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Application of 2nd generation stability code for 7600DWT bulk carrier with high value of GM, being in dead ship condition in irregular waves

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Abstract

The main issue of this article is to apply and investigate the application of second stability criteria for bulk carriers in typical loading conditions sailing in irregular waves. The author, by the use of linear strip theory, calculates the significant amplitudes of the ship roll with respect to wave height, incident wave angles, and mean sea period. A basic stability analysis, in this case, could be insufficient when considering other related factors like cargo shift, taking up water on the weather deck, wind gusts, inaccuracy of transverse metacentric height, and the case of changing transverse metacentric height in long-crested waves. This article shows that, in some waving conditions, the weather criteria based on standard assumptions of the ISC 2008 may be insufficient. The application of the author's method of safety margin may increase vessel safety in view of weather criteria.

Introduction

The current way to make a ship stability assessment is included in the International Code on Intact Stability 2008, adopted on the 4th of December 2008 (IMO, 2008a). Work on a second stability criteria started in 2008 (IMO, 2008b). The criteria were developed originally to guarantee safety against capsizing for a ship losing all propulsive and steering power in severe wind and waves. It is a particular situation, one of the worst for a ship, and identified by OMI as one of the five failure modes, which is known now as a dead ship in the SGISC (ITTC, 2021). In SLF 51, five stability failure modes were presented:

- Parametric resonance in following and head seas,
- Loss of stability in the wave crest,
- Broaching to and surfing,
- Dead ship condition,
- Excessive accelerations when rolling.

IMO in the new generation of stability criteria indicates that the main cause of stability failure is "Dead Ship Condition" – the ship without its own propulsion (Bielicki, 2021). According to SOLAS Regulation II-1/26.4, dead ship condition is defined as follows. Dead ship condition should be understood to mean a condition under which the main propulsion plant, boilers, and auxiliaries are not in operation and, in restoring the propulsion, no stored energy for starting and operating the propulsion plant, the main source of electrical power, and other essential auxiliaries is assumed to be available (IMO, 2004).

Each criterion based on a 2nd generation of stability assessment involves three levels, in which the first level is a simple calculation approach and is considered the most conservative. Secondly, the less conservative but more proportional approach combines performance and simplification methods. The output of the first two levels is the "vulnerability" status of the ship. As for level 3, direct analysis is introduced using numerical or experimental methods. If the ship does not comply with those three tiers, then an operational limitation guidance shall be made (Petacco & Gualeni, 2020).

The current work presents the results of an investigation into the ship's behavior in the view of roll and a proposal to extend the stability assessment required by the ISC 2008 of additional calculations of the ship roll characteristics in rough waves when the ship is without propulsion.

During the ship's normal operation, the vessel may sustain an excessive influence of waves due to actual weather conditions. During heavy rolling of the stiff ship, we should consider the mentioned risks given below:

- static wind stronger than 504 Pa,
- cargo shift or liquefication of bulk cargo,
- taking up water on deck,
- change of GM value in waves,
- discrepancies in stability calculations,
- lack of control of ship stability during sea passage.

The above-mentioned risks and the irregularity of the sea environment justify a need for a more detailed stability assessment.

Many crews are aware of the risk of heavy roll based on seamanship practice but, in actuality, there is no requirement for additional seakeeping analysis apart from basic stability calculations required by SOLAS paragraph 7.4 (IMO, 2004).

Methodology for the analyzes

Ship roll in irregular sea states

The ship roll is a base answer of the ship for external force, which is sea waves. The most reliable method of seakeeping assessment is model tests for specified waving conditions. Due to an expensive process, most of the calculations are completed by software. Recently, the strip theory has been widely used for seakeeping analysis (Nguyen & Tran, 2018). Strip theory is currently a common method to perform seakeeping analyses of a ship; many studies are implementing the theory. It is proven in many studies that strip theory is the best option for low Froude numbers and slender bodies but loses its effectiveness as the Froude number and beam/length ratio increase (Cakici et al., 2017).

