# OPERATIONAL GUIDANCE FOR PREVENTION OF CONTAINER LOSS

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**ABSTRACT**

Lack of ship-specific operational guidance assisting the ship master can lead to excessive motions and accelerations of container ships in heavy seaways and thus loss and damage of cargo. The paper outlines considerations regarding such operational guidance, including factors related to cargo loss and damage, relevant probabilistic criteria and standards, and methodology of numerical simulations. These considerations are illustrated by numerical examples for a modern container ship.

**Keywords:** *operational guidance, cargo loss, numerical simulations*

## 1. NOMENCLATURE

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| $B_{wl}$ | waterline breadth |
| $f$ | long-term probability density distribution of wave heights and periods |
| $f_v$ | probability density function of the forward speed |
| $g$ | acceleration due to gravity |
| $h_s$ | significant wave height |
| $L_{pp}$ | length between perpendiculars |
| $p$ | probability |
| $r$ | exceedance rate |
| $R_2$ | short-term standard |
| $T_z$ | zero upcrossing period of the seaway |
| $T_1$ | mean seaway period |
| $T_\varphi$ | roll period |
| $v$ | ship speed |
| $\mu$ | mean seaway direction (0 and 180° for following and head seas, respectively) |

## 2. INTRODUCTION

Modern container ships may be susceptible to excessive motions and accelerations in waves, partly due to their hull form, and partly due to the lack of operational guidance assisting the master. According to the analysis by Langbecker et al. (2007) of the historic accident data from Lloyd (2004) for the period 1993-2004, heavy weather is accountable for about 62% of the container loss events. In addition, the present tendency of increasing ship sizes and changing typical relations of main dimensions may challenge the established experience of ship designers and operators and increase the frequency of dynamic stability accidents in the future.

This issue should be dealt with both in design and operation. IMO is currently developing the new generation intact stability criteria, containing also requirements to ship-specific operational guidance, which should address dynamic stability problems including cargo loss and damage. GL is working on guidelines, aiming at the reduction of intact stability accidents for container ships. These guidelines will support the ship designer with design assessment procedures, and the ship operator with ship-specific operational guidance. Both developments build upon numerical simulations of ship motions and probabilistic measures of safety in seaway.

This paper outlines considerations regarding operational guidance, including identification of factors related to cargo loss and damage, discussion of the relevant probabilistic criteria and standards, methodology of numerical simulations and ideas about a convenient form of operational guidance. Examples are presented for a container ship with $L_{pp}$=317.4 m and $B_{wl}$=43.2 m, for a range of *GM* values.

## 3. FACTORS RELEVANT TO CARGO LOSS AND DAMAGE

Cargo loss and damage occurs due to several factors, including large accelerations, green water events and wave impacts, deformed and pre-damaged containers, locks and lashing, improper vertical mass distribution in a container stack etc. Only some of these problems can be dealt with in operational guidance, namely those which can be related to motions and accelerations. The remaining factors should be covered by other regulations. All such regulations should be harmonised in order to ensure a consistent approach.

Large lateral accelerations occur mostly due to excessive roll, and to some extent also due to yaw and sway motions. For container ships, excessive roll motions can happen due to principal and fundamental parametric resonance, synchronous rolling, pure loss of stability on wave crest and successive oblique wave impacts. Lateral accelerations due to excessive roll consist of a gravity component, maximum of which grows as sine of roll amplitude, and inertial contribution, growing as roll amplitude times squared roll frequency. The first term is usually dominating; however, the second can also be significant for load cases with larger *GM* and high container stacks. Large lateral accelerations are also possible due to slamming impacts and whipping.

Large normal accelerations are caused most frequently by heave and pitch motions. These motions can usually be assumed linear with sufficient accuracy, and therefore, Gaußian-distributed in natural seaways. Thus statistical measures of vertical accelerations can be derived from linear hydrodynamic calculations in the frequency domain in combination with e.g. Rice formula for the exceedance rate of the limiting levels of normal accelerations.

