On the Consideration of Lateral Accelerations in Ship Design Rules

Vladimir Shigunov, Helge Rathje, Ould El Moctar and Boris Altmayer
Germanischer Lloyd

ABSTRACT

Vulnerability criteria concerning excessive lateral accelerations with respect to crew and deck cargo safety are proposed.

KEYWORDS

Dynamic Stability; Lateral Accelerations; Vulnerability Criteria

INTRODUCTION

Increasing size of container ships and changing ratios of their main dimensions, as well as quickly varying loading and operational profiles challenge designer and operator expertise and require continuous improvement of design rules. One example is the growing absolute and relative breadth of large container carriers, which may lead to on the average larger *GM* values and thus larger lateral accelerations. Another example is the now frequent practice of operation with little cargo in loading conditions close to ballast. The investigation of the accident onboard container ship Chicago Express (Krüger et al, 2010, BSU, 2009) indicated that large *GM* value (and thus, large wave moment and small natural roll period) together with low roll damping due to speed loss in waves led to lateral accelerations in excess of 1.0*g* on the bridge, causing injuries and one fatality.

A possible solution against excessive lateral accelerations is a ship-specific onboard operational guidance, indicating dangerous combinations of ship speed and course for seaways expected during operational life or based on onboard simulations; (Shigunov, 2009) whether a vessel requires an operational guidance is found out by applying direct performance assessment. Note however that the Chicago Express accident shows that derivation of operational guidance should not only identify safe combinations of ship speed and course for given seaways, but also ensure that they can be achieved, taking into account propulsion efficiency for the former and course keeping ability for the latter, in waves and wind.

In order to avoid the application of direct assessment procedures to ship designs which have large safety margins, a vulnerability check can be performed, which verifies by a simple calculation whether a more accurate assessment is required; this paper considers such a vulnerability check with respect to excessive lateral accelerations.

Vulnerability criteria are currently being developed for excessive roll motions due to parametric rolling, which can also lead to excessive accelerations. These procedures can also be used as vulnerability check for excessive lateral accelerations: either lateral accelerations with appropriate standards should be directly verified, or the employed standards for roll amplitude should be adjusted to take into account the inertial part of lateral acceleration, e.g. following SLF 51/INF.3. Therefore, parametric roll is not considered here.

Direct excitation and synchronous rolling have not yet been considered by vulnerability criteria; the present paper addresses this gap. If the proposed vulnerability check is not fulfilled, the designer can either modify the design by increasing roll damping, reinforcing lashing or by reducing *GM*, or perform direct assessment. Following the results of the direct assessment, an operational guidance may need to be developed which will assist the ship master in avoiding situations leading to excessive lateral accelerations

HUMAN SAFETY FACTORS, CRITERIA AND STANDARDS

The influence of lateral accelerations on human body has been addressed in studies concerning motion-induced interruptions (MII) (Graham, 1990) and motion-induced fatigue (MIF) (Colwell, 1989). The former are defined as events of excessive ship motions, forcing an unsupported person to abandon the performed task and to adjust the balance or catch for support. This appears more relevant to operational efficiency: in extreme conditions, the need to adjust the balance or catch for support may not be considered yet as a limiting event. MIF quantifies the increased relative energy expenditure in moving environment because of the effort required to overcome inertia forces or restore balance. Both MII and MIF, as well as mental fatigue due to motion sickness (induced mostly by vertical accelerations) may reduce people efficiency in both routine and emergency situations and thus deteriorate safety due to the increased rate of human errors. Therefore, they should be considered in design once the connection between fatigue and accident rate proves significant; ship-specific operational guidance appears an appropriate means to address these issues.

Here, only such events of extreme lateral accelerations are addressed that may lead to people loosing balance despite their efforts to restore balance or catch for support. Following the ideas of MII, the ratio of lateral to normal (with respect to the deck) accelerations will be used as the relevant factor for the human safety. Definitions follow Fig.1: the ship rotates around an instantaneous roll axis indicated by its intersection R with the section. This point experiences vertical acceleration a_v due to pitch and heave and lateral acceleration a_h due to yaw; both depend on the longitudinal position along the ship. Rolling brings about an acceleration a_φ proportional to the roll acceleration $\ddot{\varphi}$ and the distance to the roll axis; centrifugal and Coriolis forces are neglected.

