Analysis of the Influence of Pressure Field on Accuracy for Onboard Stability Codes

Luca BRAIDOTTI[a,b,1], Giorgio TRINCAS[a],
and Vittorio BUCCI[a]
[a] *Department of Engineering and Architecture, University of Trieste, Italy*
[b] *Faculty of Engineering, University of Rijeka, Croatia*

Abstract. Over last decades, due attention was paid to development of new stability criteria, especially probabilistic rules for damage stability, strongly influenced by the loss of many ro-ro ships in last decades of past century. In the last years, also a revision of intact stability code started and proposals have been implemented introducing stability in waves. These proposals deal with the equilibrium of a ship in regular waves to evaluate initial stability (GM) as well as righting arm curve in waves (GZ). This paper is not intended to critically review the present and proposed initial stability code, but is limited to assess how expected behavior of intact ships in waves is affected by accuracy in computer programs for assessing actual hydrostatic properties. An updated computer code, designed for onboard application and based on 3D pressure integral, has been developed and tested for a ro-ro ship. Then a comparison between hydrostatic and Airy effective waves has been carried out to analyze the relevance of differences between the two correspondent pressure fields affecting the equilibrium position and hydrostatic properties of the ship. It is demonstrated that these differences appear relevant beginning from sea state 4.

Keywords. Accuracy Analysis, Loading Computer System, Pressure Integration, Airy Wave Theory, Ro-ro ship.

1. Introduction

Nowadays, second generation of intact stability criteria is under finalization by IMO [1], aimed at introducing rules devoted to reduce the probability of occurrence of parametric rolling, pure loss of stability and surf-riding/broaching. After coming into force, the second generation criteria will be added to loading computer systems (LCSs), which are based on the evaluation of geo-mechanic properties (especially *GM*), equilibrium position as well as the righting arm curve. In order to check the compliance with new criteria, the stability codes shall perform such evaluations also in regular waves. Therefore, the problem of assessing these characteristics with due precision shall be analyzed by taking advantage of the improved computational power of present hardware that assures the large application of methods that were too much time-consuming in the past. Many research groups [2, 3] have tested the proposed criteria on different ship types criticizing different aspects in a purposing way. But all these works do not consider the effect of the pressure field on the accuracy of the results provided by the stability codes.

[1] Corresponding Author, Luca Braidotti, ISD Lab, Department of Engineering and Architecture, Via Alfonso Valerio 6/1, 34127 Trieste, Italy; E-mail: vbucci@units.it.

With the primary goal of improving the onboard systems, in particular the LCS, as a part of "Risk-Based System to Control Safety Level of Flooded Passenger Ships" [4], an updated method to assess ship stability has been developed, which is capable to depict the physical behavior of the operating ship in intact and damage condition being the basis for a continuous ship safety monitoring. Unlike classical methods which utilize transverse sections integration through the body of the ship to calculate the displaced volume characteristics [5], the pressure integral method has been applied allowing to evaluate the hydrostatics in regular waves by the application of different pressure fields (PFs).

Thus, it is possible to compare the outcomes corresponding different PFs in different sea states. The ship sailing through the waves is simulated as a "static placement on the wave" [6] in order to study the significance of errors depending on the wave associated pressure field. This technique has been applied to a ro-ro ship by comparing the hydrostatic pressure field, capable to reproduce exactly the results of a commercial LCS, with the Airy pressure field, which better reproduces the dynamic component of the pressure under a regular wave.

2. Pressure Fields

It is well known [7] that in a seaway the pressure distribution differs from the hydrostatic pressure near the free surface. For a regular wave, on the crest the pressure is higher than the hydrostatic one, whilst in the trough it is just the opposite. In other terms, the PF associated to the free surface depends on the free surface type. It is therefore advisable to evaluate the total pressure p at each field point $P = (x, y, z)^T$ by summing two components, namely, the static pressure p_s and the dynamic pressure p_d:

$$p(P) = p_s(P) + p_d(P) \tag{1}$$

The PF is assumed to be null above the free surface. Two types of PF are considered:

- Hydrostatic PF
- Airy PF

The two PFs are the same in calm water where the free surface corresponds to the waterplane, but they differ from one another in a seaway. For both wave types, a sinusoidal regular wave, characterized by height H, length λ and position of the first ascending zero x_0, is assumed as shape of the free surface. In the earth fixed reference system, the profile is assumed constant along the transverse y-axis and has the x-axis oriented along the wave propagation direction.

