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# A Numerical Application of Ship Parametric Roll under Second Generation Stability Criteria

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## Abstract

*In this study, the parametric roll motion for the benchmark container ship form C11 is investigated by using the second generation stability criteria, which were intensively studied by IMO (International Maritime Organization). According to the IMO regulations, vulnerability criteria range between 1 and 3. While level 1 is only dependent on ship geometry and speed, level 3 is required to perform direct stability assessment with reliable robust software. The application of level 1 is considerably easy yet it is extremely conservative. Therefore, in the present study, level 2 application is performed that is less conservative than level 1 and easier than level 3. Parametric roll motion is analysed based on GM variation technique. Based on C2 assessment procedure which is calculated as an average of values of different Froude numbers and wave directions, it is found that the benchmark hull C11 was not vulnerable for the parametric roll resonance.*

***Keywords:*** *Benchmark Hull C11, Parametric Roll, GM Variation Approach.*

# Yeni Nesil Stabilite Kriterleri Çerçevesinde Parametrik Yalpa Hareketi için Sayısal bir Uygulama

## Öz

*Bu çalışmada, IMO (Uluslararası Denizcilik Organizasyonu) tarafından yoğun bir şekilde çalışılan yeni nesil stabilite kriterlerinin kullanımı ile referans konteyner gemisi formu C11 için parametrik yalpa hareketi araştırılmıştır. IMO kurallarında göre zafiyet kriteri 1 ve 3. seviye arasında değişmektedir. Seviye 1 uygulaması sadece gemi geometrisine ve hızına bağlı iken, seviye 3 uygulaması güvenilir sağlam yazılımlarla doğrudan stabilite değerlendirmesi yapılmasını gerektirir. Seviye 1'in uygulaması oldukça kolaydır fakat bu seviye aşırı derecede tutucudur. Bu sebeple, mevcut çalışmada uygulaması seviye 1'e kıyasla daha az tutucu ve seviye 3'e göre daha kolay olan seviye 2 uygulanmıştır. Parametrik yalpa değerlendirmesi GM varyasyon yaklaşımı ile elde edilmiştir. Değişik gemi hızları ve dalga yönlerine dayalı olan C2 hesabı kullanılarak yapılan değerlendirme ile mevcut gemi formunun parametrik yalpa rezonansı için zayıf olmadığı tespit edilmiştir.*

***Anahtar Kelimeler:*** *C11 Konteyner Gemisi, Parametrik Yalpa, GM Varyasyon Yaklaşımı.*

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## 1. Introduction

Parametric roll is usually known as an amplification of roll motion caused by periodic change in restoring terms in waves, which leads to dynamic instability of motion. Generally, this phenomenon is observed in head and following waves when encounter frequency of the ship is about twice of roll natural frequency in the absence of sufficient damping to dissipate additional accumulated energy as described in the report of Belenky et al., 2011 [1]. Once parametric roll starts, excessive roll angles are achieved and eventually ship could capsize. Even when the parametric roll does not result in capsizing, in some situations, the cargo could be damaged and it might be dangerous for the crew as well.

First researches on the parametric roll of ships were conducted in Germany in the late 1930s. The main objective of this research was to explain the reason for capsizing of some small ships in severe following seas. After this study, researchers continued to investigate parametric roll phenomena for decades [2]. Kerwin (1955), and Paulling &Rosenberg (1959) published milestone studies on parametric roll motion by considering the temporal variation of metacentric height, GM [3, 4]. Using this approach, IMO [5] also considered parametric roll phenomena by publishing informative documents. In this approach, restoring and damping terms are handled nonlinearly.

In the 1990s, there were some incidents where relatively large ships such as container ships and cruise ships experienced severe roll motion in head seas. These incidents started to attract the attention of researchers on the parametric roll in head seas as well (for example, APL CHINA casualty in October 1998) [2]. Apl China case was studied by France et al. (2003) [6] and they established detailed consideration in terms of the practical importance of parametric roll motion [7].