The response of ship motions to ocean waves is considered as an input/output system with a known linear characteristic as shown in Figure 1. If the input wave is random, stationary, and ergodic, then the output response is described by the same properties due to the linearity of the system. It means that the ship roll is also a stationary and ergodic process, whereby the density probability of roll amplitudes is given by a Rayleigh distribution (Dudziak, 2008). This characteristic is called the response amplitude operator (RAO) and is a function of wave frequency. By considering a known wave energy spectrum with a known ship's response frequency characteristics (RAO), the response spectra can be calculated (Bielicki, 2021). With the response spectra, the statistical properties of the response can be found in Eq. (1).

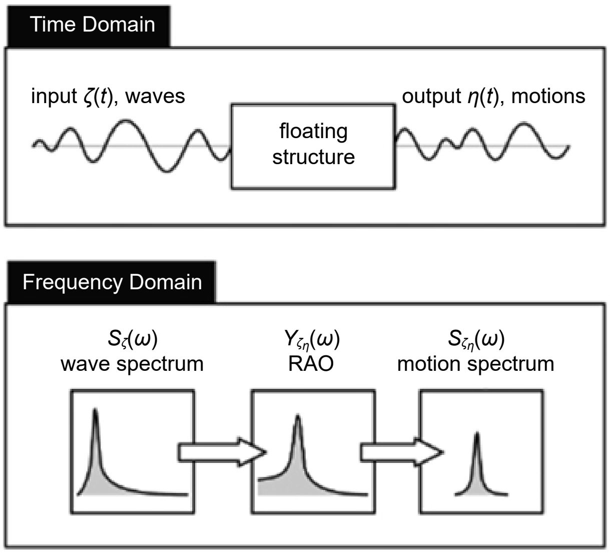

Figure 1. Linear relationship between waves (input) and motion (response) (Bielicki, 2021)

The response spectrum may be shown as follows:

$$S_{\zeta_\eta}(\omega)d\omega = S_\zeta(\omega)d\omega\, Y_\eta^2(\omega) \tag{1}$$

where S_{ζ_η} represents the response spectrum, ω signifies the angular frequency, $d\omega$ is the differential of angular frequency, S_ζ is the density of wave energy, and $Y_\eta^2(\omega)$ is the response amplitude operator (RAO). The variance of the response spectrum is defined by:

$$D_{uu}^2 = \int_0^\infty S_{\zeta_\eta}(\omega)d\omega \tag{2}$$

By the variance of ships motion (in this case, roll) given in Eq. (2), according to the Rayleigh distribution, we are able to derive the roll amplitudes with p% safe range, the mean roll amplitudes, significant roll amplitudes, and many more parameters (Dudziak, 2008).

Sea spectrum

A wave spectrum describes the energy distribution among wave components of different frequencies of a sea state. Wave spectra can be obtained directly from measured data. A fully developed sea is a sea state that will not change if the wind duration or fetch is further increased (for a fixed wind speed). The Bretschneider spectrum is applicable to fully developed seas; this spectrum is also known as the ISSC spectrum (represented by significant wave height and mean period) and is the spectrum recommended for open-ocean wave conditions (e.g., the Atlantic Ocean) (ABS, 2016; ITTC, 2021).

The formula for the Bretschneider ocean wave spectrum is written as:

$$S(\omega) = \frac{5\omega_m^4}{16\omega^5} H_{1/3}^2 e^{-5\omega_m^4/4\omega^4} \quad (\text{m}^2/(\text{rad/s})) \tag{3}$$

where ω signifies the wave frequency (rad/s) and $H_{1/3}$ is the significant wave height (m). Moreover,

$$T_S = \frac{2\pi}{\omega_m} \tag{4}$$

Here, ω_m is the peak wave frequency and T_S is the characteristic wave period.

