Assessment of current criteria for dynamic stability of container vessels

C Stanca 1, C Ancuta 1, N Acomi 1 and C Andrei 1
1 Constanta Maritime University, Faculty of Navigation, 104 Mircea cel Batran Street, 900663, Constanta, Romania

E-mail: costel.stanca@gmail.com

Abstract. Container vessels sailing through heavy weather are exposed to a significant variation of stability due to specific shape of the hull combined with the action of the waves. Even if the weather forecast is transmitted to vessels, the way of acting it is a matter of officers’ experience. The Maritime Safety Committee, under the International Maritime Organization, has approved the Guidance to the master for avoiding dangerous situations in adverse weather and sea conditions. Adverse weather conditions include wind induced waves or heavy swell. The development of dangerous phenomena such as surf-riding and broaching to, synchronous and parametric rollings is a result of these adverse conditions which has to be encountered by the vessels. Understanding the dynamic stability of the vessel in the waves and ship’s behaviour based on mathematical and physical rules is a difficult task, any effort in order to assess these components are salutary. To avoid excessive acceleration and forces which can damage the hull of the vessel, lashing and integrity of containers, course and speed may need to be changed for the vessel’s motion in heavy seas. Specific software have been developed as aids for evaluating the response of the vessel in heavy seas according to parameters variations. The paper aims at assessing of current criteria for dynamic stability of a container vessel model ship in order to determine the ways for avoiding dangerous conditions. The results should be regarded as a supporting tool during the decision making process.

1. Actual context of assessment ships dynamic intact stability in waves

The present intact stability criteria are based on righting energy relationship and provide a measure of intact stability. This measure illustrates a level of safety but did not provide guidance for avoid stability failure in severe sea conditions. Today, the assessment of ship stability in waves, based on dynamic criteria, became an important task among researchers. This is because the ship response to large waves is associated with significant nonlinearities [1, 2]. The development of such criteria proved to be a very complex task. The first proposals was contained in SLF 49/5/2 (presented in SLF 49/INF.3) but was rejected in July 2006 by the working group at 49th session of SLF, thereafter a new approach was discussed in May 2007 at 50th session of SLF, where was presented the distinctions between performance-based criteria, probabilistic criteria and deterministic criteria [3].

Many papers discussed at international conferences presented new forms of stability criteria based on vulnerability and direct assessment, among them being Belenky [4], Bassler [5], Umeda [6], Shigunov [7]. Having in view the importance of the development of a new intact stability criteria, following the coming into force of new IS Code 2008, the agenda of the 52nd session of SLF (January, 2010) has been changed from “Revision of Intact Stability Code” to “Development of New Generation
of Intact Stability Criteria”. The new task of the correspondence groups was to bring proposals for assessment of all the modes of stability failures in severe seas based on vulnerability criteria.

2. The scope and the principle of the proposed dynamic stability criteria for containerships

The parametric rolling, pure loss of stability, broaching or surf-riding are stability failure modes in severe sea conditions. The main event during those phenomena is the alterations of righting lever between different positions of the ship in relation with the wave (crest and trough). The variations of areas below the righting lever curves at crest and trough condition express the energy induced into the ship’s hull form. Based on the actual IMO intact stability requirements for the minimum GM value there is the possibility that at the time when vessel is on the wave crest practically the vessel has no stability and may capsize. This aspect is a result of the fact that GM value can decrease far enough below minimum value and vessel is exposed to large rolling amplitudes (figure 1).

![Figure 1. Representation of righting lever curves for still water and waves.](image)

Despite the progress of researches in this domain, a few issues remained open, such as the development of effective stability criteria for the assessment of dynamic intact stability in waves as well as prevention of stability failure in waves by empirical mode.

Presently, the assessment of those phenomena by ship’s officers on board vessel is in a form of a guidance issued by IMO, based on the statistics of stability failures, and not as a stability criterion. The statistics of stability failures cannot be any more the single approach of stability criteria as the design and modes of operations of new generation of ships has a great influence on that. Moreover, the new stability criteria can be considered as a method of risk analysis which become a standard tool in other industries. The scope of the proposed dynamic intact stability criteria for containerships in this work is:

- To provide methods to assess particular intact stability failure modes for containerships in severe sea conditions, insufficiently treated by the existing criteria (these ships may have design typologies or dimensions outside the ships for which the present regulations were developed).
- To ensure that the minimum initial value of GM in calm water, obtained for a specific vessel with a specific hull form, is enough to balances the crest-trough variation in a particular condition of wave.