For harmonic roll with the amplitude φ_a and frequency ω, the roll angle is $\varphi = \varphi_a \sin\omega t$ and the roll acceleration is $\ddot{\varphi} = -\varphi_a\omega^2 \sin\omega t$; the projections of the relative acceleration at the observation point on the y- (lateral) and z- (normal) axes fixed to the ship are

$$a_y = \left(g + a_v\right)\sin\varphi + h\omega^2\varphi\,, \tag{1}$$

$$a_z = \left(g + a_v\right)\cos\varphi - y\omega^2\varphi\,, \tag{2}$$

$h=z-z_R$ is the height of the observation point above the roll axis (z and z_R are respectively the heights of the observation point and roll axis). The maximum ratio a_y/a_z occurs according to (1) and (2) when $\varphi=\varphi_a$, i.e. when

$$a_y = \left(g + a_v\right)\sin\varphi_a + h\omega^2\varphi_a\,, \tag{3}$$

$$a_z = \left(g + a_v\right)\cos\varphi_a - y\omega^2\varphi_a\,. \tag{4}$$

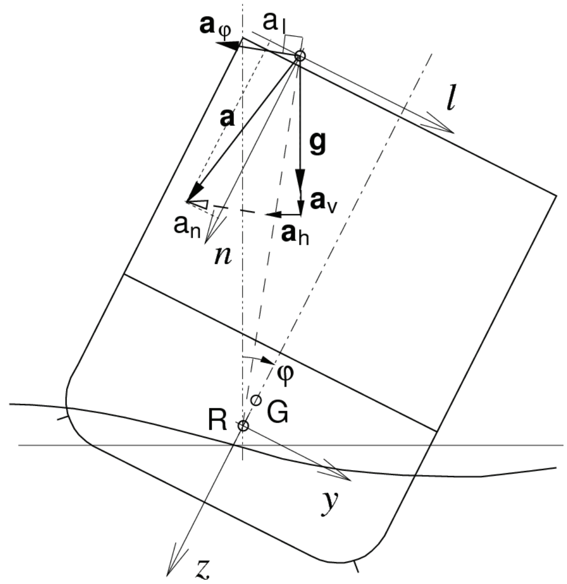

Fig.1: Definitions of accelerations

Extreme lateral accelerations can lead to either loss of postural stability (stumbling) or sliding due to overcoming the lateral friction provided by the feet (Crossland and Rich 2000, Baitis et al 1995). For an unsupported person, stumbling happens when the total acceleration $\vec{a}$ points outside the base provided by the feet, i.e. when $a_y/a_z > l/t$, where l is the base half-breadth and t is the height of the centre of gravity above the feet; typical values are 0.9 m for, 0.23 m for l and 0.25 for the ratio l/t (called tipping coefficient) for an unsupported standing person facing aft or forward. For a person facing board wise, l/t reduces to about 0.12; we assume however that people take the most resistant stance in extreme conditions.

The tipping coefficients are usually defined empirically; (Crossland and Rich 1998) measured the value of tipping coefficient 0.27 in experiments on a swaying platform for side motion of a standing person, which is marginally greater than the theoretical value of 0.25 due to the ability of human to cope with the motion (Baitis et al 1995). From real life observations, (Crossland and Rich 2000) reported the tipping coefficient of 0.232 for higher frequency motions in bow-quartering seas and 0.254 for low-frequency motions in stern-quartering seas.

Sliding happens when lateral acceleration exceeds the value $\nu_s a_z$, where ν_s is the static friction coefficient (from 0.2 to 0.7 for wet and dry deck, respectively). In a moderate seaway and for an unsupported person standing on a dry deck, stumbling is more likely than sliding because the static friction coefficient is greater than the tipping coefficient.

The investigations of accidents report much higher accelerations during accidents than those implied by the above tipping and sliding coefficients, such as 1.0g to 1.1g (Krüger et al, 2010, BSU, 2009); the reason is that the tipping coefficient of 0.25 assumes an unsupported person. Note that when taking a support into account, sliding may become the limiting factor if the person uses hands for support and not for holding (then the limit for ay/az is 0.7); if the person can hold on something, this ratio may be even greater but is still limited because of the limited human strength and the possibility of feet sliding even when the hands are holding.