Intact stability code

The basic principle of the weather criterion is an energy balance between the beam wind heeling and righting moments with a roll motion taken into account (Mata-Alvarez-Santullano, 2015). The ability of a ship to withstand the combined effects of beam wind and rolling shall now be demonstrated (Figure 2):

1. the ship is subjected to a steady wind pressure acting perpendicular to the ship's centerline, which results in a steady wind heeling lever, l_{wl};
2. from the resultant angle of equilibrium φ_0, the ship is assumed to roll owing to wave action to an angle of roll, φ_1, to windward. The angle of the heel under the action of steady wind, φ_0, should not exceed 16° or 80% of the angle of deck edge immersion, whichever is less;
3. the ship is then subjected to a gust of wind pressure which results in a gust of wind heeling lever, l_{w2};
4. under these circumstances, area b shall be equal to or greater than area a, as indicated in Figure 2.

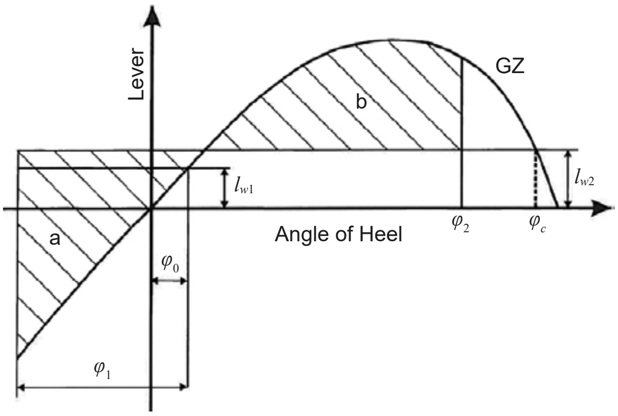

Figure 2. Severe wind and rolling (IMO, 2008a)

In Figure 2, the angles are defined as the following: φ_0 signifies the angle of heel under action of steady wind, φ_1 is the angle of roll to windward due to wave action, φ_2 is the angle of down-flooding, φ_f, or 50° or φ_c, whichever is less, and φ_f is the angle of heel at which openings in the hull, superstructures, or deckhouses that cannot be closed are weathertight immerse.

The wind heeling levers l_{w1} and l_{w2} are constant values at all angles of inclination and shall be calculated as follows:

$$l_{w1} = \frac{P \cdot A \cdot Z}{1000 \cdot g \cdot \Delta} \tag{5}$$

$$l_{w2} = 1.5 \cdot l_{w1} \tag{6}$$

where P is the wind pressure 504 Pa, A is the projected lateral area of the portion of the ship and deck cargo above the waterline (m^2), Z is the vertical distance from the center of A to the center of the underwater lateral area (m), Δ is the displacement (t), and g is the gravitational acceleration of 9.81 m/s^2.

Conditions and algorithm for the analysis

Ship for the analysis

In this study, the influence of irregular waves on weather criteria was conducted. This study was performed for a 7600 DWT bulk carrier with the following characteristics:

- length between perpendiculars, LBP = 103.90 m,
- breadth moulded, B = 18.20 m,
- design draught, T = 7.057 m,
- deadweight, DWT = 7600 t.

Notably, a 7600 DWT bulk carrier is a worldwide ship without any limits regarding the sailing area.

The body lines plan of a 7600 DWT bulk carrier is shown in Figure 3.

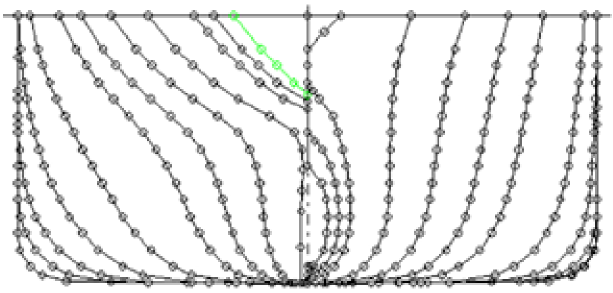

Figure 3. Body lines of 7600 DWT bulk carrier

For this investigation, a typical loading condition described as heavy cargo was used. A vessel in such a loading case has a large transverse metacentric height, GM = 3.866 m, and was loaded with a maximum deadweight.

Research method

The following calculations were completed by the author's algorithm. Calculations of the ship roll in irregular sea states were solved by simulation using Seaway software. The latter is a frequency-domain ship motions program based on the linear strip theory (Journee & Adegeest, 2003). Linear strip theory is a well-known method for seakeeping analysis.