Different solution techniques for direct stability assessment, level 3, were applied by the researchers in terms of computation of parametric roll as well. For instance, Shin et al. (2003) implemented Rankine panel methods for parametric roll analyses and obtained reasonable results. However, this method is computationally expensive [8]. Retardation (impulse response) function approach proposed by Cummins (1962) that has solution of convolution integrals can be another powerful choice in terms of accuracy and efficiency of numerical computation for the solution of the parametric roll [9, 10]. In this approach, time-domain damping forces are calculated in the equation of motion by adopting the frequency-based damping forces in the retardation function. Then the nonlinear restoring force on an instantaneous wetted surface is introduced [10]. By taking advantage of being computationally cheaper, Spanos and Papanikolaou (2007) have used the retardation function approach in the parametric roll analysis of a fishing vessel [11]. Kim and Kim (2011) proposed a multi-level approach for parametric roll analyses to compare three techniques which are GM variation approach, retardation function approach, and Rankine panel method approach [12]. Pesman (2016) investigated the effects of the variable accelerations on parametric roll motion during operation by using a commercial flow solver [13]. Umeda et al. (2016) performed a numerical study of parametric roll in oblique waves using low –speed manoeuvring forces and they supported their numerical predictions with experiments [14]. Lee and Kim (2017) investigated numerically effects of parametric roll motion on added resistance. They noted significant increase in the added resistance induced by parametric roll [15]. Wang et al., studied on parametric roll of ship under the random wave by a numerical simulation. The authors reported that the parametric roll motion of ship remarkably change when the ship undergoes the wave group rather than a single wave [16].

In this study, GM variation approach is used to predict parametric roll motion. Restoring terms in the equation are deduced by fitting a seventh order polynomial for accurate representation of righting arm, GZ curve. Viscous roll damping forces are calculated by adopting the most prominent and commonly used model proposed by Ikeda to have an accurate simulation of the parametric roll [17].

## 2. GM Variation Approach

In level 2 vulnerability criterion of the parametric roll, two values are calculated: C1 and C2. If one of these criteria is less than 0.06 limit value, ship is considered invulnerable for the parametric roll motion. It is noted that 'C1 assessment procedure' is easier to implement but more conservative compare to 'C2 assessment procedure'. The value of C1 is found more than 0.06 meaning the ship is vulnerable to parametric roll motion. Therefore, in this study, C2 assessment procedure, which is calculated as an average of values of different Froude numbers, is applied step by step for the benchmark hull C11. Main properties of C11 are given in Table 1.

***Table 1.** Ship Data of C11*

| | |
|---|---|
| $L_{PP}$ (m) | 262 |
| T (m) | 12 |
| B (m) | 40 |
| Volume ($m^3$) | 71559.52 |
| KG (m) | 17.51 |
| GM_calm water (m) | 2.749 |
| Vs (m/s) | 10.51 |
| $C_B$ | 0.576 |
| $C_M$ | 0.957 |
| OG/d | -0.459 |
| $T_\omega$ ,wave period (s) | 21.78 |
| $L_{BK}/L_{pp}$ | 0.277 |
| $B_{BK}/B$ | 0.01 |

In Table 1, while $L_{pp}$ denotes the ship perpendicular length, T denotes the ship draught, B denotes the ship breadth. KG denotes the vertical position of the center of gravity. GM value in calm water denotes the metacenter height. Vs denotes the service speed. $C_B$ denotes the block coefficient. $C_M$ denotes the mid ship coefficient. $L_{BK}$ denotes the bilge keel length, $B_{BK}$ denotes the bilge keel breadth. $T_\omega$ denotes the period of the selected wave ($\lambda_\omega = L_{pp}$). Here $\lambda_\omega$ denotes the wavelength of the wave.

