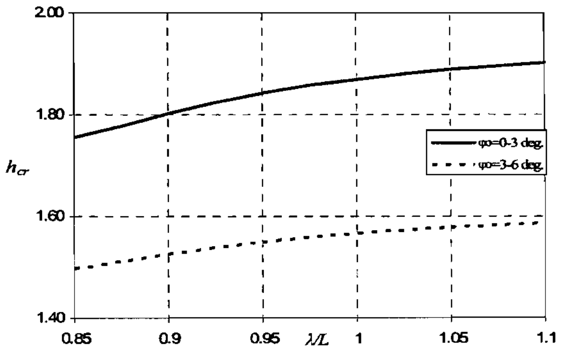

Figure 13: Critical values of h for pure-loss of stability for the two ranges of initial roll angles.

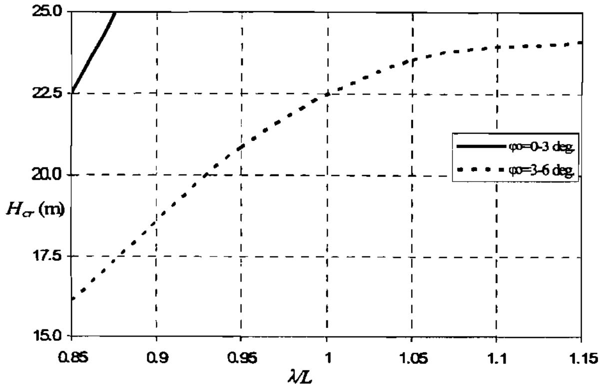

Figure 14: Critical wave heights for pure-loss of stability

7. LONG-TERM PROBABILITIES OF INSTABILITY DURING JOURNEY

The performed assessment study had a "long-term" character. It focused on the ferry's operability during the winter season with reference to the prescribed Mediterranean route. For the calculation of basic probabilities the JONSWAP spectrum has been used. Also, rather than using probability figures that refer essentially to number of wave encounters irrespectively of their periods, we considered as more meaningful to convert probabilities of instability into "critical time ratios" using the formula $\bar{t}_i = \frac{t_i}{t_{tot}} = P_i \frac{T_i}{T_m}$ where P_i is the calculated probability of a wave group i having wave period around the value T_i; t_{tot} is the duration of the part of the voyage inside the rectangle of the considered node and T_m is the mean spectral period associated with the same node.

Critical time ratios were subsequently calculated for the mean "winter" values of H_S and T_P for each one of the placed weather nodes of the Mediterranean route. The obtained results are presented by means of a new type of performance diagram that illustrates the scaled critical time per node for each type of instability along the route. From this diagram one can easily deduce which type of instability is more likely to occur at any specific stage of the journey. Such a "localised" probabilistic figure of instability could be a valuable piece of information for weather routeing and decision support. It should be remarked that the time scaling is local (time in vicinity of node).

In Figure 15 and Figure 16 are overlaid the three obtained "critical time ratio" curves, for the ship and her cargo respectively. In Table 2 are presented the total probabilities and critical time ratios for the complete voyage taking into account the percentage of exposure to beam, head and following seas.

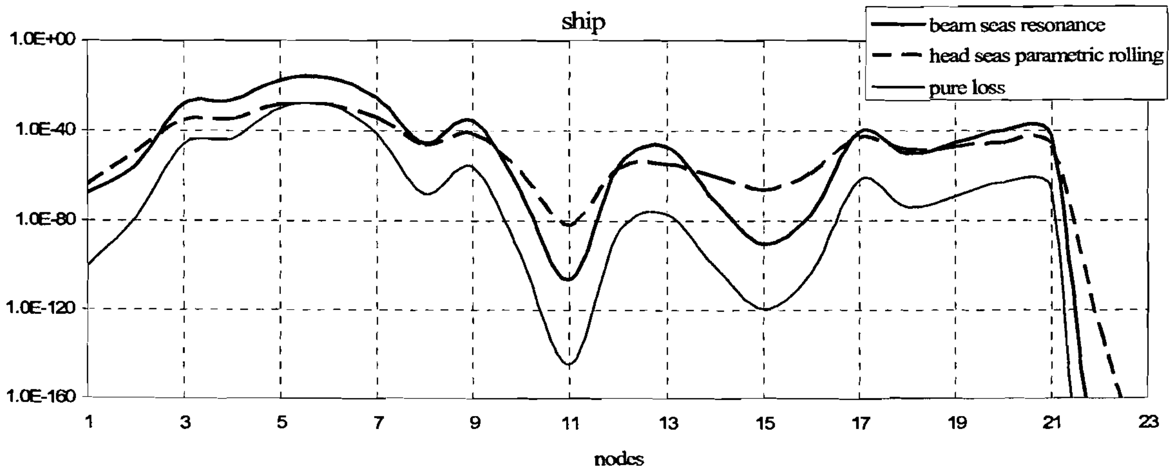

Figure 15: Collective view of "critical time ratio" diagrams for ship.

