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Evaluation of Parametric Roll Mode Applying the IMO Second Generation Intact Stability Criteria for 13K Chemical Tanker

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Abstract: In this paper, the evaluation procedure for Level 1, Level 2A, and Level 2B for the parametric roll among the five modes of the IMO second generation stability criteria was explained in detail. Parametric roll mode evaluation was performed using the design data of a medium-sized 13K chemical tanker instead of a well-known container ship. As a result of the Level 1 evaluation, $\delta GM_1/GM$ was smaller than the standard value, thus satisfying the first criterion, but the second criterion value was smaller than 1, so it was found that the Level 1 criterion was not satisfied. Subsequently, in the Level 2A evaluation, the weighted sum value was larger than the standard value under the ship speed and given wave conditions, so it was also not satisfied. In particular, the process of numerical analysis in the time domain was described through the equation of motion when estimating the maximum roll angle of a ship in the Level 2B evaluation, which was not detailed in previous studies. The calculation result was larger than the standard value, so it was not satisfied, and consequently, the 13K chemical tanker did not satisfy Level 1, Level 2A, and 2B.

Keywords: IMO second generation intact stability criteria; parametric roll; 13K chemical tanker; maximum roll angle

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1. Introduction

The behavior of ships in waves is a very important issue related to the safety of ships. The IMO (International Maritime Organization) establishes stability standards for the safe operation of ships and applies them to all ships to ensure safer maritime movement. As part of these efforts, the IMO prepared the SGISC (Second Generation Intact Stability Criteria) over the past 10 years and prepared to apply it to all ships. It is known that last-minute work is underway to develop new stability criteria with the goal of achieving stability [1–3]. The conventional ship stability standard does not reflect the situation in which the stability of the ship in the wave is significantly lost because the stability in the still water is calculated. Accordingly, the IMO has recently presented the second-generation intact stability criteria for the five stability vulnerable states corresponding to dynamic phenomena in waves [4–11].

Parametric roll is caused by periodic stability changes that occur with specific cycles in large ships including container ships or passenger cargo ships with bow flares. The parametric roll of a ship is a resonance phenomenon that occurs when the period of the wave incident on the hull is 1/2 of the general rolling resonance period, and it can be seen that it is distinguished from the general rolling resonance. Therefore, parametric rolling may occur when a ship encounters a wave corresponding to 1/2 times of the rolling resonance period among longitudinal waves. When the center part of the ship crosses the wave crest and through, it has a strong restoring moment from the increased restoring force under certain conditions. The ship's rolling speed increases due to the additional restoring force, and it tilts to the opposite side beyond the initial inclination angle when the resistance is exceeded. Parametric roll occurs due to repetition of this phenomenon. The frequency of the parametric roll has a value twice the roll resonance frequency of the wave, but is also affected by the wave slope in the same way as the roll resonance. In particular, a high wave height tends to widen the frequency at which a parametric roll can occur, and this point well shows that a high wave height is a factor that increases the possibility of a parametric roll occurring at sea. Especially recently, it is common for the roll resonance period to increase with the size of the vessel. The reason why parametric roll is important is that large vessels have a period equivalent to half of the resonance period even if they do not reach a very rare resonance period. After the parametric roll phenomenon occurred in the C11 container ship in 1998 in Figure 1, it was recognized as a real risk to the shipping industry through container ships, and many studies on parametric roll were conducted.

Figure 1. APL China after extreme parametric rolling in rough seas. This figure shows from [12], France et al. (2001) is an example of accidents with parametric rolling.

For the parametric roll phenomenon occurring in container ships, a study was performed on whether or not parametric roll occurred according to the change in the amplitude of the wave and the speed of the ship [13]. In addition, there is a study on whether parametric roll occurs when water depth is shallow due to proximity to a port using a KCS vessel [14]. In another study, CFD analysis was performed on the parametric roll phenomenon, and the results of CFD analysis were compared and verified with experiments [15]. There is also reviewed the results of investigations with various numerical solutions used to predict hydrodynamic loads on ships with forward speeds [16]. In their study, several types of numerical methods were evaluated in terms of complexity, from the simplest linear potential theory to the highest level CFD-based nonlinear method. In fact, many interesting studies have been conducted using linear potential theory and are being used as very useful tools for practical purposes. However, it is emphasized that this classification does not guarantee the accuracy of the solution. Therefore, there have been several studies based on CFD computation for parametric roll [17,18].