If a ship sailing in longitudinal seas is considered (following or head), there is no heeling moment based on waves and the nonlinear equation of parametric roll can be written as follows:

$$(I_{44}+A_{44})\ddot{\phi}+B_{44L}\dot{\phi}+B_{44NL}\dot{\phi}^3+\Delta GZ(\phi,t)=0 \quad (1)$$

Where, $B_{44L}$ stands for the linear roll damping coefficient, $B_{44NL}$ stands for the nonlinear (cubic) roll damping coefficient, $A_{44}$ stands for the added mass in roll motion, $I_{44}$ stands for transverse moment of inertia, Δ stands for displacement force of the ship and finally GZ($\phi$,t) denotes for the righting arm with respect to time which is introduced with a seventh order polynomial.

$$GZ(\phi,t)=\left[GM_m+GM_a\cos(\omega_e t)\right]\left[a\phi^7+b\phi^5+c\phi^3+d\phi\right] \quad (2)$$

Since the waves are passing through the ship in time, a periodic cosine function is used to correct the value of GM. Here, $GM_m$ is mean value of GM for ten different wave crest positions, $GM_a$ is the amplitude of GM changes for ten different wave crest positions $GM_a = 0.5(GM_{max} - GM_{min})$In other words, $GM_{max}$ and $GM_{min}$ are maximal and minimal instantaneous values of $GM_m$'s for a number of wave crest and trough positions along the ship. In Equation (1), $\omega_e$ is the encounter frequency and *a, b, c, d* are the restoring coefficients calculated using least squared method (see Table 4).

In our case, ten different wave crests positions and ten different effective heights are used. $GM_m$ , $GM_a$ and effective wave height values for the benchmark hull C11 are taken from IMO document (SDC 5/INF.4 Annex 13, page 6) and given as follows [18]: 13, submitted by France). Please note that $H_{eff}$ (the maximum effective wave height) is equal to 11.936 m [18]. This value is used to generate ten effective waves where heights of these waves varied between 1.194 and 11.936 m with a step of 1.194 m. Length of all waves ($\lambda_\omega$) is equal to the length of the ship.

***Table 2.*** *Effective Wave Heights, $GM_m$ and $GM_a$ Values [18]*

| $H_{eff}$ (m) | 1.194 | 2.387 | 3.581 | 4.774 | 5.968 | 7.162 | 8.355 | 9.549 | 10.742 | 11.936 |
|---|---|---|---|---|---|---|---|---|---|---|
| $GM_m$ (m) | 2.764 | 2.84 | 2.909 | 2.961 | 3.001 | 3.044 | 3.095 | 3.155 | 3.224 | 3.303 |
| $GM_a$ (m) | 0.473 | 0.936 | 1.315 | 1.605 | 1.851 | 2.087 | 2.301 | 2.5 | 2.697 | 2.883 |

***Table 3.*** *Effective Wave Heights, $GM_m$ and $GM_a$ Values (A Stability Software)*

| $H_{eff}$ (m) | 1.194 | 2.387 | 3.581 | 4.774 | 5.968 | 7.162 | 8.355 | 9.549 | 10.742 | 11.936 |
|---|---|---|---|---|---|---|---|---|---|---|
| $GM_m$ (m) | 2.785 | 2.856 | 2.908 | 2.949 | 2.988 | 3.035 | 3.088 | 3.150 | 3.218 | 3.301 |
| $GM_a$ (m) | 0.487 | 0.953 | 1.305 | 1.593 | 1.850 | 2.091 | 2.311 | 2.519 | 2.741 | 2.947 |

***Table 4.*** *$GM_m$ and $GM_a$ Differences Between IMO and Used Stability Software*

| $H_{eff}$ (m) | 1.194 | 2.387 | 3.581 | 4.774 | 5.968 | 7.162 | 8.355 | 9.549 | 10.742 | 11.936 |
|---|---|---|---|---|---|---|---|---|---|---|
| $GM_m$ (m) | 0.76% | 0.56% | 0.03% | 0.41% | 0.43% | 0.30% | 0.23% | 0.16% | 0.19% | 0.06% |
| $GM_a$ (m) | 2.96% | 1.82% | 0.76% | 0.75% | 0.05% | 0.19% | 0.43% | 0.76% | 1.63% | 2.22% |

On the other hand, $GM_m$ and $GM_a$ values for the benchmark hull C11 are also calculated with the help of a stability software and results are given in Table 3. Differences between Table 2 and Table 3 are given in Table 4.