In order to get another reference value for a_y/a_z from the available observations, note that the observed performance limits onboard can be used to derive either the limiting values of tipping coefficient or the acceptable frequency of tipping with assumed coefficients. Full-scale observations (Crossland and Rich 2000) indicated the risk levels in terms of MII per minute shown in the second column of Table 2; for reference, columns are added showing the corresponding root-mean-square (r.m.s.) values of lateral acceleration and the number of sliding events with sliding coefficient of 0.7 for 10.0 s roll period.

As a limit for extreme lateral accelerations, the r.m.s. value of 0.19g or slightly greater appears suitable; it corresponds to less than one sliding event per hour on a dry deck. Here, the value 0.2g will be used as an assumption for the r.m.s. standard for lateral accelerations; it can be yet adjusted by the application of the resulting procedure to several vessels.

Table 1: Risk levels in terms of MII per minute from (Crossland and Rich 2000) and corresponding r.m.s. values of lateral accelerations and number of sliding events per 3 hours

Risk Level	MII per min.	σ_{ay} / g	Sliding events per 3h
possible	0.1	0.081	0.0000
probable	0.5	0.099	0.0000
serious	1.5	0.123	0.0002
severe	3.0	0.150	0.0411
extreme	5.0	0.189	2.2573

The proposed standard assumes that a person is taking hold or support; because of body inertia, this action requires some time and thus, the speed of the increase of the lateral acceleration (lateral jolt) has also to be limited. Lateral jolt has not been studied yet anywhere; therefore, here the standard for jolt r.m.s. is adopted of 1.0 m/s3, which means an increase of lateral acceleration from zero to 0.8*g* in 2.0 s about once per 3 hours.

DECK CARGO SAFETY FACTORS, CRITERIA AND STANDARDS

Loss or damage of deck cargo can be dangerous for the ship or its crew, other ships or environment. Cargo securing and lashing for ships carrying deck cargo (container ships, multi-purpose vessels, ferries, heavy-lift transports, offshore service vessels etc.) is dimensioned according to some design values of lateral accelerations, usually taking into account static loads from container weights and dynamic loads due to ship motions, wave impacts and wind.

Lashing of container carriers is dimensioned, e.g. (Germanischer Lloyd, 2007), in such a way that the racking loads and the vertical loads on container corners do not exceed ISO Standard strength limits and uplifting of container corners does not happen. The lateral design accelerations are calculated taking into account ship size, initial GM, longitudinal and lateral location of the container stack and its height, using either direct seakeeping calculations or tabulated values for the most typical cases. The design limits of lateral accelerations employed in (Germanischer Lloyd, 2007) assume prudent seamanship; the rules of other classes may rely on other assumptions or aim at different safety levels. Therefore, it appears necessary to ensure that the operational performance standard assumed in the design is met under all allowed operational and loading conditions for any rules used and for any ship including innovative designs. This is possible with ship-specific operational guidance.

For deck cargo other than containers on container ships, various approaches exist to setting design accelerations. This may lead to varying, sometimes insufficient safety level; in such cases, operational guidance should be used to bring the safety level up to a uniform minimum standard. For example, IMO CSS Code (IMO, 2003) is frequently used in practice to set the design values of lateral accelerations: the advanced calculation method of this Code defines the limits of lateral accelerations vs. the ship length, the initial GM and the vertical position of the cargo; the Code warns however that the given accelerations can be exceeded due to roll resonance. Thus when these values are used for lashing dimensioning and cargo securing, a guarantee for proper ship handling in seaway may still be necessary.

This calls for onboard ship-specific operational guidance for ships with both standardized and non-standardized deck cargoes if it can be expected that the used design values of accelerations may be exceeded during the operational life. In the same way as for the other dynamic stability problems, the need for an operational guidance is verified with a direct assessment, which must check whether the used dimensioning assumptions may be violated with a sufficiently high probability under allowed operational and loading conditions.

For a vulnerability check, which verifies if there is a need for such a direct assessment, the same design values of lateral accelerations can be used (probably, with some conservative simplifications); when the vulnerability criteria are violated for the selected loading conditions and locations on the ship, direct assessment should be performed.