In this study, the parametric roll mode among the stability vulnerable states was evaluated according to the most recent second-generation intact stability criteria. The IMO 2nd generation intact stability criteria goes through the evaluation procedure by the formulas of Level 1 and Level 2. If the standard formula is satisfied in the Level 1, there is no need to perform the next step. If the evaluation by the formula up to Level 2 is not satisfactory, DSA (Direct Stability Assessment) corresponding to Level 3 is performed. DSA can be evaluated experimentally or through simulations. Therefore, in this paper, hydrodynamic modeling and calculation procedures for detailed calculation of Level 2 based on the latest update draft [19–21] defined by the IMO SDC subcommittee are presented in the case where Level 1 is not satisfied. In particular, Level 2, including dynamic stability against waves, is presented in detail and calculated by applying the design data of a domestic ship (13K chemical tanker) instead of the existing C11 container ship through the developed code.

2. Level 1 Evaluation Procedure

The Level 1 criterion for judging vulnerability in parametric roll is considered non-vulnerable when the conditions of Equation (1) [19].

$$\frac{\delta GM_1}{GM} \leq R_{PR} \text{ and } \frac{\nabla_D - \nabla}{A_W(D-d)} \geq 1.0 \tag{1}$$

where

$$R_{PR} = 1.87, \text{ ifthe ship has a sharp bilge; and, otherwise} \tag{2}$$

$$= 0.17 + 0.425\left(\frac{100A_k}{LB}\right), \text{ if } C_{m,full} > 0.96; \tag{3}$$

$$= 0.17 + \left(10.625 \times C_{m,full} - 9.775\right)\left(\frac{100A_k}{LB}\right), \text{ if } 0.94 \leq C_{m,full} \leq 0.96; \tag{4}$$

$$\begin{gathered} = 0.17 + 0.2125\left(\tfrac{100A_k}{LB}\right), \text{ if } C_{m,full} < 0.94; \\ \text{for each formula, } \left(\tfrac{100A_k}{LB}\right) \leq 4. \end{gathered} \tag{5}$$

R_{PR} in Equation (1) is a value related to the shape of the ship and the bilge area, and can be obtained as in Equation (2) above. GM is a metacentric height of the loading condition in calm water and δGM_1, which can be obtained as in Equation (6), is the amplitude of the variation of the GM. In addition, ∇ is a volume of displacement [m^3] corressponding to the loading condition under consideration and ∇_D is the volume of displacement at waterline equal to D at zero trim. A_w is waterplane area at the draft, D is moulded depth and d is mean draft. A_k is total overall area of the bilge keels, L is length of the ship and B is moulded breath of the ship.

$$\delta GM_1 = \frac{I_{TH} - I_{TL}}{2\nabla} \tag{6}$$

In Equation (6), I_{TH} and I_{TL} represent the transverse moment of inertia [m^4] of the waterplane at drafts d_H and d_L, and d_H and d_L can be obtained from Equations (7) and (8).

$$d_H = d + \min\left(D - d, \frac{L \cdot S_w}{2}\right) \tag{7}$$

$$d_H = d - \min\left(d - 0.25d_{full}, \frac{L \cdot S_w}{2}\right) \tag{8}$$

where, S_W is 0.0167 and $d - 0.25d_{full}$ should not be taken less than zero.

3. Level 2 Evaluation Procedure

When Level 1 vulnerability is dissatisfied, Level 2 evaluation should be performed. The vulnerability judgment under parametric roll conditions when the following Equations (9) and (10) condition is satisfied for the Level 2 criterion [19], the ship can be judged to be stable under parametric roll conditions. In the Level 2 evaluation, it is recommended to conduct the Level 2A evaluation in Equation (9) first, and to perform the Level 2B evaluation in Equation (10) if the Level 2A is not satisfied.

$$\mathrm{C1} \leq R_{PR1}(= 0.06) \tag{9}$$

$$C2 \leq R_{PR2}(= 0.025) \tag{10}$$

where, R_{PR1} and R_{PR2} were presented as 0.06 and 0.025 in the latest IMO drafts [19–21] as coefficients for vulnerability assessment, respectively, and the values for Level 2A assessment are calculated as in Equation (11).