In this study, Table 2 complies with related to document (SDC 5/INF.4 Annex

## 2.1. Calculation of Restoring Terms

For the restoring terms, seventh order polynomial is applied for more accurate representation. First, Gz-$\phi$ curve of the C11 is obtained with the help of a stability software, Maxsurf, Stability [19], as seen in Figure 1.

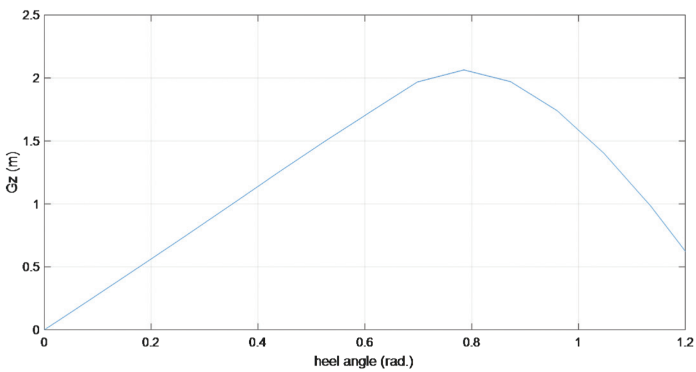


***Figure 1.*** *Gz-$\phi$ Curve of C11*

Then, seventh order polynomial is fitted by using MATLAB software curve fitting toolbox as seen from Figure 2.

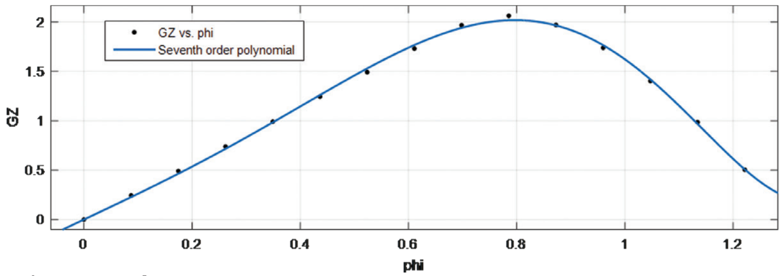


***Figure 2.*** *Gz-ϕ Curve and Curve Fitting*

Related coefficients are calculated as in Table 5:

***Table 5.*** *Coefficients for Restoring Terms*

| | |
|---|---|
| a | 0.6017 |
| b | -1.8610 |
| c | 0.9087 |
| d | 0.9316 |

## 2.2. Calculation of Damping Terms

To evaluate damping terms, simplified prediction method is used. Method for determining linear and cubic roll damping coefficients by using the equivalent linear roll damping coefficients in Ikeda's simplified formula is given in related document (SDC 4/5/1/Add. Page 18) [20]. B1 ($B_{44L}$) and B3 ($B_{44NL}$) linear and cubic damping coefficients are found as presented in Table 6. It should be noted that Ikeda's simplified formula divides the equivalent roll damping into the frictional ($B_F$), the wave ($B_W$), the eddy ($B_E$) and the bilge keel ($B_{BK}$) components. These four components are calculated empirically according to Ikeda's formula at zero speed. On the other hand, the lift component ($B_L$) is added empirically to the total damping coefficient (the one which is obtained using Ikeda's empirical formula at zero speed) considering forward speed of the ship [17, 20]. It is interesting to note that the linear damping coefficient B1 increases as the forward speed of the ship increases since the lift damping is linear.

Here k denotes the speed factor. k=0 denotes zero forward speed, k=0.5 denotes 5.255 m/s forward speed, k=0.866 denotes 9.102 m/s and finally k=1 denotes service speed 10.51 m/s. Negative speed factor is only related to the heading angle which corresponds to following waves.