In the examples considered in this paper, selected locations on the sample ships were used for illustration. As the standards for the lateral accelerations, the design values used for lashing dimensioning (Germanischer Lloyd, 2007) were used for container ships and the acceleration values according to the advanced calculation method (IMO, 2003) were used for the other ship types. The design accelerations from the rules were interpreted as the maximum expected lateral accelerations during 20 years of operational life and applied in the procedure as the maximum expected accelerations with 1% conditional exceedance probability in the design seaway (see below) of 3 hour duration.

DERIVATION OF THE PROCEDURE

The proposed assessment procedure follows Söding (1979). Roll equation in a linearized form is used,

$$I_\varphi \ddot{\varphi} + b_\varphi \dot{\varphi} + c_\varphi \varphi = M \sin(\omega_e t + \varepsilon)\,; \qquad (5)$$

lateral accelerations are considered below, see eqs. (8) and (9). I_φ is the moment of inertia around the roll axis, including dry and hydrodynamic parts, b_φ is the effective roll damping coefficient, depending on the roll amplitude φ_a and encounter frequency ω_e, c_φ is the effective linearized stiffness and M is the amplitude of the exciting moment.

I_φ is used in the form $I_\varphi = mk_\varphi^2$, where m is the ship mass and k_φ is the wet radius of inertia with respect to the roll axis. To describe the equivalent roll damping, logarithmic decrement of free roll decay $\delta = \pi b_\varphi / (\omega_\varphi I_\varphi)$ was used; $\omega_\varphi = \sqrt{gGM} \big/ k_\varphi$ is the natural roll frequency.

The stiffness coefficient $c_\varphi = mg\,GM$, where GM is the effective metacentric height, may strongly depend on the motion amplitude in waves, especially for low values of the initial metacentric height GM_0, see an example from SLF 51/INF.3 in Fig.2.

For large GM0 values (which are most relevant for synchronous rolling of large vessels), the effect of GM variation in waves is small and reduces to an insignificant shift of the resonance frequency with increasing wave amplitude; this effect is relevant for operational guidance but can be neglected in a simplified design assessment for cases with large GM0. If the procedure is to be used for sufficiently small GM0 values where the influence of stiffness nonlinearity cannot be neglected, this effect will be taken into account. Here, the stiffness coefficient is linearized as mgGM0; the subscript 0 at the initial metacentric height will be hereafter omitted.

Neglecting diffraction effects, the amplitude of the exciting moment can be written as

$$M = \kappa\alpha_{\mathrm{w}} mg\, GM \sin\mu\,,$$

where $\kappa(\omega)$ is the reduction factor of the exciting heel moment due to the finite wave length, α_{w} is the maximum wave slope and μ is the wave direction (0, 90 and 180° respectively for the following, starboard and head seaway); ω is the wave frequency.

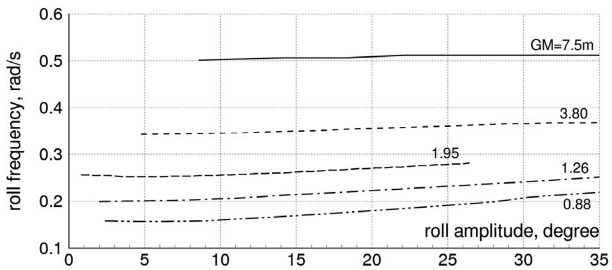

Fig. 2 Natural roll frequency vs. resonance roll amplitude for different initial *GM* values for a 8400 TEU container carrier

Accident investigations (Krüger et al, 2010, BSU, 2009) report very low forward speeds (2 to 4 knots) at the time of accidents, which happens because of resistance forces due to waves, wind and large drift angles; it appears therefore not overly conservative to neglect the effect of forward speed on both the encounter frequency and roll damping; with all of the above assumptions eq. (5) becomes

$$\begin{aligned} k_\varphi^2\ddot{\varphi} + (\delta/\pi)\omega_\varphi k_\varphi^2\dot{\varphi} + g\,GM\,\varphi \\ = \kappa\alpha_{\mathrm{w}} g\,GM \sin\mu \sin(\omega t + \varepsilon) \end{aligned}$$