2.1.1. Hydrostatic PF

For a hydrostatic PF the dynamic pressure component is null, whereas the static component is the hydrostatic pressure evaluated as:

$$p(P) = p_s(P) = \rho g \left\{ \frac{H}{2} \sin\left[\frac{2\pi}{\lambda} (x - x_0) \right] - z \right\} \tag{2}$$

by considering the wave elevation on the free surface, and where ρ is the water density and g the gravity constant.

The hydrostatic PF does not allow to reproduce the actual pressure associated to a regular wave; nonetheless, the hydrostatic PF is often (and implicitly) used to evaluate the ship's longitudinal strength where hydrostatics are evaluated by integrating transverse cross sections.

2.1.2. Airy PF

The Airy theory [8, 9] better describes the PF associated to a sinusoidal regular wave. In this case, both the components of pressure are non-null, whereas the free surface is assumed to have the same profile defined for a static wave. Since in the Airy approach the waves are assumed to have a small height, the pressure field is defined below the mean waterplane only. Therefore, a discontinuity on this plane is introduced since the Airy theory does not define the pressure under the crests above the waterplane.

To remove this discontinuity, a hydrostatic PF is applied under the wave crests as:

$$\begin{aligned} p_s(P) &= -\rho g z && \text{if} \quad z \le 0 \\ p_s(P) &= \rho g \left\{ \frac{H}{2} \sin\left[\frac{2\pi}{\lambda}(x - x_0) \right] - z \right\} && \text{if} \quad z > 0 \end{aligned} \tag{3}$$

whilst the dynamic field is defined as:

$$\begin{aligned} p_d(P) &= -\rho g \exp\left(\frac{2\pi}{\lambda} z \right) \left\{ \frac{H}{2} \sin\left[\frac{2\pi}{\lambda}(x - x_0) \right] - z \right\} && \text{if} \quad z \le 0 \\ p_d(P) &= 0 && \text{if} \quad z > 0 \end{aligned} \tag{4}$$

3. Calculation Methodology

The method developed by ISD Lab expands upon the technique introduced by Chapman [10] and has its fundamentals in the seminal paper by Schalck & Baatrup [11], where the authors went beyond the assumption of hydrostatic PF only by providing an updated methodology to avoid errors in hydrostatic properties determination, especially in

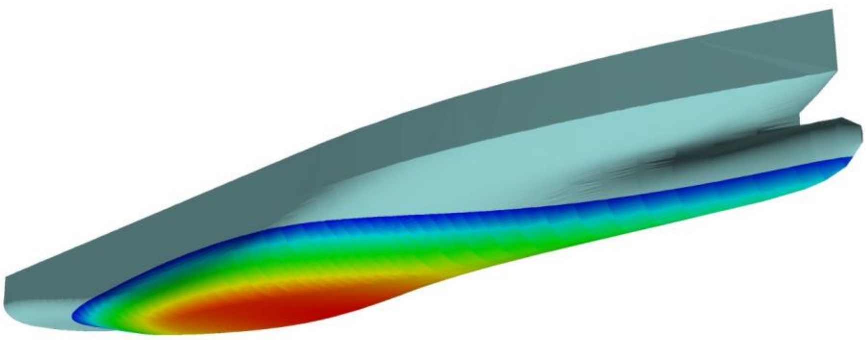

Figure 1. Airy PF in sea state 6 equivalent wave (hogging condition)

assessing the waterplane area characteristics. The magnitude and line of action of the buoyant force are thus assessed more exactly resulting in the correct location of the metacenter even at large list angles and in a seaway. The updated pressure integral method combined with a fast equilibrium algorithm guarantees high precision in calculating the transverse stability of a ship sailing in regular waves with whichever heel and trim angles (Fig. 1).