$$C1 = \sum_{i=1}^{N} W_i C_i \tag{11}$$

where, W_i and N are weights and numbers for wave conditions to evaluate parametric roll, respectively, as shown in Table 1. C_i has a value of 0 when Equations (12) or (13) is satisfied, and has a value of 1 when it is not satisfied. $GM(H_i,\lambda_i)$ in Equation (12) is the average value of the metacentric height calculated for the ship and $\delta GM(H_i,\lambda_i)$ is half the difference between the maximum and minimum values of $GM(H_i,\lambda_i)$ calculated for the ship in waves characterized by H_i and λ_i. H_i is the wave height and λ_i is the wavelength specified in Table 1 [19].

$$GM(H_i, \lambda_i) > 0 \text{ and } \frac{\delta GM(H_i, \lambda_i)}{GM(H_i, \lambda_i)} < R_{PR} \tag{12}$$

$$V_{PRi} > V_s \tag{13}$$

Table 1. Wave cases for parametric rolling evaluation. This data is from [19], IMO SDC 7/WP.6 (2020).

Wave Case Number	Weight Factor W_i	Wavelength λ_i (m)	Wave Height H_i (m)
1	0.000013	22.574	0.350
2	0.001654	37.316	0.495
3	0.020912	55.743	0.857
4	0.092799	77.857	1.295
5	0.199218	103.655	1.732
6	0.248788	133.139	2.205
7	0.208699	166.309	2.697
8	0.128984	203.164	3.176
9	0.062446	243.705	3.625
10	0.024790	287.931	4.040
11	0.008367	335.843	4.421
12	0.002473	387.440	4.769
13	0.000658	442.723	5.097
14	0.000158	501.691	5.370
15	0.000034	564.345	5.621
16	0.000007	630.684	5.950

In the calculation of $\delta GM(H_i,\lambda_i)$ and $GM(H_i,\lambda_i)$, the wave crest should be located amidships, and at 0.1 λ_i, 0.2 λ_i, 0.3 λ_i, 0.4 λ_i, and 0.5 λ_i forward and 0.1 λ_i, 0.2 λ_i, 0.3 λ_i, and 0.4 λ_i aft of them. V_{PRi} in Equation (10) is the reference ship speed corresponding to the parametric resonance condition and can be obtained as in Equation (14).

$$V_{PRi} = \left| \frac{2\lambda_i}{T_r} \cdot \sqrt{\frac{GM(H_i, \lambda_i)}{GM}} - \sqrt{g \frac{\lambda_i}{2\pi}} \right| \tag{14}$$

where, T_r represents the parametric roll resonance period.

The calculation for Level 2B in Equation (10), which was previously mentioned that Level 2B evaluation should be performed if the Level 2A evaluation was not satisfied, is as shown in Equation (15).

$$C2 = \left[\sum_{i=1}^{12} C2(F_{n_i}, \beta_h) + \frac{1}{2}\left\{ C2(0, \beta_h) + C2\left(0, \beta_f\right) \right\} + \sum_{i=1}^{12} C2\left(F_{n_i}, \beta_f\right) \right] / 25 \quad (15)$$

where
$F_{n_i} = V_i / \sqrt{Lg}$, Froude number corresponding to ship speed V_i
$V_i = V_s \cdot K_i$, Ship speed (m/s)
K_i, as obtatined from Table 2 [19]

Table 2. Speed factor, K_i. This data is from [19], IMO SDC 7/WP.6 (2020).

i	K_i
1	1.0
2	0.991
3	0.966
4	0.924
5	0.866
6	0.793
7	0.707
8	0.609
9	0.500
10	0.383
11	0.259
12	0.131

β represents the angle of the incident wave, and F_{n_i} represents the Froude number corresponding to the ship speed V_i. In addition, V_S is the forward speed of the ship and K_i is the speed coefficient, which is given as shown in Table 2 [19].

$C2(F_{n_i}, \beta_h) = C2(F_n, \beta)$ and $C2\left(F_{n_i}, \beta_f\right) = C2(F_n, \beta)$ are calculated as specified in Equation (16) with the ship proceeding in head and following waves with a speed equal to V_i. The weighted criteria $C2(F_n, \beta)$ are calculated as a weighted average of the short-term parametric rolling failure index considering the set of waves in Table 3 [19].

$$C2(F_{n_i}, \beta) = \sum_{i=1}^{N} W_{ij}(H_s, T_z) C_{S,i} \quad (16)$$

where
$\sum_{i=1}^{N} W_{ij}(H_s, T_z) C_{S,i} = \sum_{i=1}^{NH_s} \sum_{j=1}^{NT_z} W_{ij}(H_s, T_z) C_{S,i}$, Weighting factor for the repective wave cases specified in Table 3