There is, however, another important cause of large vertical accelerations, namely the whipping response of a ship to slamming impacts. This cause becomes increasingly important with container ships growing in size and becoming relatively less stiff. Here, both hydrodynamics and statistics are highly nonlinear and can only be dealt with by special numerical tools.

Green water events and wave impacts are also responsible for a large share of cargo loss and damage on container ships. They are more relevant for smaller ships with lower freeboards, although larger ships can also experience them. For example, the investigation by France et al. (2003) of the well-known accident with the C11 container ship in 1998, most of losses in which are attributed to parametric rolling, also mentioned that wave impact damage occurred to forward container stacks from bow seas and along the entire starboard side from boarding seas.

## 4. GENERAL APPROACH TO OPERATIONAL GUIDANCE

Operational guidance should differentiate, which combinations of operational parameters are acceptable and which not, for any given loading and seaway conditions. In order to do this, operational guidance needs some short-term measures of safety, i.e. measures related to the particular loading, seaway and operational conditions (short-term criteria), as well as the boundary between acceptable and unacceptable values of the short-term criteria (short-term standards).

One possible approach to setting a short-term standard is to require that this standard should insure, on the average, the necessary level of safety expected by the society from the operation of cargo ships. Therefore, this approach requires also long-term (i.e. average over large number of ships, loading conditions, routes, seaways and operational parameters) measures of safety – long-term criteria – and the corresponding long-term standards (the boundary between the acceptable and unacceptable levels of long-term criteria). This approach is discussed in sections 5 and 6.

Another way to defining the short-term standards is possible, based on cost-benefit considerations: the selected value of the short-term standard should maximise the difference between the additional benefits per time and additional costs per time incurred due to the use of operational guidance. For example, a stricter short-term standard increases costs due to the increase of the not allowed conditions and thus time on route with the same load, while benefits increase because of reduced rate of cargo loss and damage. Such an approach however requires simulation tools, which are able to predict the increase of the time on route due to various operational decisions, and the corresponding additional costs. Besides, the results will be sensitive to input variables which are difficult to estimate, e.g. the average cost of a lost container, costs due to schedule changes and delays etc.

## 5. LONG-TERM CRITERIA AND STANDARDS

The consequences of cargo loss and damage are mostly economical, therefore long-term criteria should make economical sense. It is convenient therefore to express the long-term criteria and standards in terms of the average rate of losses, i.e. the expected number of losses per time. As a starting point, TEU lost and damaged per TEU transported for the considered fleet (e.g. particular ship series or type) appears appropriate. A similar, but easier to use measure is TEU lost and damaged per ship per time.

The drawback of such criteria is that they are difficult to calculate with the usual seakeeping tools, because they require an estimation of the number of lost and damaged containers in each event. Therefore, other long-term criteria are often used, e.g. the number of cargo loss and damage events per ship per time.

Both types of criteria can be easily related to historical accident data; the criteria of the second type can be calculated using the usual seakeeping simulations. Their drawback is that the consequences of cargo loss events are not taken into account, therefore criteria of this type may require different standards for different ship sizes, container allocation etc.

In order to ensure the appropriate level of safety, long-term standards can be defined from historical data about cargo losses, e.g. data from insurance companies. Another possibility is harmonisation with other rules, regulations and expectations, related to the risk of losses and damages: cargo risks in other transport modes, acceptable insurance risks etc. For example, the average rate of cargo losses estimated from numerical simulations for several ships with a good cargo safety record can be set as the long-term standard.

## 6. SHORT-TERM CRITERIA AND STANDARDS

The ‘long-term’ criteria as such are average safety measures over all conditions encountered by the fleet under consideration (load cases, seaways, operational conditions etc.) Although they are necessary as a starting point, support of decision-making onboard requires criteria and standards expressed in terms of the actual seaway parameters and operational conditions (i.e. ‘short-term’ criteria and standards). There is certain freedom in the selection of the short-term criteria and standards, as long as they ensure the acceptable long-term level of safety.