## 3. Simulation Studies

Parametric roll motion equation is solved for each of the ten effective wave heights and seven speeds. (Equation 1 is solved 70 times and time series of solution is obtained). Solution is performed numerically by using MATLAB-Simulink with the Runge Kutta solver at fourth order. Solution time is set to $T_\omega \times 15$ and time step size is set to $T_\omega / 40$. Encounter frequency is

***Table 6.*** *Obtained Damping Coefficients Using Ikeda's Simplified Method*

| k (speed factor) | -1 | -0.866 | -0.5 | 0 | 0.5 | 0.866 | 1 |
|---|---|---|---|---|---|---|---|
| B1 (kNms) | 503495 | 447860 | 295902 | 88308 | 295902 | 447860 | 503495 |
| B3(kNms$^3$) | 76833120 | 76833120 | 76833120 | 76833120 | 76833120 | 76833120 | 76833120 |

***Table 7.*** *Encounter Frequencies*

| k (speed factor) | -1 (following) | -0.866 (following) | -0.5(following) | 0 | 0.5 (head) | 0.866 (head) | 1 (head) |
|---|---|---|---|---|---|---|---|
| $\omega_e$ (rad/s) | 0.233 | 0.267 | 0.359 | 0.485 | 0.611 | 0.703 | 0.737 |

calculated as $\omega_e = \omega - k_0 V_s \cos(\chi)$ (see Table 7). Here ω is wave frequency and it is found by using dispersion relation in deep water ($\omega=\sqrt{2\pi g/\lambda}$). While λ is wavelength and it is equal to $L_{pp}$ in our case, g denotes the gravity, $k_0$ denotes wave number ($k_0=2\pi/\lambda$) and χ denotes the heading angle.

Please note that Initial conditions are taken as identical in simulations. ($\phi$ = 0.0872 rad and $\dot{\phi}$ = 0 rad/s). Table 8 reveals the simulation parameters. For calculation of added mass value in roll motion, Bhattacharyya's method [21] which approximates the value of roll added mass %20 of the roll inertia moment is used.

***Table 8.*** *Simulation Parameters*

| | |
|---|---|
| I44+A44 ($tonm^2$) | 23761121 |
| B44L (kNms) | Depends on the case, see table 6 |
| B44NL($kNms^3$) | 76833120 |
| *Δ* (kN) | 719549 |
| $GM_m$ | Depends on the case, see table 2 |
| $GM_a$ | Depends on the case, see table 2 |
| a | 0.6017 |
| b | -1.8610 |
| c | 0.9087 |
| d | 0.9316 |
| $\omega_e$ | Depends on the case, see table 7 |