Its solution is harmonic roll motion with the amplitude φ_a satisfying equation

$$\frac{\varphi_a}{\zeta_a} = \frac{\kappa\omega^2\omega_\varphi^2 \sin\mu}{g\left[(\omega_\varphi^2 - \omega^2)^2 + \omega^2\omega_\varphi^2(\delta/\pi)^2\right]^{1/2}}$$

with $\zeta_{\mathrm{a}} = \alpha_{\mathrm{w}}\lambda_{\mathrm{w}}/(2\pi)$ the wave amplitude and λ_{w} the wave length. Lateral acceleration satisfies eq. (1) and the lateral jolt is

$$j_y = \dot{a}_y = -g\varphi_{\mathrm{a}}\omega\cos\omega t\cos\varphi - \varphi_{\mathrm{a}}\omega^3 h\cos\omega t$$

Linearized eq. (3) with respect to $\sin\varphi_{\mathrm{a}}$ (lateral acceleration due to yaw is omitted here and will be considered below) and the above equation yield the amplitudes of lateral acceleration and lateral jolt in regular waves:

$$a_y = \varphi_{\mathrm{a}}\left(g + \omega^2 h\right),\ j_y = \varphi_{\mathrm{a}}\omega\left(g + \omega^2 h\right).$$

The variance of the roll angle in a natural seaway with a spectrum $D(\mu - \mu_0)S_\zeta(\omega)$ (D is the spreading function, μ_0 is the main wave direction and S_ζ is the one-dimensional seaway spectrum) is

$$\begin{aligned} \sigma_\varphi^2 &= \int_0^\infty\int_0^{2\pi}\left(\frac{\varphi_a}{\zeta_a}\right)^2 D(\mu - \mu_0)S_\zeta(\omega)\,\mathrm{d}\omega\,\mathrm{d}\mu \\ &= \frac{\omega_\varphi^4}{g^2}\int_0^{2\pi} D\sin^2\mu\,\mathrm{d}\mu \int_0^\infty \frac{\kappa^2\omega^4 S_\zeta\,\mathrm{d}\omega}{(\omega_\varphi^2 - \omega^2)^2 + \omega_\varphi^2\omega^2(\delta/\pi)^2} \end{aligned} \qquad (6)$$

The first integral on the second line of eq. (6) introduces the influence of the main wave direction and directional spreading; it changes from minimum in head waves to maximum in beam waves; an example for a cos²-spreading function is shown in Fig. 3

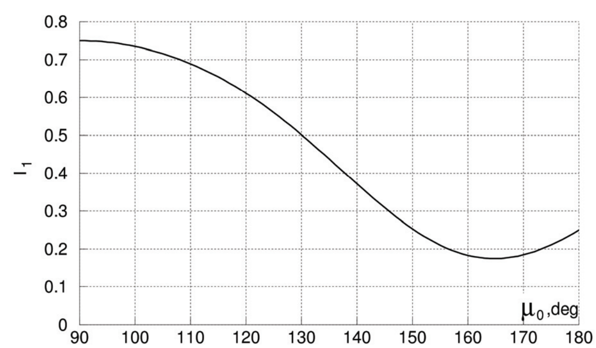

Fig 3. Example of the first integral on the second line of eq. (6) for cos²-spreading function

According to accident investigations (Krüger et al, 2010, BSU, 2009), the crew tried to keep heading direct into waves. However, critical wave groups were reported as coming from directions about 120 to 150° because of reduced course keeping ability of the vessels at reduced draughts, not fully submerged rudder and low forward speed (the influence of cross seas is also possible). Thus, 0.5 seems a suitable assumption for the first integral.

n the second integral on the second line of eq. (6), the numerator remains finite in the integration region while the denominator approaches zero for excitation close to the natural roll frequency and low roll damping; thus the dominating contribution to this integral comes from the region of frequencies close to the natural roll frequency. Replacing ω with ω_φ in the numerator allows calculating the resulting integral as

$$I_2 \approx \pi^2\kappa^2\omega_\varphi S_\zeta(\omega_\varphi)/(2\delta)$$

and the variance of the roll angle becomes

$$\sigma_\varphi^2 = 0.0256\kappa^2\omega_\varphi^5 S_\zeta(\omega_\varphi)/\delta$$

similarly for lateral acceleration and lateral jolt:

$$\sigma_a^2 = \sigma_\varphi^2\left(g+\omega_\varphi^2 h\right)^2,\ \sigma_j^2 = \sigma_\varphi^2\omega_\varphi^2\left(g+\omega_\varphi^2 h\right)^2.$$

For a wind sea, the spectrum $S_\zeta(\omega_\varphi)$ converges within about 0.5 hour to JONSWAP spectrum

$$S_\zeta = 0.203(h_s\omega_p^2)^2 s(\omega_\varphi/\omega_p)/\omega_\varphi^5$$

$$s = \exp\left\{-1.25\left(\frac{\omega_p}{\omega_\varphi}\right)^4 + \ln\gamma \exp\left[-\frac{\left(\omega_\varphi/\omega_p - 1\right)^2}{2b^2}\right]\right\}$$

h_s is the significant wave height, ω_p is the peak frequency, γ is the peak enhancement factor and b=0.07 for $\omega_\varphi<\omega_p$ and 0.09 otherwise.