The method has been validated through comparison with the outcomes of commercial computer programs in steel water and hydrostatic PF conditions.

3.1. Updated Pressure Integration Method

In order to apply pressure integration, the hull is modelled by triangular panels with small area. The pressure acting on each of them is assumed to be constant and equal to the pressure acting on the panel's centroid. This approach allows a simple application of a generic PF associated to the free surface even if the PF is not conservative (this is a necessary assumption to apply Green theorem). The assumption of constant pressure on a panel compels to control the maximum size of the panels and to decompose the panels crossed by the free surface in completely emerged or completely submerged subpanels.

The overall forces and moments acting on the hull surface are directly evaluated summing the contribution of each panel, thus allowing to immediately derive the hydrostatic properties. A new method has been applied to evaluate the waterplane area characteristics in order to avoid the errors connected to large angles when using the Schalck & Baatrup approach: the submerged panels are projected on the waterplane and their contribution to each characteristic is multiplied by a sign function depending upon the direction of panel normal in the earth fixed reference system.

Old difficulties related to long run computation times (20-25 CPU seconds on a CRAY supercomputer or roughly 7 CPU minutes on a DEC VAX 11/750 minicomputer for a 120-panel hull) are overcome nowadays due to dramatic development` of IT. Therefore, even with a large number of panels this technique provides an accurate and very fast result (0.15 CPU second on a standard laptop for a 65,000-panel mesh).

3.2. Equilibrium Assessment

A floating body is considered in equilibrium when the center of mass G belongs to the line of the buoyancy force and the buoyancy force is equal to the ship weight. In the earth-fixed reference system, this statement means to verify that the vertical component of the buoyancy force is equal to weight W, while G and the center of buoyancy B have the same longitudinal and transversal coordinates.

In whichever floating position defined univocally by the triple $T=(T_M,\ \vartheta,\ \varphi)^T$ composed respectively by the mean draught, the trim angle and the heel angle, the residual vector D representing the distance between such a position and the equilibrium floating position is defined as:

$$D = (dW, dx, dy)^T = (W - \Delta, x_B - x_G, y_B - y_G)^T \tag{5}$$

With linear approximation, the increment vector $dT=(dT_M,\ d\vartheta,\ d\varphi)^T$ to reach the equilibrium floating position can be found from the Jacobean matrix of residual vector $\mathbf{J}_D$ solving for the following system of equations:

$$\mathbf{J}_D \times dT = D \tag{6}$$

According to Grinnaert et al. [12] the Jacobean matrix can be approximated as:

$$\mathbf{J}_D = \begin{pmatrix} \dfrac{dW_T - dW}{\varepsilon_T} & \dfrac{dW_\vartheta - dW}{\varepsilon_\vartheta} & \dfrac{dW_\varphi - dW}{\varepsilon_\varphi} \\ \dfrac{dx_T - dx}{\varepsilon_T} & \dfrac{dx_\vartheta - dx}{\varepsilon_\vartheta} & \dfrac{dx_\varphi - dx}{\varepsilon_\varphi} \\ \dfrac{dy_T - dy}{\varepsilon_T} & \dfrac{dy_\vartheta - dy}{\varepsilon_\vartheta} & \dfrac{dy_\varphi - dy}{\varepsilon_\varphi} \end{pmatrix} \tag{7}$$

where ε_T is a small increment in draft (1% of ship depth), ε_ϑ is a small increment in trim (0.1 deg), ε_φ is a small increment in heel (1 deg), D_T, D_ϑ and D_φ are the residual vectors as defined in (5) evaluated respectively at the floating positions $T_T = (T_M+\varepsilon_T, \vartheta, \varphi)^T$, $T_\vartheta = (T_M, \vartheta+\varepsilon_\vartheta, \varphi)^T$ and $T_\varphi = (T_M, \vartheta, \varphi+\varepsilon_\varphi)^T$.