It appears however convenient to use probabilistic measures as short-term criteria, because they can be easier related to long-term criteria. Several authors (see e.g. McTaggart and DeKat, 2000, and McTaggart et al., 2002) successfully used hourly or half-hourly exceedance probability of certain (large) roll angle as short-term criterion for the likelihood of capsize.

Exceedance rate appears a more convenient basis for short-term criteria, because it does not depend on the (arbitrarily) chosen time intervals. Besides, exceedance probability depends exponentially on the exceedance rate, which makes criteria based on rate more sensitive.

An even more convenient short-term criterion appears to be the product $r_f = r \cdot f$ of the short-term exceedance rate $r$ with the probability density function $f$ of the corresponding seaway: using such a criterion automatically allows higher short-term risks in severe (and very rare) seaways while increases safety margin in frequent seaways.

An example of colour polar plots of $r_f$, based on the exceedance rate of the maximum lateral acceleration $0.5g$ is shown in Figure 1 in the axes mean wave direction $\mu$ – mean seaway period $T_1$ (circumferential and radial coordinates, respectively) for several ship speeds for three load cases.

Irrespectively of the particular short-term criterion used in the operational guidance, their polar plots cannot be used directly to support decision-making onboard: the ship master cannot decide, what risk levels are acceptable, especially because the relation between the short-term criteria and long-term safety is not straightforward. Therefore, the operational guidance should unambiguously differentiate between acceptable and unacceptable conditions, using pre-defined short-term standards. Here, the following rule is used: to avoid conditions, for which

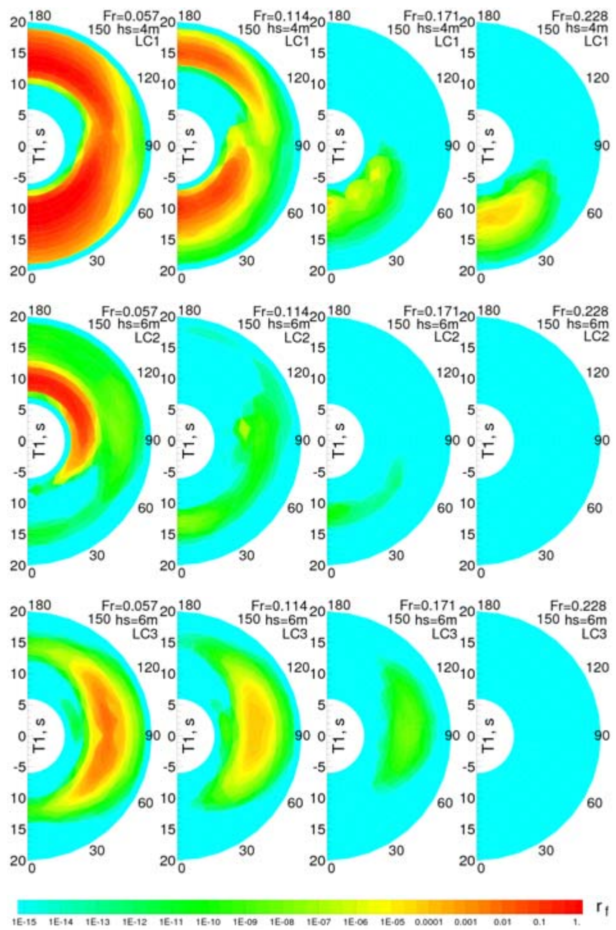


Figure 1. Polar plots of $\ln(r_f)$ vs. mean wave direction and mean wave period for different ship speeds (increasing from left to right); $GM$=0.97 (top), 2.28 (middle) and 4.66 (bottom) m.

$$r_f > R_2 , \tag{1}$$

where $R_2$ is the short-term standard.