Assuming that the ship body is slender, the strip theory simplifies the 3D flow problem into a 2D formulation, modeling the ship hull as a set of multiple 2D ship stations. Stability calculations were completed by the author's software. The algorithm displayed in Figure 4 shows the way of calculating the process.

For this analysis, only the fact that the ship is without propulsion was considered and is not making any movement through the waves (ship speed $V = 0$ knt – relative to the ground). Other related factors remained standard, including static and dynamic wind levers.

Results and discussion

The RAO roll motions in regular waves were calculated for each incident wave ranging from 000° to 180° headings, as shown in Figure 5, and for typical loading conditions given in the ships' loading manual. Figure 5 shows that the maximum values of the RAO roll are obtained for beam waves condition, being a narrow frequency band response amplitude operator.

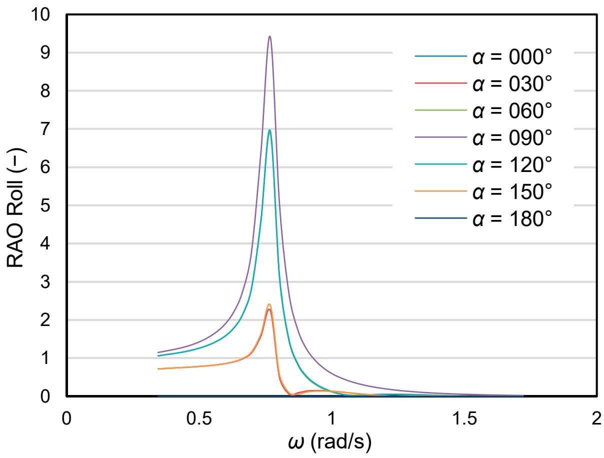

Figure 5. RAO roll functions of a ship on a regular wave for incident waves starting from α = 000° to α = 180° in increments of 030°, where GM = 3.866 m

For the purpose of this paper, only the highest value of the characteristic wave period was considered. According to Figure 6, the highest values of