The system is solved by means of Lower Upper Decomposition method finding out the increments for draft, trim and heel. These increments are used to update the floating position to approach the equilibrium floating position in an iterative process. A low number of iterations is required to find out the equilibrium floating position within the required accuracy defined through tolerances on residuals.

4. Accuracy Analysis

The loading computer systems which verify onboard the compliance with stability and structural strength regulations, are subject to certification by class societies. In particular, the accuracy of the results provided by a LCS is governed by IACS requirements [12]. In order to obtain the certification, whichever new LCS has to be capable to reproduce the outcomes obtained using an already certified code. Thus, when introducing the regular waves, it is important to analyze how different PFs affect the accuracy of the outcomes of onboard stability codes in different sea states.

With this objective in mind, the pressure integration technique is applied to a ro-ro/pax ship whose main characteristics are given in Table 1. The underwater hull form is discretized by a mesh of 63,464 panels having maximum area of 0.5 square meters.

4.1. Non-dimensional Compliance Index

If different PFs are applied to a regular sinusoidal wave, they lead to different results. In this study, the differences resulting in application of the two PFs in each sea state are considered relevant if they exceed the tolerances on hydrostatic characteristics defined in IACS UR L5.

Table 1. Ship main dimensions

L_{PP}	L_{OA}	L_{WL}	B	T
177.00 m	197.50 m	181.42 m	29.50 m	6.40 m

Thus, in a defined sea state it is possible to evaluate the equilibrium position of the ship on a related equivalent wave. In this position all the hydrostatic properties a_i, subject to IACS tolerances, are evaluated in both hydrostatics and Airy PFs in order to define their difference Δa_i. To consider all the properties together, a non-dimensional compliance index is defined as:

$$I_C = \max_i \left(\frac{\Delta a_i}{\Delta a_{i,max}} \right) \tag{8}$$

where $\Delta a_{i,max}$ is the maximum allowed difference for the property a_i provided by IACS. If the property is subject to a percentage threshold, it is converted into a dimensional value. When both dimensional and percentage thresholds are imposed, the minimum value is assumed in evaluating the non-dimensional compliance index.

With this assumptions, two set of outcomes are assumed as equal with reference to IACS regulations if $I_C < 1$.

4.2. Accuracy as Function of Sea State

The non-dimensional compliance index is herein evaluated by assessing the equilibrium position of the ro-ro ship on an "equivalent design wave" height in sea states ranging from 2 to 8 as defined by Douglas Sea Scale [14]. The equivalent wave is assumed to have constant length λ equal to ship length and height H equal to the central value for each sea state under analysis. Both hogging and sagging conditions are taken into account.

The loading condition assumed in this analysis presents the following data:

- Water density: 1.025 t/m^3
- Weight: 18788.1 t
- Centre of mass (*LCG*, *TCG*, *VCG*): 89.1 m, -0.037 m, 13.166 m
- Free surface moment (transversal, longitudinal): 7670.75 t·m, 0 t·m

Table 2 provides a summary of results. It is worth noticing that the differences become relevant already in sea state 3, where the longitudinal metacentric height *GML* exceeds its tolerance on dimensional value for both hog and sag conditions.

Table 2. Comparison between Airy and Static pressure fields

Sea State	H	H/L_{PP}	IC	Same Results within IACS Thresholds	Critical Properties
1	0.050	0.00028	0.00	✓	-
2	0.300	0.00170	0.66	✓	-
3	0.875	0.00494	2.60	✗	*GML*
4	1.875	0.01059	8.31	✗	T_M, T_F, *GM*, *GML*
5	3.250	0.01836	18.19	✗	T_M, T_F, *GM*, *GML*, *MTC*
6	5.000	0.02825	17.19	✗	T_A, T_M, T_F, *GM*, *GML*, *MTC*
7	7.500	0.04237	25.39	✗	T_A, T_M, T_F, *VCB*, *GM*, *GML*, *MTC*
8	11.500	0.06497	19.21	✗	T_A, T_M, T_F, φ, *VCB*, *GM*, *GML*, *MTC*