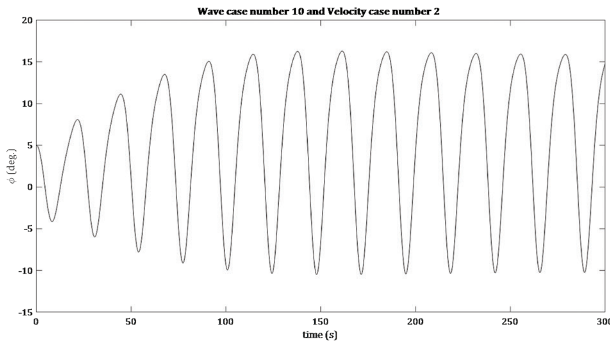


***Figure 3.*** *Time Series of Roll Motion for the Case WS10, k=-0.866*

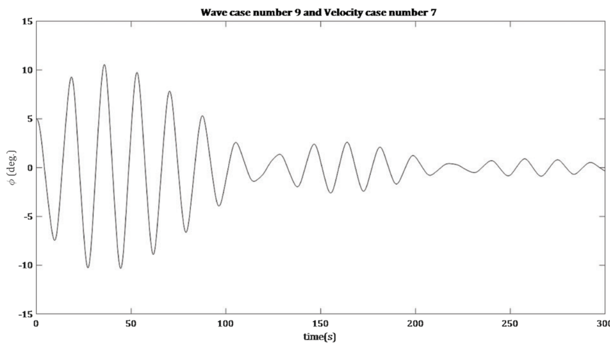


***Figure 4.*** *Time Series of Roll Motion for the Case WS9, k=1*

***Table 9.*** *Obtained Maximum Roll Angles as a Results of Seventy Simulations*

| Speed Factor, k | maximum roll angle (deg.) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | WS1 | WS2 | WS3 | WS4 | WS5 | WS6 | WS7 | WS8 | WS9 | WS10 |
| -1 | 5.0 | 5.0 | 5.0 | 5.3 | 5.6 | 5.9 | 6.1 | 6.3 | 6.4 | 6.3 |
| -0.866 | 5.0 | 5.0 | 5.0 | 5.4 | 6.4 | 7.9 | 10.2 | 13.0 | 15.3 | 16.3 |
| -0.5 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| 0 | 5.6 | 6.6 | 7.5 | 8.5 | 10.6 | 12.8 | 15.6 | 17.3 | 18.3 | 18.0 |
| 0.5 | 5.3 | 16.5 | 28.2 | 32.0 | 34.7 | 37.1 | 39.0 | 40.7 | 42.1 | 43.5 |
| 0.866 | 5.0 | 5.0 | 5.7 | 6.6 | 7.4 | 8.6 | 11.9 | 28.0 | 31.1 | 33.3 |
| 1 | 5.0 | 5.0 | 5.0 | 5.5 | 6.2 | 6.9 | 7.7 | 8.5 | 10.5 | 26.0 |

Table 9 reveals maximum roll angles as a result of seventy simulations. In Table 9, WS depicts the wave case i.e. WS1 refers to wave case 1 ($H_{eff}$ = 1.194m). Time series of the solution for WS10, k=-0.866 and WS9, k=1 are illustrated in Figure 3 and Figure 4, respectively.

## 4. Calculation of C2

C2 (Fn) is calculated as a weighted average from the set of waves given in Table 10 for a given Froude number and speed factor:

$$C2 = \left[ \sum_{i=1}^{3} C2_h(Fn_i) + C2(0) + \sum_{i=1}^{3} C2_f(Fn_i) \right] / 7 \quad (3)$$

$$V_i = V_s k_i$$

$k_i$ =1, 0.866, 0.5

$$C2_h(Fn) = \sum_{i=1}^{N} W_i C_i \quad (4)$$

$$C2_f(Fn) = \sum_{i=1}^{N} W_i C_i \quad (5)$$

$$C_i = \begin{cases} 0 & \phi_{roll,max} < 25 \deg \\ 1 & otherwise \end{cases} \quad (6)$$

$W_i$ is the weighting factor for the respective wave, divided by the number of occurrence, and N is number of wave cases specified in Table 10. These formulations can also be found in [22].

***Table 10.*** *Wave Case Occurrences [22]*

| Hs(m)/ Tz(s) | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 | sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 1.3 | 133.7 | 865.6 | 1186 | 634.2 | 186.3 | 36.9 | 5.6 | 0.7 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 3050.4 |
| 1.5 | 0 | 29.3 | 986 | 4976 | 7738 | 5569.7 | 2375.7 | 703.5 | 160.7 | 30.5 | 5.1 | 0.8 | 0.1 | 0 | 0 | 0 | 22575.4 |
| 2.5 | 0 | 2.2 | 197.5 | 2158.8 | 6230 | 7449.5 | 4860.4 | 2066 | 644.5 | 160.2 | 33.7 | 6.3 | 1.1 | 0.2 | 0 | 0 | 23810.4 |
| 3.5 | 0 | 0.2 | 34.9 | 695.5 | 3226.5 | 5675 | 5099.1 | 2838 | 1114.1 | 337.7 | 84.3 | 18.2 | 3.5 | 0.6 | 0.1 | 0 | 19127.7 |
| 4.5 | 0 | 0 | 6 | 196.1 | 1354.3 | 3288.5 | 3857.5 | 2685.5 | 1275.2 | 455.1 | 130.9 | 31.9 | 6.9 | 1.3 | 0.2 | 0 | 13289.4 |
| 5.5 | 0 | 0 | 1 | 51 | 498.4 | 1602.9 | 2372.7 | 2008.3 | 1126 | 463.6 | 150.9 | 41 | 9.7 | 2.1 | 0.4 | 0.1 | 8328.1 |
| 6.5 | 0 | 0 | 0.2 | 12.6 | 167 | 690.3 | 1257.9 | 1268.6 | 825.9 | 386.8 | 140.8 | 42.2 | 10.9 | 2.5 | 0.5 | 0.1 | 4806.3 |
| 7.5 | 0 | 0 | 0 | 3 | 52.1 | 270.1 | 594.4 | 703.2 | 524.9 | 276.7 | 111.7 | 36.7 | 10.2 | 2.5 | 0.6 | 0.1 | 2586.2 |
| 8.5 | 0 | 0 | 0 | 0.7 | 15.4 | 97.9 | 255.9 | 350.6 | 296.9 | 174.6 | 77.6 | 27.7 | 8.4 | 2.2 | 0.5 | 0.1 | 1308.5 |
| 9.5 | 0 | 0 | 0 | 0.2 | 4.3 | 33.2 | 101.9 | 159.9 | 152.2 | 99.2 | 48.3 | 18.7 | 6.1 | 1.7 | 0.4 | 0.1 | 626.2 |
| 10.5 | 0 | 0 | 0 | 0 | 1.2 | 10.7 | 37.9 | 67.5 | 71.7 | 51.5 | 27.3 | 11.4 | 4 | 1.2 | 0.3 | 0.1 | 284.8 |