For a spectrum with $\omega_p = \omega_\varphi$ and $\gamma = 3.3$,

$$\sigma_\varphi = 0.07\kappa k_s/\sqrt{\delta},$$

$k_s = h_s\omega_p^2$ is the seaway steepness parameter.

DESIGN SEAWAY STEEPNESS

To estimate the characteristic maximum wave steepness parameter $k_s = h_s\omega_p^2$ of the encountered seaways for an unlimited service vessel, the annual average seaway scatter table of ISSC (Jeffery and Kendrick, 1994) for the North Atlantic was used; other possibilities should be tested as well, e.g. IACS (2001)

The seaway of the cumulative duration of 3 hours over the entire operational life (20 years) was used to define h_s vs. ω_p; the following was considered:

- the probabilities of different loading conditions (factor 0.2 applied)
- the portion of the operational life in the North Atlantic or similar seaway climate (factor 0.3)
- Time at sea and in port (factor 0.75)

This leads to the upper boundary of seaway encounter probability density function of $3.805\cdot10^{-4}$; Fig. 4 shows an approximation of $k_s(\omega_p)$ for this boundary.

Additionally, it was assumed that even an inexperienced ship master without an operational guidance avoids seaways with h_s more than 12.0 m.

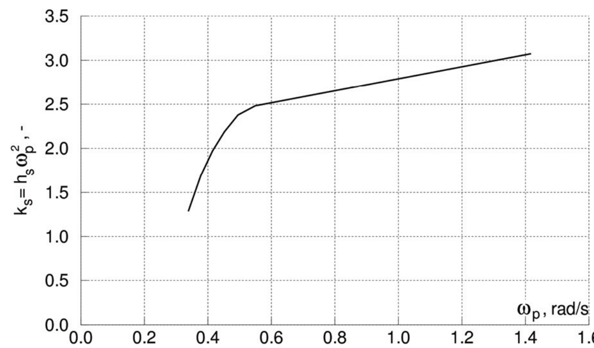

Fig 4. Boundary $k_s(\omega_p)$, corresponding to 3 hour cumulative seaway duration over operational life of 20 years in the North Atlantic wave climate (Jeffery and Kendrick 1994)

PRACTICAL CONSIDERATIONS

The following procedure is derived: first, roll motion is defined from the equation

$$\sigma_\varphi = 0.07\kappa k_s/\sqrt{\delta}. \tag{7}$$

Using the found r.m.s. of roll σ_φ, the lateral acceleration criterion

$$k_1\sigma_a = k_1\sigma_\varphi\left(g+\omega_\varphi^2 h\right) \le 0.2g, \tag{8}$$

is checked, both for crew (for the bridge and maybe other relevant locations) and for deck cargo (for all relevant locations; the r.h.s. for deck cargo varies depending on the particular local design accelerations). The factor k_l takes into account lateral acceleration due to yaw and is calculated as a function of longitudinal position following (Germanischer Lloyd, 2007) and IMO (2003) for container vessels and other ship types, respectively. Finally, lateral jolt criterion

$$k_l \sigma_j = k_l \sigma_\varphi \omega_\varphi \left(g + \omega_\varphi^2 h \right) \le 1.0 g \tag{9}$$

is checked for the crew safety related locations.

This procedure requires the parameters κ, k_φ and h and the logarithmic roll decrement δ. The parameter κ (the ratio of the exciting roll moment from a wave with the length $\lambda = 2\pi g / \omega_\varphi^2$ to the exciting roll moment from a wave of the same steepness and infinite length) was calculated as a function of wave length using hydrostatic software. Roll damping of the bare hull was found using measurements (Blume, 1979); any other reliable methods can be used. The roll damping due to bilge keels was calculated with the method (Gadd, 1964), which requires the position of the bilge keel and bilge radius at its location. The dry part of the roll radius of inertia was found following IMO (2003a); for the hydrodynamic part, an empirical correlation was derived from linear seakeeping computations vs. B_{wl}, T_m and GM.