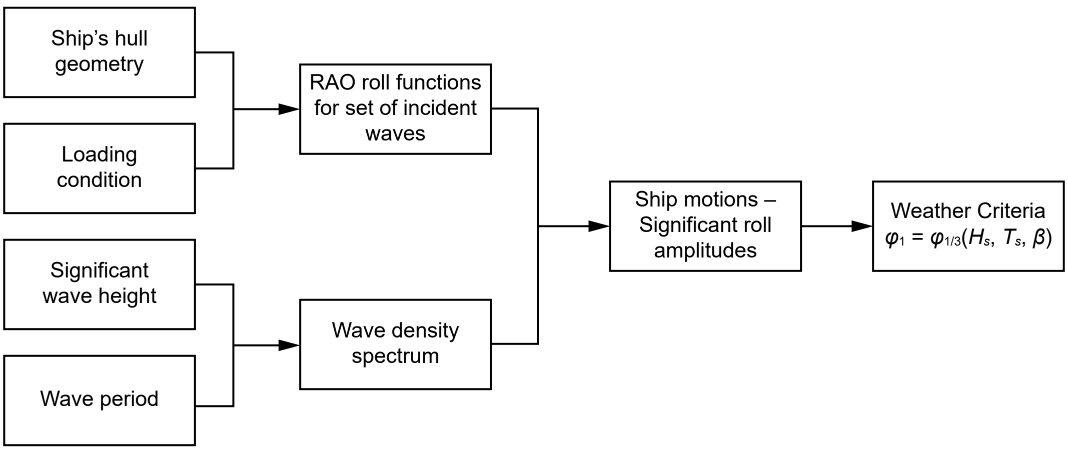

Figure 4. Algorithm of computation

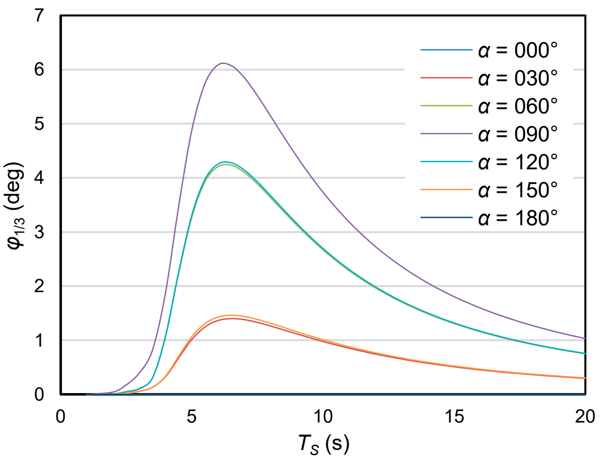

Figure 6. Significant amplitudes of roll motion on an irregular wave ranging from α = 000° to α = 180° in increments of 30°, where the significant wave height H_S = 1 m and GM = 3.866 m

significant roll motion exist for characteristic wave period T_S = 6.5 s, and the most limiting value is 6.5 s for each incident wave angle. Figure 6 also confirmed that the highest values of roll exist for beam waves. For this reason, the author has presented an analysis of the most unfavorable characteristic wave period and all ranges of incident wave angles. Due to the linearity of the system, the responses are linear and, thus, simplify calculations. Results of the calculations of significant roll amplitudes for variable significant wave height H_S, selected incident wave angles α, and constant characteristic wave period T_S are shown in Table 1.

Table 1. Significant roll amplitudes of the ship for variable significant wave height H_S and variable wave angle α (deg) for selected characteristic wave period T_S = 6.5 s

H_S (m)	α (deg)						
	000	030	060	090	120	150	180
1	0.00°	1.40°	4.24°	6.08°	4.28°	1.46°	0.00°
2	0.00°	2.80°	8.47°	12.15°	8.56°	2.93°	0.00°
3	0.00°	4.20°	12.71°	18.23°	12.84°	4.39°	0.00°
4	0.00°	5.60°	16.94°	24.30°	17.12°	5.86°	0.00°
5	0.00°	7.01°	21.18°	30.38°	21.40°	7.32°	0.00°
6	0.00°	8.41°	25.41°	36.45°	25.68°	8.78°	0.00°
7	0.00°	9.81°	29.65°	42.53°	29.96°	10.25°	0.00°

The A/B ratio was calculated by a standard shown in the ISC 2008 Code. For the implementation of the above analysis parameter, the angle of roll to windward due to wave action φ_1 is replaced by the ship's significant roll amplitudes in irregular waves shown in Table 1. Then the way of counting the ratio of areas A and B is as follows:

$$\frac{A}{B} = \frac{\int_{\varphi_0}^{\varphi_Z} GZ(\varphi)d\varphi}{\int_{\varphi_0}^{\varphi_{1/3}} GZ(\varphi)d\varphi} \tag{7}$$

According to formula (7), the A/B ratio is a function of the significant wave height H_S, constant characteristic wave period T_S, and incident wave angle α (shown in Table 2).

Table 2. A/B ratio counted for irregular waves for characteristic wave period T_S = 6.5 s, variable incident wave angle α (deg), and significant wave height H_S for selected loading conditions

H_S (m)	α (deg)						
	000	030	060	090	120	150	180
1	13404.4	452.2	64.3	32.6	63.1	420.8	13404.4
2	13404.4	137.1	17.3	8.7	16.9	126.6	13404.4
3	13404.4	65.2	7.9	3.9	7.7	60.1	13404.4
4	13404.4	38	4.5	2.2	4.8	35	13404.4
5	13404.4	24.9	2.9	1.5	3	22.8	13404.4
6	13404.4	17.5	2.1	1.1	2.1	16.1	13404.4
7	13404.4	13	1.5	0.9	1.5	11.9	13404.4

It is observed, in the case of wave angle α = 090°, significant wave height H_S = 7 m, and characteristic wave period T_S = 6.5 s, that the weather criteria are not fulfilled (highlighted in red). The ISC Code states that the A/B ratio area B shall be equal to or greater than area A. The values of the A/B ratio close to 1 (highlighted in yellow) shall also be considered dangerous.