./..

***Table 10.*** *Wave Case Occurrences [22] (Cont')*

| Hs(m)/ Tz(s) | 3.5 | 4.5 | 5.5 | 6.5 | 7.5 | 8.5 | 9.5 | 10.5 | 11.5 | 12.5 | 13.5 | 14.5 | 15.5 | 16.5 | 17.5 | 18.5 | sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.5 | 0 | 0 | 0 | 0 | 0.3 | 3.3 | 13.3 | 26.6 | 31.4 | 24.7 | 14.2 | 6.4 | 2.4 | 0.7 | 0.2 | 0.1 | 123.6 |
| 12.5 | 0 | 0 | 0 | 0 | 0.1 | 1 | 4.4 | 9.9 | 12.8 | 11 | 6.8 | 3.3 | 1.3 | 0.4 | 0.1 | 0 | 51.1 |
| 13.5 | 0 | 0 | 0 | 0 | 0 | 0.3 | 1.4 | 3.5 | 5 | 4.6 | 3.1 | 1.6 | 0.7 | 0.2 | 0.1 | 0 | 20.5 |
| 14.5 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.4 | 1.2 | 1.8 | 1.8 | 1.3 | 0.7 | 0.3 | 0.1 | 0 | 0 | 7.7 |
| 15.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.4 | 0.6 | 0.7 | 0.5 | 0.3 | 0.1 | 0.1 | 0 | 0 | 2.8 |
| 16.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0 | 0 | 0 | 0.9 |
| sum | 1.3 | 165.4 | 2091.2 | 9279.9 | 19921.8 | 24878.8 | 20869.9 | 12898.4 | 6244.6 | 2479 | 836.7 | 247.3 | 65.8 | 15.8 | 3.4 | 0.7 | **100000** |

For C2 calculation, maximum roll angles obtained from the simulations are updated by linear interpolation in the pre-computed values in Table 10. If the resulting maximum roll angle is larger than 25 degrees, weighting factor of the wave cases is added to C2. Final value of C2 is calculated as the average value of the seven intermediate coefficients as following:

$$C2 = \frac{0+0+0+0+17524+18.2+0.1}{100000 \times 7} = 0.0251$$

Since the value of C2 is lower than 0.06, the ship is considered to be invulnerable to parametric roll motion.

## 5. Results and Discussion

In this section, results of IMO and current study are compared to each other and presented in terms of maximum roll angles. Results are shown in Table 11. In Table 11, the coloured highlighted region is extremely important when considering the contribution to the C2 calculation since these values are close to 25 degrees (interpolation region).