Table 2: Maximum initial *GM* values for lateral accelerations and lateral jolt on crew

Ship	LC	GM_{max} (lat.acc.)	GM_{max} (lat.jolt)	KB/L_{pp}	B_{wl}/L_{pp}
ppm13k	BA	4.00	5.42	0.190	0.138
	BD	3.89	4.83		
ppm8.6k	BA	4.52	6.34	0.162	0.134
	BD	3.74	4.72		
pm4.1k	BA	3.98	4.96	0.184	0.151
	BD	3.53	4.41		
feeder	BA	0.98	1.21	0.226	0.166
	BD	0.91	1.12		
BC	BA	5.82	7.27	0.139	0.169
	BD	5.82	6.06		
OSV	BA	1.42	1.86	0.258	0.228

TEST CASES

The procedure was applied to the ships listed in Table 2: 13000 (ppm13k) and 8600 (ppm8.6k) TEU post-panamax container carriers, a 4100 TEU panamax container ship (pm4.1k), a feeder, a bulk carrier (BC) and an offshore service vessel (OSV). The procedure was applied to loading conditions with large *GM* values, ballast arrival (BA) and ballast departure (BD); Table 3 lists the midship draughts as percentage of the design draught and initial *GM* values from stability booklets.

Table3:Used sample ships

Ship	L_{pp}, m	B_{wl}, m	Design draught, m
ppm13k	350.0	48.2	14.5
ppm8.6k	320.0	42.8	13.0
pm4.1k	264.4	40.0	12.0
feeder	108.0	17.9	7.1
BC	254.0	43.0	13.0
OSV	96.7	22.0	6.8

The ships are considered to be equipped with bilge keels of typical dimensions for each of the ships considered (height 0.25 to 0.4 m, length at each board of about $0.3L_{pp}$); the influence of the bilge keel parameters on the maximum *GM* value was out of scope and will be studied elsewhere.

Table 4: Loading conditions

Ship	Loading condition	T_m, % of design draught	GM, m
ppm13k	BA	53.9	15.85
	BD	60.8	13.91
ppm8.6k	BA	53.0	12.18
	BD	62.8	11.44
pm4.1k	BA	55.9	5.81
	BD	63.9	5.48
feeder	BA	60.0	2.52
	BD	66.3	2.54
BC	BA	53.2	15.02
	BD	54.6	14.18
OSV	BA	64.6	4.21

VERIFICATION

The proposed criteria do not simply limit the maximum GM_0 values, not requiring an operational guidance; they can also be applied for dimensioning of bilge keels or definition of design accelerations for deck cargo lashing. Nevertheless, for the crew safety criteria, the lowest initial *GM* values can be sometimes found from those that lead to the violation of these criteria for given bilge keel parameters; Table 4 presents such initial *GM* values for the bridge together with the loading condition, ratio of the bridge height above the keel *KB* to L_{pp} and B_{wl}/L_{pp} ratio.

For the tested (relatively large) vessels, the lateral jolt criterion is less limiting than the lateral acceleration criterion; the situation might be different for smaller ships. The most stringent limitations on GM_0 from the crew safety point of view result for the two vessels with the largest realtive bridge height (OSV and feeder). They also have the largest B_{wl}/L_{pp} ratio with the exception of the bulk carrier, which has however the lowest bridge in the sample.

Although the draughts used in the tests correspond to ballast conditions, the same cases were used to verify lateral accelerations on the deck cargo (note that only few locations were considered in the exercise) in order to compare the relative severity of the vulnerability criteria for the crew and the deck cargo; a more comprehensive study for more loading conditions and more locations is under way. While the requirements of deck cargo safety appear (for the tested locations) slightly more stringent than those related to crew safety (the minimum required initial *GM* values for deck cargo safety are 0.2 to 1.2 m lower than those implied by the lateral accelerations on crew), these GM_0 values are much easier to ensure for a loaded carrier because of the presence of cargo. Regarding the comparison with the existing rules, the larger container ships used in the exercise (panamax and post-panamax) would pass the present vulnerability criterion regarding accelerations on deck cargo at the considered locations if rules (Germanischer Lloyd, 2007) are used for lashing dimensioning: the minimum GM_0 values required by the present criterion are up to 20% greater than those implied by the rules when using the *standard accelerations* and about 60% greater than those implied by the *standard reduced accelerations* (allowed for ships with L_{pp}>120.0 m). However, the feeder would not pass the present vulnerability check if the lashing is dimensioned according to the rules: minimum GM_0 values required by the cargo safety vulnerability check are up to 40% lower than those implied by the rules.

