Current state of the second generation intact stability criteria – achievements and remaining issues

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ABSTRACT

The paper summarises background and current status of the development of the second generation intact stability criteria at the International Maritime Organization (IMO) by January 2016. The decisions at the IMO so far together with the remaining issues, such as the required safety levels for vulnerability criteria, and operational limitation and the guidelines are presented.

Keywords: *IMO, intact stability, pure loss of stability, parametric roll, broaching, dead ship stability, excessive acceleration*

1. INTRODUCTION

The second generation intact stability criteria development launched in 2001 was a part of the revision of the Intact Stability Code at the IMO (Francescutto, 2015). The existing intact stability code known as IS Code 2008 (IMO, 2009) consists of the purely empirical criteria based on Rahola's work, which was adopted at the IMO in 1968, and the semi-empirical criterion using energy balance of simplified ship roll model in irregular beam wind and waves, which was adopted at the IMO in 1985. In the empirical criteria casualty data of ships having their length of 100 metres or less were used for obtaining the relationship between GZ curve parameters and ship stability safety. In the semi-empirical criterion casualty data of ships by 1950's were used to determine the critical value of average wind velocity, i.e. 26 m/s. Since they are directly or indirectly based on casualty data of ships existing before their developments, these two criteria could be regarded as the first generation criteria. As a result, applicability of these existing criteria to current ships cannot be straightforwardly guaranteed. The current major ship types, such as containerships, car carriers, RoPax ships, were not so easily found in 1950's and the sizes of these ships, particularly containerships and cruise ships, are drastically increasing year by year. For properly guarantee the stability safety for contemporary ships, new criteria are required, which can be named as the second generation intact stability criteria.

The adopted approach for the second generation intact stability criteria is physics-based, and multi-layered. Since progress of ship design is faster than accumulating accident data, empirical approaches are not practical. If criteria are based on physics, limitation of their applicability can be significantly removed. Current ship dynamics together with ship hydrodynamics seem to be sufficient for assessing safety of intact ships by using numerical simulation in time domain and scaled model experiments. However, the use of such advanced tools for practical purpose cannot be mandated because these tools require experts, qualified experimental facilities and time. Since the IS Code shall be applied to all passenger and cargo ships of 24 metres or larger, the number of experts and experimental facilities are definitely insufficient. Since intact stability could be related to both details of hull form and basic specifications of contract, the use of advanced tools could be impractical for early design stage. Therefore, it was agreed that, if a ship complies with simplified criteria, the application of advanced tools can be exempted. Here the simplified criteria as lower level ones should be still physics-based but with larger margin. As a result, the framework of the whole criteria can avoid inconsistent judgement in which a ship complying with the lower level criterion could fail to comply with the higher level criterion. During the discussion, the lower level criteria were made to consist of two levels: level 1 only requires a pocket calculator while level 2 requires a spread sheet-type calculation. These are named as "vulnerability criteria". On the contrary, the assessment using an advanced tool, named “direct stability assessment”, requires a computer and, occasionally experimental facilities.

This set of intact stability criteria deals with five major failure modes, i.e. pure loss of stability, parametric roll, broaching, dead ship stability and excessive acceleration.

In case that a ship fails to comply with these criteria, the ship could be allowed to navigate with operational guidelines based on the direct stability assessment procedures or operational limitations based on the level 2 vulnerability criteria.

By the 3rd session of the Sub-Committee on Ship Design and Construction (SDC) in February 2016, all vulnerability criteria with a limited number of remaining issues were agreed (IMO, 2015a and 2016). Major remaining issues are the standards, which specify the required safety levels. For supplementing the descriptions of calculation procedures in vulnerability criteria for each failure mode, explanatory notes were also developed again with a limited number of remaining issues. This paper summarises these remaining issues in the vulnerability criteria and their explanatory notes. Furthermore, discussion points for direct stability assessment, operational limitation and guidelines are also highlighted.

2. PURE LOSS OF STABILITY

When a wave is positioned with the crest amidships, the roll restoring moment could be reduced. This is due to the effect of transom stern and/or bow flare. If the ship runs with high speed in following seas, this reduction continues longer than in head waves. If the ship speed is slightly smaller than the surf-riding threshold, the ship speed increases at a wave crest so that the duration of reduced restoring moment could be extremely long. If the ship with high speed significantly heels because of reduction of restoring moment, asymmetry of the underwater submerged volume could induce a hydrodynamic yaw moment, which could act as external heel moment on a wave crest amidship.