$C_{S,i} = 1$, If the maximum roll angle evaluated according to the recommened method exceeds 25 degree;

= 0, oherwise;

N, Total number of wave cases for which the maximum roll angle is evaluated for a combination of speed and heading;

$W_{ij}(H_s,T_z)$ represents the value in Table 3 divided by the value of N as the weighting factor for the wave environmental condition, and N is the total number of cases in which the maximum roll angle is evaluated for the combination of the ship speed and the incident wave. $C_{s,i}$ takes a value of 1 when the maximum angle at which the roll occurs exceeds 25 degrees, and takes a value of 0 when it is less than 25 degrees. The evaluation of the maximum roll angle should be performed by simulation calculations in the time domain with GZ calculated in waves [19].

Table 3. Wave case occurrences. This data is from [19], IMO SDC 7/WP.6 (2020).

Number of Occurrences: 100,000/T_z (s) = Average Zero Up-Crossing Wave Period/H_s (m) = Significant Wave Height																
T_z → / H_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**
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
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
16.5	0	0	0	0	0	0	0	0.1	0.2	0.2	0.2	0.1	0.1	0	0	0

4. Evaluation Results of Parametric Roll Mode in Level 1 Vulnerability Criterion

Based on the specifications of the 13K chemical tanker in Table 4, the vulnerability criterion Level 1 evaluation was performed in the parametric roll mode. First, the specifications for the 13K chemical tanker are shown in Table 4 below. For Level 1 evaluation, the value of R_{PR} of Equation (1) were calculated using the design data in Table 4. Figure 2a is the result of calculating the R_{PR} values according to the change of the bilge keel area factor ($\frac{100A_k}{LB}$) by classifying the values of the specific midship section coefficient C_M in Equation (2). On the other hand, Figure 2b is the result of calculating the R_{PR} value according to the change in C_M under the condition that a specific bilge keel area is given in Equation (2).

Table 4. Specification of 13K chemical tanker. This data is from [22], Lee & Kang (2004).

Parameters (Unit)	13K Chemical Tanker
Length L (m)	120.4
Breadth B (m)	20.4
Depth D (m)	11.5
Draft d (m)	8.7
Block coefficient C_B	0.797
Midship section coefficient C_M	0.995
Displacement ∇ (ton)	17457.3
Waterplane area A_W (m^2)	2260.6
Length of waterline L_W (m)	123.76
Bilge keel area A_k (m^2)	14.344
GM (m)	1.472

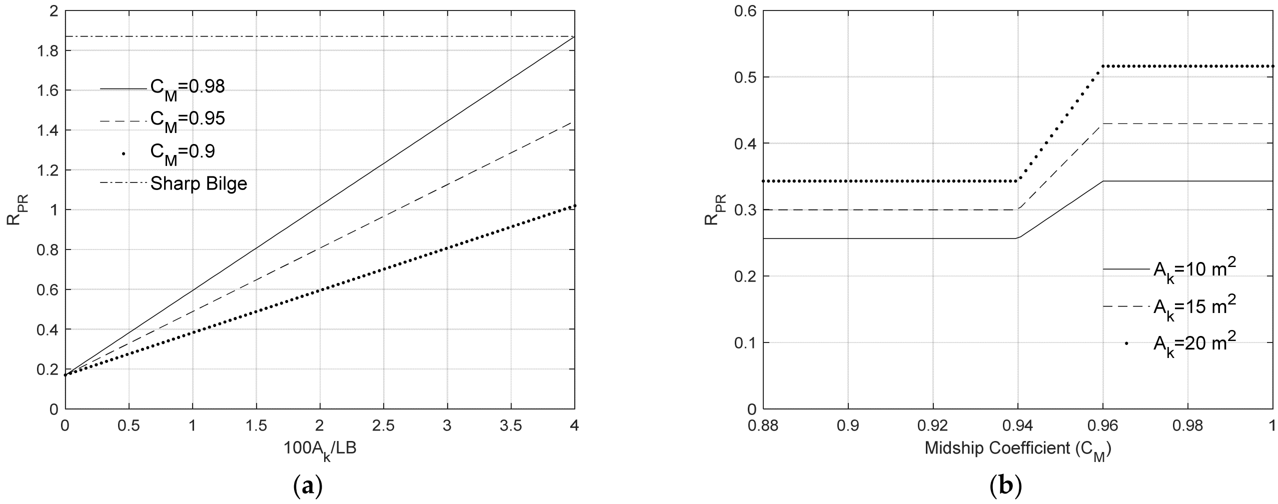

Figure 2. Calculation result of the values of R_{PR} according to Equations (2)–(5). (**a**) R_{PR} according to the change of the bilge keel area factor ($100 \cdot A_k/LB$) by classifying the values of the specific midship section coefficient C_M (=0.9, 0.95, 0.98, Sharp Bilge), (**b**) R_{PR} according to the change in C_M under the condition that a specific bilge keel area is given (A_k = 10, 15, 20 m^2).