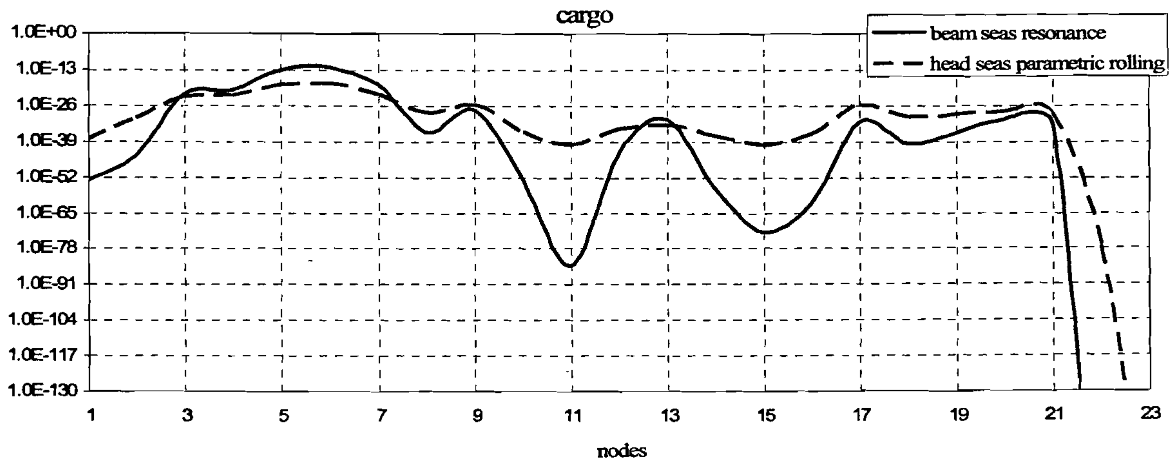

Figure 16: Collective view of "critical time ratio" diagrams for cargo.

Table 2 Summed probability of instability and associated "critical time".

	P_i	$\bar{t}$
Ship: ($\varphi > 35^0$)	6.58E-17	9.55E-17
Cargo: ($a_y > 6.04 m/s^2$)	7.84E-13	1.14E-12

8. FURTHER STUDIES

A key finding accruing from the analysis of the ROPAX is that she shows extremely low probability of instability when mean seasonal values are considered, even for the winter season. Such a perspective of analysis could produce valuable inputs towards decision-making in the course of ship design process as the risk of specific capsize modes could be assessed quantitatively and in an objective manner. On the other hand, from an operability perspective, it could be of equal interest for investigating how the obtained probability figures vary according to short-term values of H_S and T_P. For such a calculation the joint probability (H_S, T_P) needs to be taken into account. Here two cases have been selected for further investigation, representing comparatively extreme wave conditions. In Table 3 are defined the assumed ranges of variation of wave parameters together with their mean values. In Figure 17 is shown the joint probability of significant wave height and peak period per weather node (again for winter). All other assumptions, for example concerning initial conditions, are identical with those of the previous application.

Susceptibility to dangerous beam-sea resonant rolling could be assessed from Fig. 18. Indeed, the strong dependence of probability on the peak wave period is well reflected. Also, the higher range of peak periods corresponds to higher probability as this range is nearer to resonance.

Table 3: Wave parameter values of parametric study.

Case	H_S (m)	Mean H_S (m)	T_P (s)	Mean T_P (s)
1	3–4	3.5	9.795–10.775	10.285
2	3–4	3.5	10.775–11.885	11.330

Similarly, susceptibility to parametric rolling is shown in Figure 19. As the wave periods obtain lower values, it is more probable to encounter critical wave groups. In Figure 20 is shown the dependence on initial conditions and is obvious the considerable effect of these on the obtained probability.

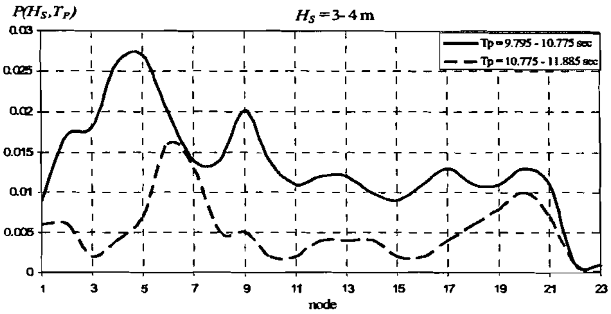

Figure 17: Joint probability of H_S and T_P along the route for two different bands of T_P values (winter).

Respective diagrams for pure-loss of stability are presented in Figure 21 and Figure 22.

Finally, the modified collective result for the harsher weather conditions considered in this example, assuming rather simplistically to hold uniformly for the entire route, is shown in Table 4.