The following approach to the definition of a ship-specific short-term standard $R_2$ was tested: the long-term exceedance rate was calculated as a function of the short-term standard $R_2$ by averaging over load cases, seaway conditions and operational parameters. The value of $R_2$ leading to the appropriate long-term safety level can then be used in the ship-specific operational guidance. For this purpose, the average (long-term) exceedance rate was calculated as

$$\bar{r}(R_2) = s \sum_{LC_i} p_{LC_i} \cdot \int_{\mu}\int_{T_1}\int_{h_s}\int_{v} \min\left(r_f , R_2\right) f_v \, dv \, dh_s \, dT_1 \, d\mu , \tag{2}$$

where $s$ is the fraction of time at sea (50% used here as an example), $r(\mu,T_1,h_s,v,LC)$ in $r_f = r \cdot f$ is the short-term exceedance rate of the maximum lateral acceleration 0.5*g*, found from numerical simulations, and $f(\mu,T_1,h_s)$ is the p.d.f. of the encountered seaway conditions. The seaways were simulated using JONSWAP spectrum with $\gamma = 3.3$ and $\cos^2$-spreading of wave directions. The long-term probability density function of wave heights and periods was calculated from the long-term scatter table for the North Atlantic from Söding (2001), while wave directions were assumed uniformly distributed.

$p_{LC_i}$ in (2) is the probability of the loading condition $LC_i$. Here, for the loading conditions with *GM*=0.97, 2.28 and 4.66 m, the respective probabilities were taken equal to 0.25, 0.5 and 0.25. Finally, $f_v(\mu,T_1,h_s,v)$ is the probability density function of the forward speed.

Establishing the speed profile is an important step in the preparation of ship-specific operational guidance, because the likelihood of extreme roll motions is very sensitive to the forward speed.

One factor to consider is the involuntary speed loss due to the added resistance and reduced propulsion efficiency in waves.

Another part, voluntary speed reduction, occurs due to the attempts of the ship master to reduce the risk of vertical accelerations, slamming, green water events etc. These factors require a special treatment in the integration (2): if the operational guidance addresses all or some of these phenomena when it provides recommendations to the ship master about acceptable and unacceptable conditions, the reduced likelihood of these phenomena is already accounted for in the factor $\min(r_f, R_2)$. In this case, their consideration also in the speed profile $f_v$ would lead to double-counting.

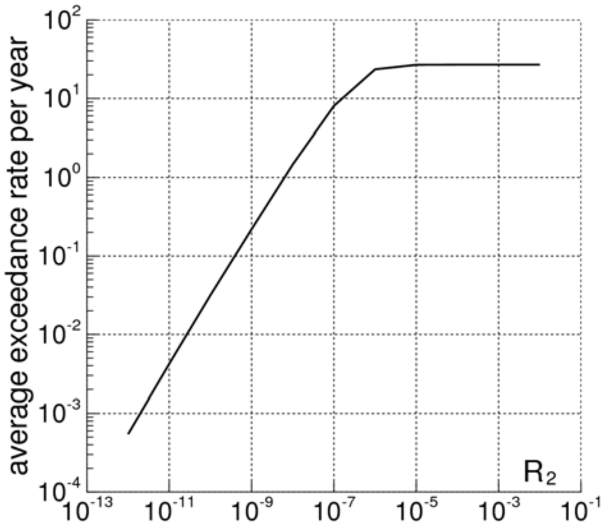


Figure 2. Average annual exceedance rate $\bar{r}$ vs. short-term standard $R_2$.

Therefore, the following approach to the definition of the speed profile $f_v(\mu,T_1,h_s,v)$ seems appropriate when the short-term ship-specific standard $R_2$ is established using integration (2): the forward speed profile should reflect the total involuntary speed loss, as well as the voluntary speed reduction; the latter however taking into account only those phenomena that are not addressed directly by the operational guidance and thus, not accounted for in the short-term criteria.

The resulting dependence of the average (i.e. long-term) exceedance rate $\bar{r}$ on the short-term standard $R_2$ is plotted in in Figure 2, showing that for the considered container ship, $R_2 \approx 10^{-10}$ leads to $\bar{r} \approx 0.02$ per year (i.e. the maximum lateral acceleration exceeds 0.5*g*-level once per 50 years of ship's life).