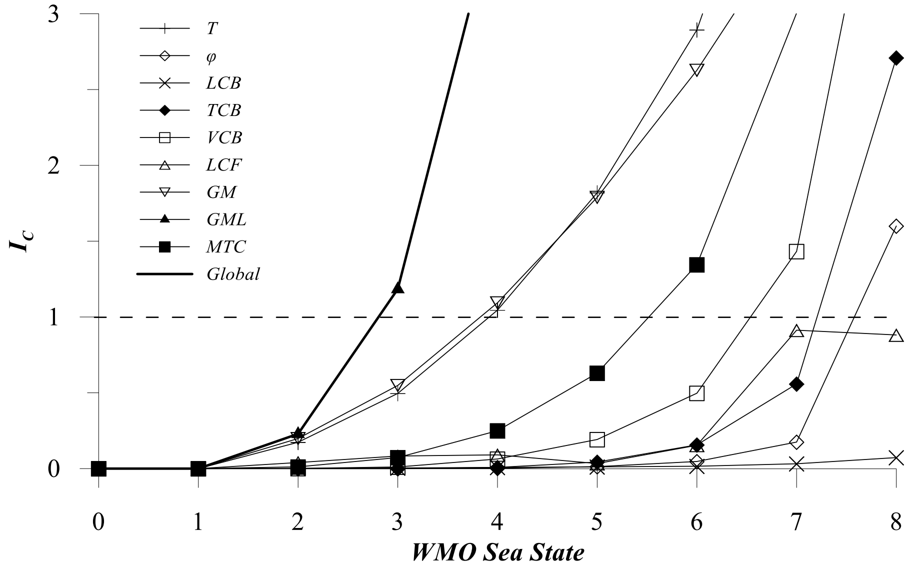

Figure 2. Non-dimensional compliance index in hogging condition

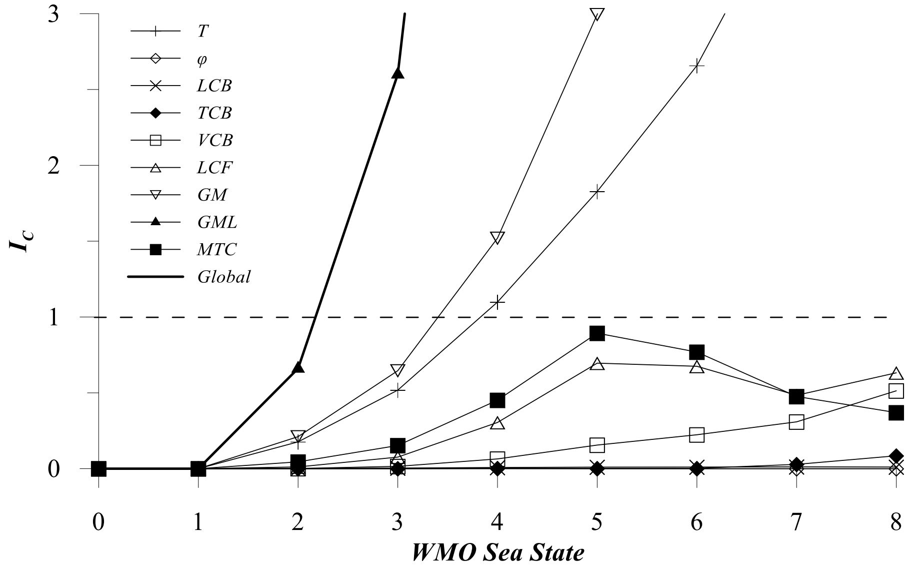

Figure 3. Non-dimensional compliance index in sagging condition

The differences in the floating position as well as ~~on~~ initial stability become relevant beginning from sea state 4 and increase exponentially with the sea state. The vertical position of the center of buoyancy and the heel angle are also affected by non-negligible differences as from sea state 7 and 8, respectively.