The δGM_1 in Equation (1) was obtained using the values defined in Equations (6)–(8) and the graph of the change in moment of inertia of waterplane according to the change in draft shown in Figure 3. The moment of inertia data in Figure 3 can be fitted with a 6th order polynomial as shown in Equation (17), and the coefficients are shown in Table 5.

$$I_{Moment} = r_0 + r_1 d + r_2 d^2 + \cdots + r_6 d^6 \quad (17)$$

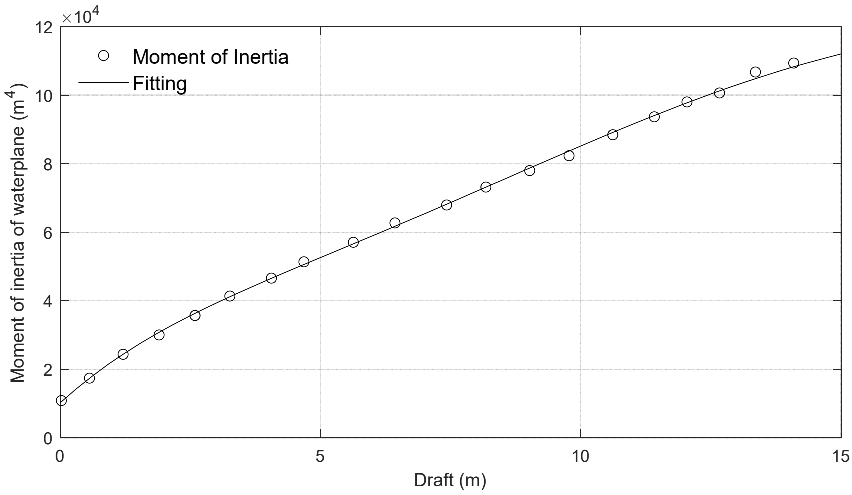

Figure 3. The relationship between the moment of inertia of waterplane of the ship. This data is adapted from [20], IMO SDC 7/INF.2 (2020).

Table 5. The moment of inertia coefficients in Equation (17).

r_0	r_1	r_2	r_3	r_4	r_5	r_6
1.0205×10^4	1.3879×10^4	-2.0446×10^3	265.5065	-16.7879	0.4803	-0.0050

Since I_{TH} and I_{TL} of Equation (6) can be obtained using the fitted approximation equation, δGM_1 is obtained and the Level 1 evaluation result of Equation (1) is presented. Results are as in Table 6.

Table 6. Evaluation of Level 1 vulnerability criterion of 13K chemical tanker.

Evaluation of Level 1 Vulnerability Criterion		
$\frac{\delta GM_1}{GM} \leq R_{PR}$ $\frac{\nabla_D - \nabla}{A_W(D-d)} \geq 1.0$	$\rightarrow$ 0.26495 < R_{PR}(=0.4182): **Satisfied** $\rightarrow$ 0.6852 < 1.0: **Unsatisfied**	**Unsatisfied**

According to the Table 6, $\delta GM_1/GM$ satisfies the first criterion because it is smaller than the R_{PR} value, but the second criterion value is less than 1, and it was found that the Level 1 criterion was not satisfied in the end.

5. Evaluation Results of Parametric Roll Mode in Level 2A Vulnerability Criterion

In this chapter, Level 2 evaluation was performed because Level 1 of the parametric roll vulnerability criterion was not satisfied in Section 4. As mentioned above, in the Level 2 evaluation, the Level 2A evaluation in Equation (9) should be performed first. In order to calculate Level 2A C1 of Equation (9), W_i and C_i of Equation (11) are arranged in Table 7 according to the conditions of Table 1. In Table 7, Equations (12) and (13) are the conditions for determining whether C_i is 0 or 1, and the ship speed (V_s) is 15.5 knots (=7.973 m/s) to obtain V_{PRi} in Equation (14).