Actually, the value of initial GM is the main factor affecting the area under the stillwater curve. It results that stillwater area is practically a constant value for a specific hull form as it should be proportional to the crest-trough variation [8]. To that effect, one of the aims of this work is to develop a new approach of dynamic intact stability criteria, which cover the dynamic effects and addresses one
of the fundamental mode of stability failure as restoring arm variation problems. The proposed criteria may be considered as additional criteria to the already existing intact stability criteria. The proposed dynamic intact stability criteria may have many advantages like: are formulated in a simple language, are easy in application, as well as make an easy checking adherence to the requirements.

The concept of the proposed dynamic intact stability criteria is in a form of a short-term assessment that can be considered as specifying the level of risk associated with a single trip. Thus, it can be an instrument in a system of departure control like the one applied in Greece for passenger ships provided by Spyrou [9], or internally within a ship management company. Moreover, it can be combined with a system of weather routing and operational guidance.

3. Proposed dynamic stability criterion for parametric rolling of containerships

The proposed dynamic stability criterion is based on the assessment on whether or not a combination of multiple factors like ship’s loading condition, ship’s speed and heading angle as well as length and celerity of the wave can lead to the onset of parametric rolling as a result of the instability in upright position due to stability variations in waves.

The proposed method, for assessment the level of ships vulnerability to parametric rolling, is based on the characteristics of the hull form in static condition used as an indicator of the hull shape change based on the maximum and a minimum dimensions of ship’s water plane area during encountering the wave.

For a ship running in longitudinal seas, an equation of motion may be described in the following form, as written by Bullian in [10], equation (1):

\[(I_x + J_x) \ddot{\varphi} + D(\varphi) + \Delta GZ(\varphi, t) = 0\]  

(1)

where, \((I_x + J_x)\) are the real and added moments of inertia, \(D(\varphi)\) is the damping force, \(\Delta\) is the ship displacement and \(GZ(\varphi, t)\) is the righting arm. If in the equation (1) are considered the damping coefficient, the ship’s natural roll frequency and the metacentric height, it can be written as, equation (2):

\[\varphi + 2\eta\varphi + \omega^2_\varphi f(\varphi, t) = 0\]  

(2)

where, \(\eta\) is coefficient of roll damping, \(\omega_\varphi\) is the natural roll frequency and \(f(\varphi, t)\) is the time dependent stiffness. The roll response is modeled as, equation (3):

\[f(\varphi, t) = \frac{GZ(\varphi, t)}{GM_0}\]  

(3)

As showed earlier, in comparison with the righting arm curve for still water, the righting arm when the vessel is on wave crest and wave trough is suffering variations. Therefore, the areas under GZ curves, as showed in figure 2, for wave crest and wave trough condition are calculated as follows, equation (4) and (5):

\[A_{\text{crest}} = \int_0^\varphi GZ_{\text{LWL}}(\varphi) d\varphi\]  

(4)

\[A_{\text{trough}} = \int_0^\varphi GZ_{\text{UWL}}(\varphi) d\varphi\]  

(5)
However, in severe longitudinal seas, the rolling angle increase and becomes significantly large. In this respect, it can be determined the area under righting arm curve on basis of the equivalent linearised metacentric heights as follows, equation (6) and (7):

\[
GM_{LWL} = \frac{\varphi^2}{2} \int_0^\varphi GZ_{LWL}(\varphi) d\varphi = \frac{\varphi^2}{2} A_{crest} \tag{6}
\]

\[
GM_{UWL} = \frac{\varphi^2}{2} \int_0^\varphi GZ_{UWL}(\varphi) d\varphi = \frac{\varphi^2}{2} A_{trough} \tag{7}
\]