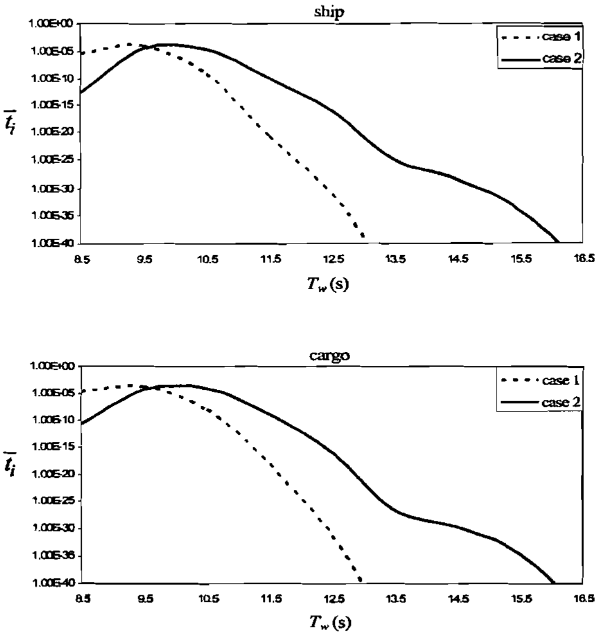

Figure 18: Critical time ratio of beam-sea resonance for the two sub-ranges of wave period (upper for ship and lower for cargo).

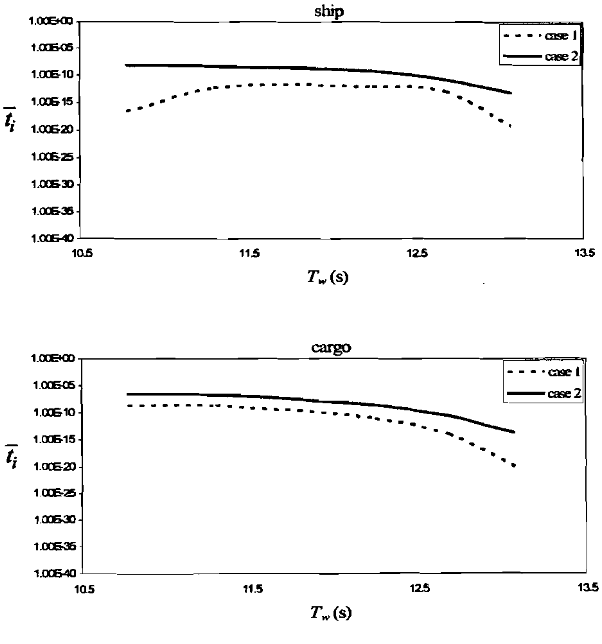

Figure 19: Critical time ratio of parametric rolling (upper for ship and lower for cargo).

Table 4: Critical time ratio for complete voyage.

	Case 1	Case 2
Ship: ($\varphi > 35^0$)	3.55E-05	2.12E-05
Cargo: ($a_y > 6.04$ m/s^2)	7.60E-05	4.08E-05

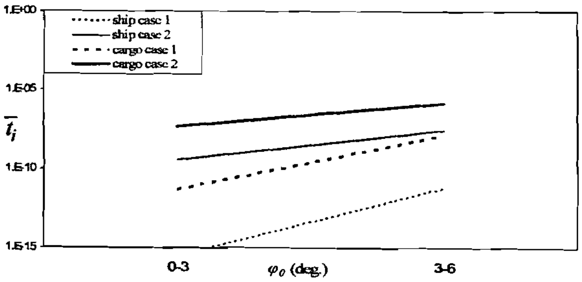

Figure 20: Critical time ratio of parametric rolling showing effect of initial condition (ship and cargo).

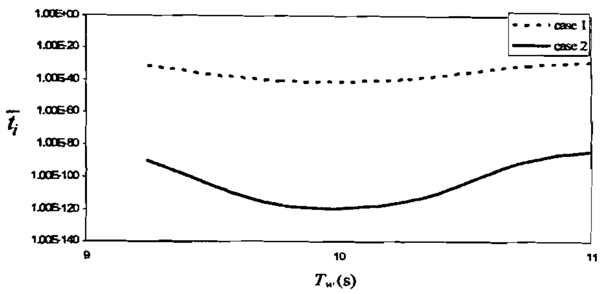

Figure 21: Critical time ratio of pure-loss for the two sub-ranges of wave period (ship).

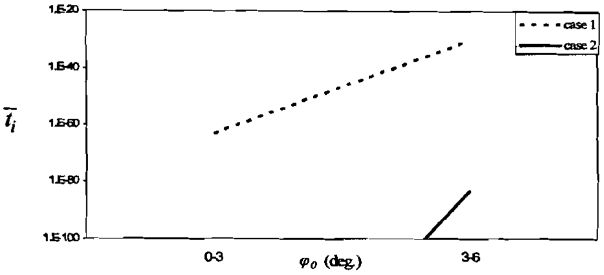

Figure 22: Critical time ratio of pure-loss of stability showing effect of initial condition (ship).

9. CONCLUDING REMARKS

The intention behind the present work was to develop a probabilistic stability assessment methodology that combines practicality with scientific rigour. Application has indicated that the methodology produces results that appear to be logical and in accordance with expected trends. The pending implementation to another ship type and the consideration of the effect of risk control options should provide a more definitive answer about its effectiveness.

10. ACKNOWLEDGEMENTS

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