Therefore, in a numerical simulation model for this failure mode, not only reduction of GZ curve but also the effect of surge motion and roll-yaw coupling should be taken into account.

Based on this understanding, the level 2 vulnerability criterion for this mode has a requirement of the ship forward speed. If the Froude number defined with calm-water velocity exceeds 0.24, the ship can be vulnerable to this failure mode. This is because it is already established that the surf-riding threshold with the wave steepness of 1/10 can be defined as the nominal Froude number of 0.3. Then the level 2 criterion requires the GZ calculation for a ship in longitudinal waves in which the wavelength is equal to the ship length as a conservative assumption. Since an actual wavelength can be different, the steepness used here is adjusted with this equivalent wave and ocean wave spectrum with the specified significant wave height and the mean wave period by using the least square method in space. This procedure is well known as Grim’s effective wave concept.

Once the GZ curve of the equivalent wave is obtained, it will be compared with an external heeling moment due to forward velocity. If the equilibrium between the restoring moment and the external moment occurs at a heel angle larger than 15 degrees for a passenger ship and 25 degrees for a cargo ship, the ship is judged to be vulnerable to this failure mode. In addition, if the angle of vanishing stability without external moment is larger than 30 degrees, the ship is also judged to be vulnerable. This procedure is repeated for all combinations of significant wave height and mean wave period, which appear in the wave scatter tables normally in the North Atlantic. Then their weighted average, which means the probability of dangerous sea states for this failure mode in the specified water area, is used for the final judgement in the level 2. If the attained value is larger than the required value, which is tentatively set to 0.06, the ship is judged to be vulnerable to this failure mode.

The critical Froude number and heel angles are determined with the recent accidents of RoPax and RoRo ships, which can be presumed to be relevant to this failure mode. The required value was determined with many sample calculation results for existing and coming passenger and cargo ships. At this moment this required value has not yet been finalised but it should be done by 2018.

The level 1 criterion was obtained by simplifying the level 2. While the speed requirement is the same as the level 2, the GZ calculation in waves is replaced with the GM calculation in waves. Furthermore, a method for a fast approximate calculation of GM is provided other than direct hydrostatic calculation. Here GM in waves can be calculated only with a conventional hydrostatic table and pocket calculator so that workload of ship designers is very small. Regarding the relationship with actual ocean waves, the representative wave steepness is determined using the wave scatter diagram, which is 0.0334 for the North Atlantic. The required value for the GM in waves is not yet determined but tentatively set to 0.05 m. This means that the effect of ship speed is ignored. Generally speaking, GM well represents GZ at least at smaller angle, with the exception of ships having a large beam to depth ratio.

During the development stage of these criteria, most sample calculations were executed with the approximate method for GM in waves, which appeared to be reasonably conservative with respect to the direct hydrostatic calculation. As a result, the outcomes of the level 1 are more conservative than those of the level 2. However, it was experienced that, using the direct hydrostatic calculation, the level 1 occasionally occurs to be less conservative than the level 2 so that some "false negative" cases appear for ships having large beam to depth ratio. Typical examples are offshore supply vessels. Finding a way to resolve this issue is an urgent matter. This may suggest that the required value for the level 1 could depend on the GM calculation methods because the current required value was set mainly with the approximate GM calculation. The current draft indicates that this criterion may not be applied to "a vessel with extended low weather deck due to increased likelihood of water on deck or deck-in-water".

3. PARAMETRIC ROLL

A ship in waves may experience the restoring variation with time. Under certain conditions, this restoring variation could induce violent roll motion, with maximum amplitude which can be much larger than beam-sea resonance. This phenomenon can be categorised as parametric resonance. Using a coupled heave-roll-pitch model in time domain, it is possible to accurately predict parametric roll resonance in irregular longitudinal waves. Such numerical simulation can be used as a tool for direct stability assessment.

For vulnerability level 2 criteria, an uncoupled roll model is used so that time-domain simulation can be avoided. Ignoring dynamic coupling effect with vertical motion normally could result in over-estimation of restoring variation in head waves so that we may provide conservative predictions in the level 2. It is noteworthy here that roll damping moment including bilge keel effect should be estimated by using simplified Ikeda's semi-empirical method or alternatives to it.

In case of the uncoupled roll model, the occurrence zone of parametric roll can be analytically evaluated. These estimations for typical 16 regular waves constitute the first check of the level 2.