The modeling of the GZ it is important because it reveals the amplitude of roll motion. Because the metacentric heights for crest and trough conditions vary with the angle of heel, in order to specify this angle, a further assumption is made for modeling an equivalent solution. It was assumed that the metacentric height on waves has a sinusoidal variation given by the relation, equation (8), (9), (10):

\[
GM_{wave} = GM_0(\alpha_1 + \alpha_2 \cos \omega t) \tag{8}
\]

where:

\[
\alpha_1 = \frac{GM_{LWL} + GM_{UWL}}{2GM_0} \quad \text{is the average variation of GM} \tag{9}
\]

\[
\alpha_2 = \frac{GM_{UWL} - GM_{LWL}}{2GM_0} \quad \text{is the amplitude of wave-induced variation of GM} \tag{10}
\]

The righting arm could be written in a linearized form as equation (11):

\[
GZ(\varphi, t) = GM_0(\alpha_1 + \alpha_2 \cos \omega t)\varphi \tag{11}
\]
Where \( \omega_e \) is encountered frequency which in order to occur the parametric rolling, it is necessary to be fulfilled the condition that the encounter frequency should be equal to twice the natural rolling frequency. Based on the fact that in longitudinal waves, the frequency of ship rolling is almost the same with the natural frequency and applying the energy balance method in the rolling angle equation, it can be expressed the condition that leading to capsize, in longitudinal waves, as follows:

- \( \eta < \frac{\pi}{2} \left( \frac{\alpha_2 - \alpha_1}{T} \right) \) in a capsizing zone;
- \( \eta = \frac{\pi}{2} \left( \frac{\alpha_2 - \alpha_1}{T} \right) \) in a risk zone;
- \( \eta > \frac{\pi}{2} \left( \frac{\alpha_2 - \alpha_1}{T} \right) \) in a risk free zone.

In this way, by fitting the results with first-degree polynomials, the risk zones for parametric rolling may be defined in connection with the area ratio and damping coefficient as per figure 3.

![Figure 3](image)

**Figure 3** Potential capsizing and parametric rolling zones related to area ratio and damping coefficient.

The equations for damping coefficients were defined for risk zones as a function of area ratio as follows:

- \( \eta > -0.0814 \frac{A_{\text{crest}}}{A_{\text{rough}}} + 0.0924 \), risk free zone
In order to show the sustainability of the proposed dynamic stability criteria for the assessment of parametric rolling, the sample calculations were extended for a number of 10 containerships of different size and different hull forms, with main characteristics given in table 1. All of the ships used for sample calculations are real and well documented ships, with well defined geometry and load cases. Part of the ships used here, were also used for sample calculations by the Correspondence Group on Intact Stability, established by IMO SLF Subcommittee, in the reports SLF 53/INF.10 and SLF 54/INF.12, that contains status of developments for new dynamic intact stability criteria.

Table 1. Main characteristics of ships used for investigations.

| Ship Type | LBP (m) | Breadth (m) | Depth (m) | Draught (m) | GM (m) |
|-----------|---------|-------------|-----------|-------------|--------|
| Containerships |        |             |           |             |        |
| C1        | 167.00  | 27.60       | 15.90     | 10.70       | 1.298  |
| C2        | 210.00  | 32.24       | 18.70     | 10.50       | 1.58   |
| C3        | 256.50  | 32.20       | 19.10     | 12.50       | 1.839  |
| C4        | 257.40  | 40.0        | 21.70     | 13.50       | 1.67   |
| C5        | 262.00  | 40.0        | 24.70     | 12.43       | 1.724  |
| C6        | 265.80  | 40.30       | 24.10     | 14.00       | 1.697  |
| C7        | 283.80  | 42.80       | 24.20     | 14.00       | 1.803  |
| C8        | 319.00  | 42.80       | 24.60     | 14.50       | 1.93   |
| C9        | 320.00  | 42.80       | 24.80     | 14.65       | 2.11   |
| C10       | 348.00  | 45.60       | 29.74     | 15.53       | 1.90   |

In the sample the containerships were considered loaded up to 80 – 90% from the total deadweight (TEU) capacity. This consideration was based on the fact that only in very rare condition, the container ships are loaded up to maximum capacity. Sample calculations, for assessment of parametric rolling, were performed following the methodology of calculation of minimum areas under righting moment curves for parametric rolling response, described in the proposed stability criteria. The results are illustrated in the table 2 and figure 4.