For the OSV, the design accelerations (IMO, 2003) were found insufficient compared to the present assessment procedure (although by a small amount, 4 to 5% of *g*) for all GM_0 values greater than 1.04 m.

CONCLUSIONS AND OUTLOOK

The proposed vulnerability check takes into account the initial *GM*, roll damping and design accelerations employed for deck cargo securing; if it is not fulfilled, the designer can either modify the design (by reducing *GM*, increasing roll damping or – for deck cargo – increasing lashing strength) or perform direct assessment, which might reveal the need for an operational guidance. Validation of the procedure by comparison with model tests and direct simulations is under way; the standards on the r.h.s. of eqs. (7) to (9) may be adjusted following application of the procedure to a sufficient number of ships. A sensitivity study of the influence of the bilge keel parameters is also ongoing. Further developments are

- practical methods for the calculation of roll damping for bare and upended hulls,
- practical methods for direct performance assessment and ship-specific onboard guidance, especially the consideration of propulsion efficiency and course keeping in wind and waves,
- effect of elastic deformations of the hull and containers on container loads.

REFERENCES

Baitis, A. E., Holcombe F. D., Conwell, S. L. Crossland, P., Colwell, J. and J. H. Pattison (1995) 1991-1992 motion induced interruptions (MII) and motion induced fatigue (MIF) experiments at the Naval Biodynamics Laboratory, Techn. Rep.No. CRDKNSWC-HD-1423-01, Naval Surface Warfare Center

Blume P. (1979) Experimentelle Bestimmung von Koeffizienten der wirksamen Rolldämpfung und ihre Anwendung zur Abschätzung estremer Rollwinkel, Schiffstechnik 26, 3-23

BSU (2009) Fatal accident on board the CMV Chicago Express during Typhoon "Hagupit" on 24 September 2008 off the coast of Hong Kong, Federal Bureau of Maritime Casualty Investigation

Colwell, J. L. (1989) Human factors in the naval environment: a review of motion sickness and biodynamic problems, DREA Technical Memo

89/220, Canadian National Defense Research Establishment Atlantic, Dartmouth

Crossland P. and K. Rich (1998) Validating a model of the effects of ship motion on postural stability, Rep. ABCD working group

Crossland, P. and K. Rich (2000) A method for deriving MII criteria, Trans. Of RINA Int. Conf. on Human Factors in Ship Design and Operation, London

Gadd G. E. (1964) Bilge keels and bilge vans, National Physical Lab. Ship Report Nr. 64

Germanischer Lloyd (2007) Rules for classification and construction, I – Ship Technology, Part 1 – Seagoing Ships, Chapter 20– Stowage and Lashing of Containers. Hamburg

Graham, R. (1990) Motion-induced interruptions as ship operability criteria, Naval Engineers J. 102(2): 65-71

IACS (2001) Recommendation No.34: Standard Wave Data IMO (2003) Code of safe practice for cargo storage and securing

IMO (2003a) Code on intact stability for all types of ships covered by IMO instruments

Jeffery N. E. and A. M. Kendrick (ed.) (1994) Int. Ship and Offshore Structures Congress, St. John's

Krüger, S., Steinbach,C. Kaufmann, J. and F. John (2010) Stability accidents in ballast/laid-up conditions – a new phenomenon? Proc. 11th Int. Symp. Practical Design of Ships and Other Floating Structures PRADS 2010, Rio de Janeiro, Brazil, pp. 545-552

Shigunov, V. (2009) Operational guidance for prevention of container loss, Proc. 10th Int. Conf. on Stability of Ships and Ocean Vehicles (STAB 2009), St.Petersburg

SLF 51/INF.3 (2008) New generation intact stability criteria. Submitted by Germany, London

Söding , H. (1979) Discussion to paper by Blume (1979)