However, since the zone for parametric roll occurrence is very wide for slender ships such as containerships, we have to evaluate amplitude of parametric roll for our final judgement even in the level 2, which is named as the second check. If we apply an averaging method or equivalent to the uncoupled roll model, the amplitudes of parametric roll can be estimated almost immediately including stability of the coexisting solutions. Here GM is assumed to vary with time but nonlinear characters of GZ curve are kept as that in calm water. For accurately modelling a hydrostatically calculated GZ curve, numerical simulations of the uncoupled roll model in time domain can be recommended. Thus, the SDC agreed to use the numerical simulation as a standard method and to keep the averaging method as an alternative. In this case, calculated results could depend on initial conditions so that use-friendly guidelines should be developed as soon as possible.

This procedure for estimating the roll amplitude is repeated for all combinations of the significant wave height and the mean wave period, which appear in the wave scattering tables normally in the North Atlantic and then their weighted average, which means the probability of dangerous sea states for this failure mode in the specified water area, is used for the final judgement in the level 2. If the attained value is larger than the required value, which is tentatively set to 0.06, the ship is judged to be vulnerable to this failure mode.

For the level 1, the procedure used in the level 2 is further simplified. If we ignore nonlinearity in both GZ and roll damping as well as the mean of

GM variation, the formula of the averaging method can be restricted to a simple estimation formula as a function of GM variation amplitude and roll damping. Regarding the relationship with actual ocean waves, the representative wave steepness is determined using the wave scatter diagram, which is 0.0167 for the North Atlantic. Further simplifying Ikeda's method and hydrostatic GM estimation, we can calculate the attained value in the level 1 only with a hydrostatic table, bilge keel area ratio and a pocket calculator.

For this failure mode, major remaining issues are the required value of the second check of the level 2 criterion, development of the guidelines for numerical simulation in time domain. In addition, estimation of the roll natural roll period should be discussed further.

4. BROACHING

Even a directionally stable ship in calm water can be directionally unstable at wave downslope. If surf-riding occurs, a ship can be captured at wave downslope so that the ship could fail to keep its straight course in stern quartering waves even with its maximum steering effort. This is known as broaching. Because of surf-riding, the ship forward speed is high. As a result, yaw angular velocity due to directional instability could result in violent centrifugal force, which could induce extremely large heel.

Probability of stability failure due to broaching can be predicted by combining a probabilistic wave theory and a coupled surge-sway-yaw-roll numerical model with accurately estimated manoeuvring coefficients. This could be utilised as a tool for direct stability assessment. Obviously accurate estimation of manoeuvring coefficients cannot be mandated for all SOLAS ships.

Thus, the SDC already agreed for the vulnerability criteria to deal with surf-riding in place of broaching. If we avoid surf-riding, possibility of stability failure due to broaching is small enough. It should be underlined that typical surf-riding can be dealt even with an uncoupled surge model in following waves so that we do not have to estimate manoeuvring coefficients.

In the level 2 criterion, critical nominal speeds for surf-riding of a self-propelled ship in regular following waves are estimated for various wavelengths and wave heights by a perturbation method starting with its solution without surge damping. Then the occurrence probability of waves that the ship can be surf-ridden is calculated with a stochastic wave theory and the North Atlantic wave statistics. Finally the probability of surf-riding occurrence when a ship meets one local wave is calculated and compared with the acceptable safety level. Based on sample calculation results for relevant ships, the acceptable safety level is tentatively set to be 0.005. It is noteworthy here that accurate prediction of calm-water resistance up to wave celerity is required and the acceptable safety level depends on prediction accuracy of wave-induced surge force.

For avoiding such difficulties and designers' workloads, the level 1 criterion was developed with sample calculation results for various ships under the wave steepness of 1/10 with measured wave-induced surge force and calm-water resistance. As a result, we concluded that, if nominal Froude number is smaller than 0.3, surf-riding is not likely to be met. This criterion and standard is the same as those in the ship-independent operational guidance in the MSC. 1/Circ. 1228. In addition, with calculated results based on the level 2, it was also concluded that, if the ship length is larger than 200 metres, the ship is out of scope of this failure mode. This is because ocean waves are too short for such longer ship to be surf-ridden.

For this failure mode, major remaining issues are curve fitting method for calm-water resistance, empirical estimations of self-propulsion factors and thrust estimation for unconventional propulsive systems.