## 7. OPERATIONAL GUIDANCE

The operational guidance should show in an unambiguous way the unacceptable combinations of seaway and operational parameters, i.e. those for which $r_f > R_2$.

An important question is whether such polar plots can be pre-calculated with standard seaway spectra and stored in a booklet or an electronic database, or they should rely on onboard simulations for the actual wave spectra.

Pre-calculated databases can be derived from more accurate (and therefore, more time-extensive) simulations, carried out by experts and, if necessary, verified by comparison with the results of other numerical tools and model experiments. On the other hand, such simulations can only be done for simplified standard seaway spectra: for example, consideration of cross-seas appears difficult because of the large number of variables necessary to describe cross-seas.

Onboard simulations, on the other hand, can be carried out for the actual seaway, taking account of the actual spectra, including cross-seas. The drawback of this approach is the need

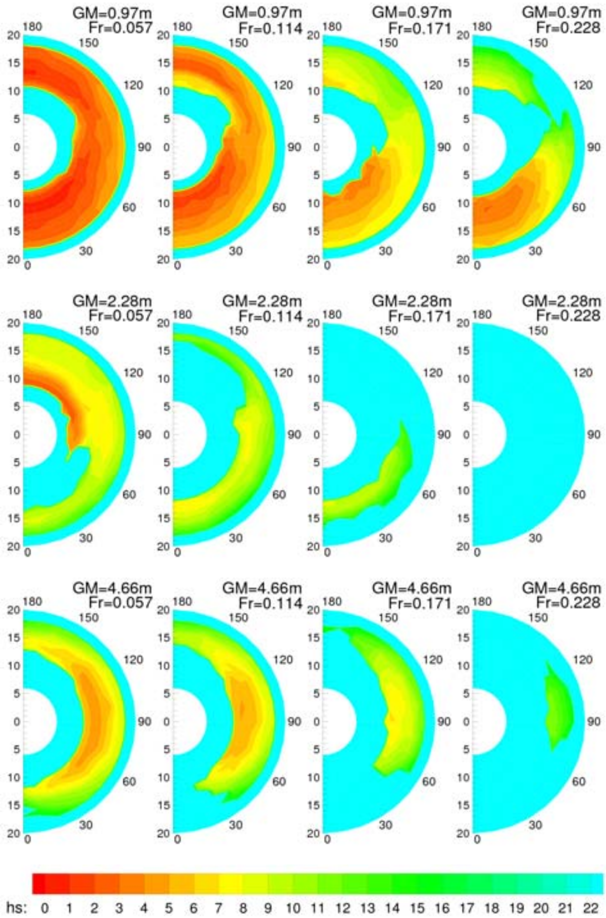


Figure 3. Maximum acceptable significant wave height vs. seaway period and wave direction for different speeds and load cases

to quickly carry out a large number of simulations (the number of possible courses times the number of possible speeds), in order to assist the ship master in the selection of the acceptable operating parameters. Besides, such onboard simulations have to be fully automatic, i.e. not requiring tuning by the user, which imposes serious requirements on the robustness of the numerical simulation tool used onboard.

As an illustration, Figure 3 shows the largest allowed significant wave height vs. ship speed (increasing from the left to the right), mean wave direction (circumferential coordinate) and mean seaway period (radial coordinate) for *GM*=0.97 (top), 2.28 (middle) and 4.66 (bottom) m, defined from the condition $r_f = 10^{-10}$; $r_f$ is based on the exceedance rate of the maximum lateral acceleration 0.5*g*.

The figure means: if the ship master avoids the combinations of the ship speed and course, for which the actual significant wave height exceeds the significant wave height shown in Figure 3 for the corresponding seaway period, then the expected long-term exceedance rate of the maximum lateral acceleration 0.5*g* will not exceed the rate of once per 50 years. Particular form of operational guidance (software with a graphical user interface, booklet, alarm or a combination of these means) is out of scope of this paper; an illustration can be found in Rathje (2004).