This comparison demonstrates that for the considered ro-ro ship the two PFs provide the same results up to sea state 2, characterized by a wave steepness 0.0017, whereas at sea state 3 (wave steepness 0.0049) they differ. This suggests that for wave steepness values exceeding 0.005 it should be good practice to use the Airy PF instead of` the hydrostatic PF.

5. Conclusions

The applications of different PFs to a ro-ro ship demonstrates that the PF type contribution in the accuracy of outcomes of an LCS is not negligible. Notable differences in assessing equilibrium and hydrostatic properties have been spotted out since sea state 3 (wave steepness greater than 0.005) and become relevant in sea state 4. Thus, since the new proposed ISC code will introduce the regular waves in ship stability assessment, the authors suggest to adopt PFs more reliable than the hydrostatic PF.

Further analysis should be performed on this topic, introducing the Stokes wave theory and testing the accuracy on all the properties subject to IACS requirements, including all values related to the righting arm curve. A systematic analysis shall be performed on different type of ships, varying their main dimensions to better define the conditions where different PFs can be applied indifferently.

Nevertheless, this paper has clearly outlined the importance of this topic and proposes a procedure to analyze the influence of PF on the accuracy of LCS results.

References

[1] IMO. Finalization of Second Generation Intact Stability Criteria, Amendments to Part B of the 2008 IS Code on Towing, Lifting and Anchor Handling Operations. In: *SDC 3/21 3rd session*. International Maritime Organization, London, 2016.

[2] Tompuri M, Ruponen P, Forss M, Lindroth D. Application of the Second Generation Intact Stability Criteria in Initial Ship Design. *Transactions - Society of Naval Architects and Marine Engineers*. 2015, **122**: 20-45.

[3] Grinnaert F, Billard J, Laurens J, KGmax curves associated with second generation intact stability criteria for different types of ships. *Journal of Marine Science and Application*. 2016; **15**(3): 223–235.

[4] Trincas G, Braidotti L, De Francesco L. Risk-Based System to Control Safety Level of Flooded Passenger Ships. *Brodogradnia*. 2017; Vol. **68**(1): 31-60.

[5] Jakić K. The Minimum Inclined Stability of the Intact and damaged Ship. *Proceedings of the First IMAM Conference*; Trieste, 1981.

[6] Voitkunsky Y. *Handbook on Ship Theory*. Sudostroenie, Leningrad, 1985.

[7] Paulling JR. The Transverse Stability of a Ship in a Longitudinal Seaway. *Journal of Ship Research*. 1981; **25**(1): 37-49.

[8] Airy GB. On Tides and Waves. In: *Encyclopedia Metropolitan*, London, 1945.

[9] Sorensen RM. Two-Dimensional Wave Equations and Wave Characteristics. In: *Basic Costal Engineering*. 3rd ed. Springer, Berlin, 2006.

[10] Chapman R. Large Amplitude Transient Motion of Two-Dimensional Floating Bodies. *Journal of Ship Research*. 1979; **23**(1): 20-31.

[11] Schalck S, Baatrup, J. Hydrostatic Stability Calculations by Pressure Integration. *Ocean Engineering*. 1990; **17**(12): 155-169.

[12] Grinnaert F, Billard J, Laurens J. Calcoque: a Fully 3D Ship Hydrostatic Solver. *Proceedings of the 12th International Conference on the Stability of Ships and Ocean Vehicles*, Glasgow, 2015.

[13] IACS. *UR L5 Rev.2 On Board Computers for Stability Calculations*. International Association of Classification Societies, London, 2006.

[14] WMO. *Manual on Codes International Codes Volume I.1 Annex II to the WMO Technical Regulations Part A – Alphanumeric Codes*. World Meteorological Organization, Geneva, 2016.