5. DEAD SHIP STABILITY

If a ship loses all propulsion power or a ship master decides to stop engine power for avoiding other dangerous phenomena, the ship would be under beam wind and wave conditions for longer duration as a worst situation. This is known as dead ship condition, and the weather criterion was originally developed for this condition but with a simplified energy balance analysis. However, the weather criterion is believed to excessively limit the freedom of designing contemporary ships such as large cruise ships. Thus, new criteria for this failure mode were developed.

Probability of stability failure under this condition can be estimated with the Monte Carlo numerical simulation in irregular beam wind and waves by using a sway-heave-roll-pitch model. This could be utilised as a tool for direct stability assessment but small probability could require so many realisations for accurately obtaining the probability for a practical ship.

The use of an analytical solution of uncoupled roll model is a way to significantly reduce computation time. In the level 2 criterion, the SDC agreed to use linear GZ curve up to the critical heel angle. Above the critical angle, the GZ is assumed to be zero. Here the critical heel angle is determined to keep the area of original GZ curve up to the angle of vanishing stability, which is responsible for dynamic ship stability, as the same as the approximate GZ. Thanks to linear GZ, we have no difficulty for calculating the probability of stability failure in irregular beam wind and waves with a wave scattering diagram. Here the roll damping and the roll exciting moment can be estimated with simplified Ikeda's method and the Froude-Krylov approach assuming rectangular hull sections, respectively. If the calculated probability for the relevant water area is larger than the acceptable safety level, the ship is judged to be vulnerable to this failure mode. The value of acceptable safety level is tentatively set to 0.06 or 0.04, based on the sample calculations using existing and actually designed ships.

Regarding the level 1 criterion, the SDC also agreed to use the current weather criterion but with the extended wave table that was already adopted in the MSC.1/Circ. 1200 for the experiment-supported weather criterion. This is because the current weather criterion can be regarded as a simplified version of the level 2 methodology with several assumptions for wind gustiness, wave irregularity and so on.

For this failure mode, major remaining issues are the required value of the level 2 criterion, development of guidelines for alternative roll damping estimation using CFD (computational fluid dynamics) and the applicability of simplified wave excitation prediction to trimmed conditions.

The use of new vulnerability criteria could change the safety level guaranteed by the current weather criterion. For this purpose, some sample calculations using many existing ships having wider loading conditions were executed by one of the authors (IMO, 2015b). Firstly, the calculated attained values, i.e. *C* values, are plotted as a function of the metacentric height, GM, as shown in Figure 1. It does not show any distinct correlation between GM and C, which corresponds to a capsizing probability index for a ship in beam wind and waves. Although larger GM is expected to provide better stability, the existence of roll resonance, which occurs at the ship-dependent natural roll period, results in no distinct correlation. Secondly, the calculated *C* values are plotted as a function of the ratio of the heeling energy and residual restoring energy, b/a, in the level 1 as shown in Figure 2. In this figure, broadly speaking, the values of *C* decrease with the increasing value of *b/a*. This is because both methods deal with stability failure mode in beam wind and waves. Looking into detail, some scatters can be found in the b/a region between 1.1 and 5.5. This is probably due to the difference in estimation accuracy of roll motions between the two different modelling. Almost vertical trend of *C* can be found when *b/a* is zero. This is because the level 1 assumes only one stationary sea state for determining loss of static balance between GZ and wind heeling lever and the level 2 uses many different sea states and their occurrence probability included in the wave scattering diagram for the same purpose. If we use 0.04 or 0.06 as the required value, no "false negative" case exists at least in these sample ships. In other words, some ships failing to comply with the current weather criterion can be regarded as non-vulnerable for dead ship stability failure keeping the safety level that the current weather criterion requires. More data are required for finalising this issue.

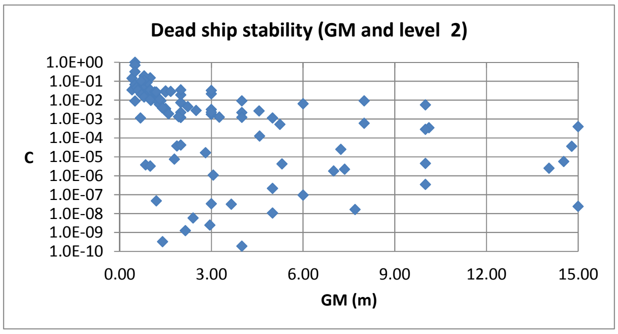

Figure 1: Relationship between the metacentric height and the C value in the level 2 criterion (IMO, 2015b).