For safety reasons, taking into consideration other factors that may exist during the exploitation of the ship, it is reasonable to apply a safety margin to assess the higher level of safety. This is based on the following expression:

$$\frac{\frac{A}{B}(H_S, T_S, \alpha_{\text{var}}) - S_L}{S_L} = \frac{A}{B}\text{Ratio} \tag{8}$$

where A/B (H_S, T_S, α_{var}) is the ratio of A/B in irregular waves, S_L is the safety ratio limit (in this example, considered as S_L = 2), H_S is the significant wave height, T_S is the characteristic wave period, and α is the incident wave angle. Table 3 shows the results of the application of the safety margin.

Table 3 should be analyzed when the safety margin S_L equals 2 and the A/B ratio is below zero, which means that the ship is not in a safe condition by taking into consideration wave angle, characteristic wave period, and significant wave height (highlighted in red). In this case, vessels should avoid

Table 3. Values of the *A*/*B* ratio, including the S_L parameter

H_S (m)	α (deg)						
	000	030	060	090	120	150	180
1	6701.2	225.1	31.2	15.3	30.5	209.4	6701.2
2	6701.2	67.5	7.6	3.4	7.5	62.3	6701.2
3	6701.2	31.6	2.9	0.9	2.8	29.1	6701.2
4	6701.2	18	1.2	0.1	1.4	16.5	6701.2
5	6701.2	11.4	0.5	-0.3	0.5	10.4	6701.2
6	6701.2	7.8	0	-0.5	0.1	7	6701.2
7	6701.2	5.5	-0.2	-0.6	-0.2	5	6701.2

such waving conditions or have a possible alternative course to avoid heavy rolling.

According to Table 2, the ratio *A*/*B* changes in relation to the power function. In selected ship and sea conditions for significant wave height H_S = 4 m, the change of *A*/*B* is linear. It may be assumed that, over significant wave height H_S = 4 m and considering other related safety factors presented in the introduction, the *A*/*B* ratio may drop close to 1 as illustrated in Figure 7.

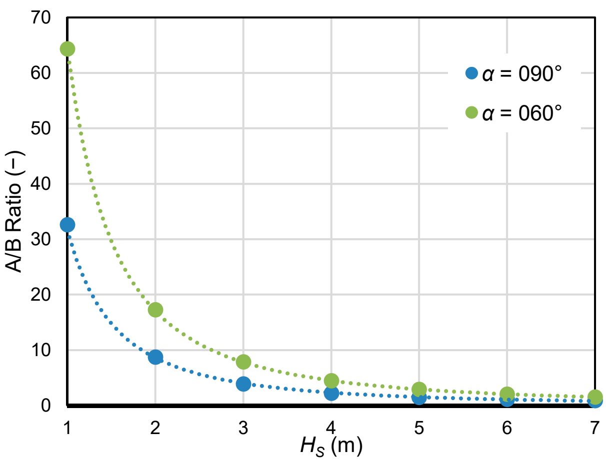

Figure 7. Change of the *A*/*B* ratio as a function of significant wave height H_S (m), characteristic wave period T_S = 6.5 s, and incident wave angle α = 060° and α = 090°

Conclusions

This paper shows a consideration of the vulnerability assessment in the dead ship condition. The process of ship rolling, under the influence of irregular waves, was derived from a linear strip theory. This article showed that, in some wave conditions, the weather stability criteria were not fulfilled.

Based on the calculation for the side wave, with characteristic period T_S = 6.5 s and significant wave height H_S = 7 m, the weather criteria *A*/*B* was not passed. This means that basic assumptions of the IS Code 2008 may be insufficient for 7600 DWT bulk carriers in heavy seas. The safety margin proposed by the author may increase vessel safety, in view of the weather criteria of the IS Code 2008, by taking into account other related factors that affect the ship's stability.

Additional documentation, including the seakeeping characteristics for selected loading conditions to typical stability report, shall be attached to inform the ship crew about the seakeeping properties of the ship, which are based on calculations but not seamanship and exploitation experience.

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