## 8. ACCELERATION OF SIMULATIONS

If the average exceedance rate is estimated from numerical simulations, they may be rather time-consuming as the exceedance rates of interest are low. Several ways have been proposed so far for the acceleration of such simulations.

McTaggart and DeKat (2000) proposed the application of a statistical fit to roll amplitudes, obtained from numerical simulations of certain duration. McTaggart (1999) has shown that a two-parametric Gumbel distribution is suitable for modelling of the distribution of maximum roll amplitudes. The parameters of the Gumbel distribution can be obtained either using the method of moments, relating the distribution parameters to the mean and standard deviation of the computed roll amplitudes, or applying a least squares fit between the c.d.f. of the computed roll amplitudes and the theoretical c.d.f. Results of McTaggart et al. (2002) suggest that 10-50 simulations of 30-60 min. duration can provide sufficient data for the estimation of hourly short-term capsize probability.

In cases with too high exceedance probability, the distribution of roll amplitudes can deviate significantly from Gumbel distribution. On the other hand, if the exceedance probability is too low, simulation data are not sufficient for a reliable extrapolation. Therefore, care is required in the selection of the range of the roll amplitudes used for the fit. Note also that the distributions of large roll amplitudes obtained from numerical simulations with the available seakeeping tools may not be accurate enough: Levadou & Gaillarde (2003) found that the distributions of the roll amplitudes differ considerably between simulations and model tests, even though the maximum values are quite close. Besides, an extrapolation to larger roll angles than those actually occurring in the simulations may be misleading if the *GZ* curve, and thus probabilistic characteristics of roll motion, change significantly for larger roll amplitudes.

The approach of Spyrou (2005) and Themelis & Spyrou (2006) relates the probability of excessive roll motions in irregular waves to the probability of encountering specific 'critical' wave groups. The parameters (height and duration) of such wave groups are determined from numerical simulations of ship motions in regular waves, while the probability of encountering wave groups with the prescribed parameters in natural seaway is derived from the integral properties of the seaway and its duration. The approach is based on some assumptions, requiring validation; besides, it is not clear yet how to handle in practice the sensitivity of the results to initial conditions.

Another possibility is the extrapolation of the exceedance rate over significant wave height proposed by Tonguć & Söding (1986), based on the assumption that rare exceedance events happen because of few large waves, which are known to satisfy Rayleigh distribution. The assumption that rare exceedance events occur with a certain, although unknown, probability, if a certain (unknown) number of successive wave amplitudes exceed a certain (also unknown) limit value leads to a linear dependency of the logarithm of exceedance rate per roll period $r_\varphi = rT_\varphi$ ($T_\varphi$ is the roll period) on the reciprocal of the squared significant wave height:

$$-\ln\left(rT_\varphi\right) = A + B/h_s^2\ . \tag{3}$$

This method works for any dynamic stability problem, although the number of successive large waves required to excite large roll angles may be different for different problems (i.e. the parameters *A* and *B* in (3) vary with wave direction and period, as well as ship speed).

Examples of the dependencies of $-\ln(T_\varphi/\tau)$, where $\tau=1/r$, on $1/h_s^2$ are shown in Figure 4 for different load cases, seaway conditions and operational parameters, including cases of resonance rolling.

A similar dependency of the exceedance rate on the significant wave height was observed recently in the application of the FORM method (Der Kiureghian, 2006) to parametric roll by Jensen (2007). In this method, wave trains are searched which lead to the exceedance of a prescribed roll angle at the given time instant. The limit state surface wrapping such wave trains is described in the space of the amplitudes of wave components modelling the given seaway spectrum. The point on the limit state surface with the shortest distance to the origin (design point) corresponds to the wave train with the highest probability of occurrence (critical wave scenario), leading to an exceedance at a given time instant. The distance $\beta$ of the design point to the origin is called the reliability index.