***Table 11.*** *Comparison Study*

| **Speed Factor** | **maximum roll angle (deg.) (Current Study)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| -1 | 5.0 | 5.0 | 5.0 | 5.3 | 5.6 | 5.9 | 6.1 | 6.3 | 6.4 | 6.3 |
| -0.866 | 5.0 | 5.0 | 5.0 | 5.4 | 6.4 | 7.9 | 10.2 | 13.0 | 15.3 | 16.3 |
| -0.5 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 | 5.0 |
| 0 | 5.6 | 6.6 | 7.5 | 8.5 | 10.6 | 12.8 | 15.6 | 17.3 | 18.3 | 18.0 |
| 0.5 | 5.3 | **16.5** | **28.2** | 32.0 | 34.7 | 37.1 | 39.0 | 40.7 | 42.1 | 43.5 |
| 0.866 | 5.0 | 5.0 | 5.7 | 6.6 | 7.4 | 8.6 | **11.9** | **28.0** | 31.1 | 33.3 |
| 1 | 5.0 | 5.0 | 5.0 | 5.5 | 6.2 | 6.9 | 7.7 | 8.5 | **10.5** | **26.0** |
| **Speed Factor** | **maximum roll angle (deg.) (IMO)** | | | | | | | | | |
| -1 | 4.59 | 4.93 | 5.16 | 5.31 | 5.42 | 5.49 | 5.54 | 5.56 | 5.56 | 5.55 |
| -0.866 | 4.73 | 5.20 | 5.54 | 5.79 | 6.00 | 6.18 | 6.32 | 6.42 | 6.48 | 6.48 |
| -0.5 | 5.03 | 5.71 | 6.35 | 6.88 | 7.40 | 7.90 | 8.40 | 8.83 | 9.27 | 9.64 |
| 0 | 5.63 | 7.21 | 8.71 | 10.09 | 11.48 | 12.92 | 14.19 | 15.19 | 16.00 | 16.40 |
| 0.5 | 4.41 | **16.36** | **27.36** | 35.38 | 42.99 | 48.53 | 50 | 50 | 50 | 50 |
| 0.866 | 4.00 | 3.91 | 3.96 | 4.02 | 4.11 | 5.97 | **22.86** | **31.11** | 37.52 | 42.19 |
| 1 | 3.89 | 3.73 | 3.73 | 3.75 | 3.81 | 3.90 | 4.00 | 4.12 | **18.53** | **28.34** |

Maximum roll angle differences between IMO and current results might differ by following reasons:

- Different calm water restoring representation.
- Different damping evaluation.
- Different added mass value in roll motion

It should be noted that the value of C2 was found 0.0251 in the related document as well ((SDC 5/INF.4 Annex 13, page 5) [18]. It means that the small variations in the solutions do not significantly affect the value of C2 as this value is obtained from interpolated data.

**Remark:** It should be noted that the solution of equation of motion is strictly dependent on the coefficients in the equation. For instance, if the experimental data for roll decay motion were available for forward speeds for related ship, it would be possible to obtain damping terms more accurately. Solution of Equation 1 is also related to added mass value in roll motion and the treatment of temporal nature of restoring terms. It should be noted that although Level 2 is less conservative compared to Level 1, it is more conservative compared to Level 3. For the cases that Level 2 is not satisfied, the direct assessment procedure based on numerical time domain solutions (3D panel methods in time domain or the state of art Unsteady Navier-Stokes Equations with suitable turbulence closure equations) should be applied to discover whether the ship is vulnerable to parametric roll motion.

## 6. Conclusion

In this study, the parametric roll motion for the benchmark container ship form C11 was analysed within the second generation stability criteria proposed by IMO. Damping terms in the motion of equation were calculated by using Ikeda's simplified method. Restoring terms were calculated with a stability software. Added mass in roll motion is approximated as %20 of the total roll inertia moment. Nonlinear one degree of freedom parametric roll motion equation was solved in the time domain with the appropriate initial conditions. Then, 'C2 assessment procedure' proposed by IMO was implemented to the benchmark hull C11 in order to obtain statistically parametric roll in irregular waves. Results showed that the hull is invulnerable for the parametric roll resonance. Since the application of Level 2 'C2 assessment procedure' represents the roll motion dynamics with a reasonable fidelity, this assessment procedure strongly recommended before direct stability assessment.

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