Table 2. Main characteristics of ships used for investigations.

| Ship | $\frac{A_{crest}}{A_{trough}}$ | $\eta$ | Risk Zone |
|------|--------------------------------|-------|------------|
| C1   | 0.392                          | 0.016 | Yes        |
C2  0.369  0.017  Yes
C3  0.399  0.018  Yes
C4  0.393  0.019  Yes
C5  0.193  0.019  Yes
C6  0.201  0.021  Yes
C7  0.238  0.024  Yes
C8  0.241  0.026  Yes
C9  0.262  0.026  Yes
C10 0.438  0.035  Yes

Figure 4 Position of containerships on the parametric roll risk map.

Figure 5 Variation of GM on wave crest.
5. Conclusions
Comparing the sample calculation results for assessment of parametric rolling it can be observed that container ships did not pass the criteria, and can be considered with a high risk for stability failures related to righting arm variations in waves. This is mainly due to geometric characteristics of the hull (large flared forms at fore and aft part of the hull with small values of volume below waterline at lower draughts), which increase vulnerability to parametric rolling and pure loss of stability.

These facts consolidate the affirmation that modern containerships are known for their vulnerability to stability failures in waves, especially to parametric rolling (e.g. France, [10]).

In order to fulfill the criteria, the GM values for container ships that failed to comply are required to be above the common GM values of ships in operations. However, it is important to be taken into consideration that such increased GM values could have a strong influence into accelerations with results over the lashings. Thus, having in view that for these types of ships a reconsidering stowage plan is not possible, the solution remained only to avoid areas with extreme seas or to induce a speed that will not make the ship vulnerable to parametric rolling in extreme seas.

The proposed dynamic stability criteria presented in this work is a contribution to the effort to introduce advanced methods for assessment of ships intact stability as well as dynamic behaviour of ships in longitudinal waves encountered during severe sea conditions.

The present work can be a useful tool for maritime organizations to be used for future development of preventing measures, used as guidance (if not as regulations) for officers on board vessels, for avoiding ship’s dynamic instabilities in waves. The study conducted in this work aimed to bring contribution on optimizing the safety of navigation through a new methodology for assessment of ships stability in severe sea conditions.

References
[1] Holden C et al 2007 Nonlinear Container Ship Model for the Study of parametric Roll Resonance Modeling Identification and Control 28(4)
[2] Umeda N and Hashimoto H 2002 Qualitative aspects of nonlinear ship motions in following and quartering seas with high forward velocity Journal of Marine Science and Technology 6
[3] Belenky V et al 2011 Development of Second generation Intact Stability Criteria Naval Surface Warfare Center Carderock Division Hydromechanics department Report
[4] Belenky et al 2011 Development of Second generation Intact Stability Criteria Naval Surface Warfare Center Carderock Division, Hydromechanics department Report
[5] Bassler et al 2009 A Review of Available Methods for Application to Second Level Vulnerability Criteria Proceedings of the 10th International Conference on Stability of Ships and Ocean Vehicles (St. Petersburg: Russia)
[6] Umeda et al New Generation Intact Stability Criteria: A Step Forward Proceedings of 10th international conference on Stability of Ships and Ocean Vehicles (St. Petersburg: Russia)
[7] Shigunov et al 2009 Conditions for Parametric Rolling Proceedings of the 10th International Conference on Stability of Ships and ocean Vehicles (St. Petersburg: Russia)
[8] Kluwe F 2009 Development of a Minimum Stability Criterion to Prevent Large Amplitude Roll Motions in Following Seas Dissertation Thesis, Technical University Hamburg.
[9] Spyrou et al 2004 Towards a risk-based system for the departure control of passenger ships in rough weather in Greece Proceedings of the 2nd International Maritime Conference on Design for Safety (Sakai: Japan)
[10] France NW et al 2001 An Investigation of Head-Sea Parametric Rolling and its Influence on Container Lashing Systems SNAME Annual Meeting Presentation