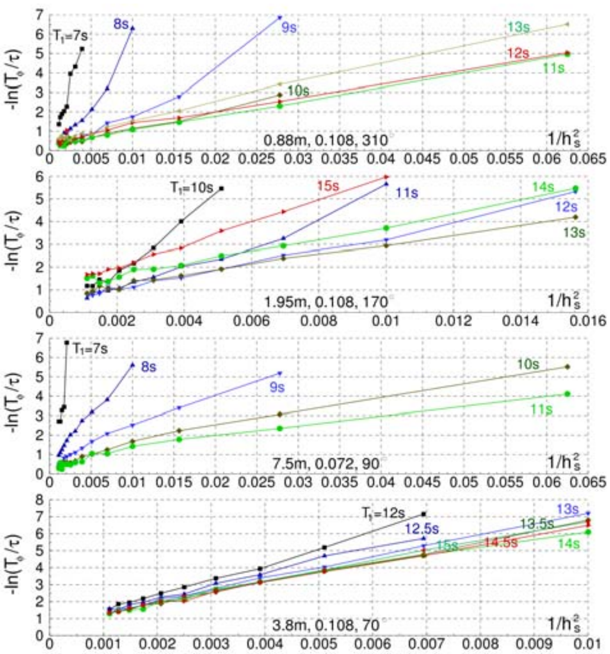


Figure 4. $-\ln\left(rT_{\varphi}\right)$ vs. $1/h_s^2$; the numbers above horizontal axes indicate *GM*, Froude number and wave direction

If, for given $\mu$, $T_1$ and wave spectrum shape, the failure mode does not change with $h_s$ (which is usually true for low exceedance rates), the shape of the critical wave episode becomes independent of $h_s$, which means that the design point coordinates simply scale with the reliability index; then the exceedance rate becomes

$$rT_z \approx \exp\left(-\beta^2/2\right), \tag{4}$$

and the reliability index $\beta$ becomes inversely proportional to the significant wave height.

A parametric study of the influence of $h_s$, $T_z$ and $v$ on $\beta$ by Jensen (2007) confirmed this dependency. Note that using $r_{\varphi}=r\,T_{\varphi}$ in (3) appears more convenient than using $r\,T_z$ in (4), because the natural roll period may change with roll amplitude and thus, with wave height; a comparison of these two forms is necessary.

In Figure 4, the dependencies of $-\ln r_{\varphi}$ on $1/h_s^2$ become linear when $r_{\varphi}$ is so small that $-\ln r_{\varphi}>4$. This means that the calculated rate can be used for extrapolation, if the average exceedance period in the simulation is not less than about 50 roll periods.

## 9. METHODOLOGY OF SIMULATIONS

In order to model random events that occur independently of each other, a model of the Poisson counting process can be used. However, the condition of the independence may be questionable for roll motions, because upcrossings of large roll angles tend to appear in groups.

In order to cancel the influence of the strong auto-correlation of roll motion, one possibility is to count exceedance events for the envelope of roll motion instead of the time history of the roll motion itself; Belenky & Breuer (2007) successfully applied this approach to parametric roll. The required number of upcrossings before achieving sufficient accuracy may however be large, therefore the required run lengths may be very long when using this method. This can lead to self-repetition of seaway in numerical simulations if the number of wave components used to model the spectrum is insufficient.

Therefore, average estimations from multiple realisations of the same seaway may be more efficient. Following Söding (1987), the following method was used here: each simulation was continued only until the first exceedance event; then the ship was returned to the upright position and the simulation was repeated with the new set of random phases, frequencies and directions of seaway components (modelling the same seaway spectrum) until the next exceedance event. The estimation of the expected exceedance period is then found as the average of the exceedance periods obtained in all simulations.

This method needs less computational time than the envelope approach; besides, the method is statistically more reliable, because the average estimates of the exceedance interval or exceedance rate are derived from many statistically independent seaway realisations.