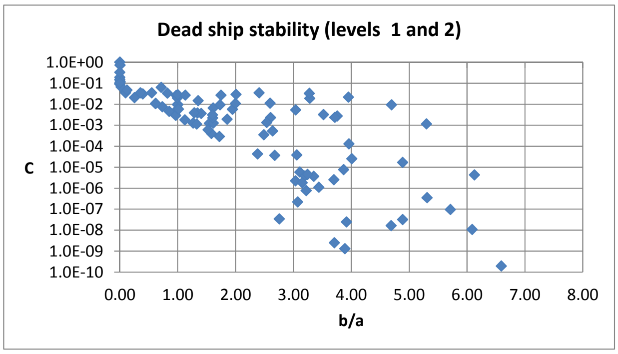

Figure 2: Relationship between the b/a in the level 1 criterion and the C value in the level 2 (IMO, 2015b).

6. EXCESSIVE ACCELERATION

If GM is excessively large, the natural roll period can be too small so that large acceleration under synchronous resonance could act on crew or cargoes. Since actual fatal accidents for modern containerships under ballast conditions were reported, this situation was also included as a stability failure. However, the problem to be solved is almost linear so that a standard seakeeping tool can be used with acceptable acceleration value. This could be a tool for direct stability assessment. However there is a different-type difficulty. A conservative estimation here could require too small GM, which can be smaller than GM required by other stability criteria.

Therefore, the vulnerability criteria should be more conservative than the direct stability assessment but its margin should be smallest. In the level 2 criterion, the uncoupled roll model in long-crested irregular waves without forward velocity is used because beam seas can be regarded as a worst situation. By using the linear response operator, wave spectrum, the Froude-Krylov wave exciting moment and the equivalent linearization of roll damping, the variance of lateral acceleration can be calculated. Then, assuming the Rayleigh distribution of roll amplitude, critical acceleration value and the wave scattering diagram, the long-term probability of lateral acceleration exceeding its critical value can be obtained. If it is larger than the acceptable level, the ship is judged as vulnerable to this failure mode. Here the critical acceleration value is tentatively set as 9.81 m/s^2 and the proposed acceptable values ranges from 1.1×10^{-4} to 0.043.

For the level 1 criterion, the level 2 procedure is simplified by approximating the wave frequency in the numerator with the natural roll frequency. As a result, we can obtain a simple formula without integral, which depends on the wave steepness from the weather criterion and roll damping coefficient. Here the roll damping and wave excitation are estimated by simplified methods. The proposed critical acceleration values here range from 5.3 m/s^2 to 8.59 m/s^2.

For this failure mode, major remaining issues are the critical acceleration values of both the level 1 and 2, the acceptable safety level of the level 2, an example application of level 2 criterion to be included in the explanatory notes.

7. OPERATIONAL LIMITATION & GUIDANCE

It can be easily presumed that a safety level estimated with a perfect direct stability assessment, if available, could be smaller than the actual accident rate. This is because operators might avoid existing dangers by avoiding some dangerous wave and operational conditions. Thus ignoring operational aspects cannot be justified. On the other hand, the outcomes from the level 2 criterion and the direct stability assessment can be useful to improve operator's actions to avoid dangers. Therefore, the SDC agreed to allow the ship operation if the ship are judged as vulnerable to a failure in the level 2 but the operational limitation based on the level 2 application outcomes is provided. Similarly, operational guidance based on the direct stability assessment can be used for a ship failed to pass the direct stability assessment.

The operational limitation agreed at the working group of the SDC can be provided with the use of alternative wave scattering diagram specifying water area and season for each loading condition. However, it is still discussed whether the operational limitation can include effects of operational elements, i.e. propeller revolution and heading angle, as well as the wave period or not. Some delegations say that estimation accuracies of the level 2 methods on these elements are not sufficient: the others say that, if we ignore these elements, most of current containerships may not be allowed to operate any more. Further discussion is needed with sample calculation results. For the operational guidelines, all wave and operational elements can be used but developing such guidelines for each ship requires tremendous computational time with a well validated numerical code.

8. CONCLUSIONS

Major remaining issues for vulnerability criteria are finalising the standards, in other words required safety levels. To do so, the relevant organisations are requested to execute sample calculations using existing and coming SOLAS and LL ships for their various GMs, draughts and trims. For direct stability assessment, more submissions of comparisons between the simulations and experiments are indispensable. We would appreciate it very much if you would contribute to these matters based on your own research projects.

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