The c.d.f. and p.d.f. of non-dimensional (with respect to the average exceedance period)

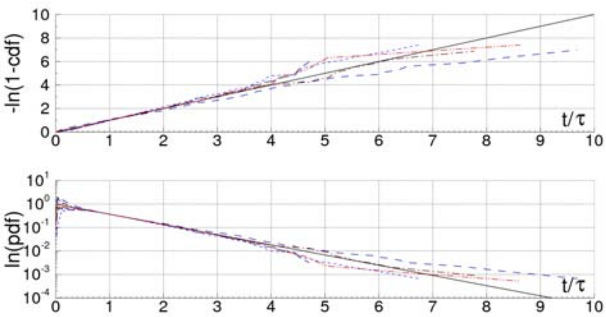


Figure 5. $-\ln(1-\text{c.d.f.})$ (top) and $\ln(\text{p.d.f.})$ (bottom) of non-dimensional exceedance periods obtained from numerical simulations

exceedance periods from individual runs are plotted in Figure 5, showing $-\ln\left(1-\text{c.d.f.}\right)$ and $\ln\left(\text{p.d.f.}\right)$ vs. non-dimensional time between upcrossings. All simulations were carried out for 2000 upcrossings, for different mean wave directions and periods and different forward speeds. The obtained distributions are sufficiently close to exponential (shown with solid lines); some deviations for small exceedance periods are because of the use of the same initial conditions (upright ship) in each run. Exponential distribution of the time interval until the first exceedance event means that the model of Poisson processes can be applied, together with the proposed simulation methodology. However, care should be taken of too small exceedance periods, for which the influence of the initial conditions may be too large.

To address this problem, the following approach was used here: to neglect in the averaging procedure all exceedance periods that are smaller than $n_\varphi T_\varphi$, where $n_\varphi$ is a given threshold and $T_\varphi$ is the average roll period in the simulation. Note however, that simply neglecting too small exceedance periods in the averaging increases the estimation of the expected upcrossing period compared to its expected value by $n_\varphi T_\varphi$, thus this value should be subtracted from the obtained estimation. Numerical tests show that $n_\varphi = 5$ is sufficient when average exceedance period is of interest.

Another question is the required duration of simulations. Here, the simulations were carried out not for a prescribed simulation time (in this case, accuracy would be too high for cases with high exceedance rates and too low for the ones with low exceedance rates), but for a prescribed number of exceedance events. According to numerical tests, the required number of exceedance events varies from about 50 to 150, depending on the conditions. Whether and how this number can be reduced (e.g. for experiments or onboard simulations), requires additional studies.

If the time period until the exceedance event is large, care is required in seaway modelling, in order to avoid self-repetition of the generated waves. For this purpose, the required range of wave frequencies and encounter angles is subdivided into a sufficient number of wave components (typically 50 to 100 frequencies per direction times 7 to 15 directions), constituting a non-uniform grid in the wave frequency – wave direction space.

In each cell of this grid, a certain combination of frequency and angle is selected, independent from the other cells, by a random procedure using a constant probability density, every time the simulation is started. The amplitudes of the wave components are calculated as the square root of the integral of the seaway spectrum over the cell. The integrals are calculated to a prescribed high accuracy using adaptive refinement. Usually, the energy spectrum is discretised into components of equal energy.

The simulation is repeated for randomly varying phases, frequencies and directions of the components. In all these realisations, different wave sequences result, thus sufficient confidence can be expected in a statistical sense, e.g. with respect to the average exceedance rate.

## 10. CONCLUSIONS

The paper has outlined some considerations related to ship-specific operational guidance, assisting the ship master to avoid cargo loss and damage in heavy weather.

Some of the identified issues require particular attention: first, definition of factors related to cargo loss and damage (motions, accelerations etc.) and their limiting values, taking into account actual lashing systems, mass distribution in a container stack etc. Secondly, setting of the boundaries (standards) for probabilistic safety criteria on the basis of the required safety level and cost-benefit considerations. Finally, practical tools and methodologies of numerical assessment are required, aiming at the reduction of the computing time and increase of robustness, especially for onboard application.

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