Table 7. C_i evaluation using the data in Table 1 for parametric roll mode Level 2A vulnerability criterion.

Wave Case Number	$\delta GM/GM$	V_{PRi} (m/s)	C_i
1	0.19649	5.4332	0
2	0.041761	6.4194	0
3	0.115511	6.3141	0
4	0.217327	5.2492	0
5	0.305677	3.6013	0
6	0.342046	2.0587	0
7	0.768832	7.0929	1
8	0.945338	13.6256	0
9	0.955487	18.4042	0
10	0.904534	22.3772	0
11	0.826754	25.6981	0
12	0.746459	28.6761	0
13	0.667079	31.2534	0
14	0.587566	33.2122	0
15	0.515518	34.8002	0
16	0.453507	36.2110	0

The calculation results of Equation (11) are shown in Table 8 using the data summarized in Table 7. It can be seen that the Level 2A criterion is not satisfied as shown as a result of the calculation. Therefore, as the Level 2A criterion is not satisfied, the Level 2B criterion is evaluated in the next chapter.

Table 8. Evaluation of Level 2A vulnerability criterion of 13K chemical tanker.

Evaluation of Level 2A Vulnerability Criterion		
$C1 = \sum_{i=1}^{N} W_i C_i \leq R_{PR1}$	$\rightarrow$ 0.2087 > R_{PR1}(=0.06)	**Unsatisfied**

6. Evaluation Results of Parametric Roll Mode in Level 2B Vulnerability Criterion

In this chapter, the Level 2B evaluation corresponding to Equation (15) was carried out following the Level 2A evaluation. First, 12 Froude numbers (Fn_i) were calculated through V_i obtained by multiplying the ship speed (V_s) by the coefficient (K_i) in Table 2. In order to classify $C_{s,j}$ in Equation (16) as 0 or 1, a method of estimating the maximum parametric roll angle of the ship under given conditions is required. The conditions given here are the Fn_i corresponding to V_i, β_h = 0° in head waves, and β_f = 180° in following waves. The equation of motion of the ship's roll motion is as follows;

$$(I_{xx} + A_{44})\ddot{\phi} + B_{44}\dot{\phi} + \rho\nabla g Gz(t,\phi) = 0 \tag{18}$$

where,

ϕ, Roll angle
I_{xx}, Transverse moment of inertia
A_{44}, Added mass in roll
B_{44}, Roll damping
∇, Displaced volume
$Gz(t,\phi)$, GZ in wave

The maximum roll angle in head and following waves is evaluated as recommended in (a), (b) for each speed, V_i [19,20].

(a) The evaluation of roll angle should be carried out using the time domain simulation method with GZ calculated in waves.
(b) The length of a representative wave equals the ship length and the wave height is calculated as follows.

$$\text{Wavelength, } \lambda = L$$
$$\text{Wave height, } Hr_i = \begin{cases} 4.0 \cdot \sigma_{Heff}; 4.0 \cdot \sigma_{Heff} \leq 0.1 \cdot L \\ 0.1 \cdot L; 4.0 \cdot \sigma_{Heff} > 0.1 \cdot L \end{cases} \tag{19}$$

where,

$$\sigma^2{}_{Heff} = \sum_{i=1}^{N_{eff}} \left(RAO_{Heff}(\omega_i)\right)^2 S_W(\omega_i)\Delta\omega \tag{20}$$

$$S_W(\omega) = \frac{H_s{}^2}{4\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-5} \exp\left(-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-4}\right) \tag{21}$$

$$RAO_{Heff}(\omega_i) = \begin{cases} \frac{k_w(\omega)\cdot L \sin(0.5k_w(\omega)\cdot L)}{\pi^2 - (0.5k_w(\omega)\cdot L)^2}; \omega \neq \omega_{\mathrm{L}} \\ 1.0; \omega = \omega_{\mathrm{L}} \end{cases} \tag{22}$$

where,

ω, Wave frequency
H_s, Significant wave height in Table 3
T_z, Mean zero-crossing period in Table 3
$k_w(\omega) = \frac{\omega^2}{g}$, Wave number in deep water condition
$\omega_i = (i+1)\Delta\omega$; i = 1,2,. . .,N_{eff} (=300)
$\Delta\omega = \frac{3\omega_L}{N_{eff}}$
$\omega_L = \sqrt{\frac{2g\pi}{L}}$

With these two values (H_s, T_z) in Equation (21), a representative wave height, Hr_i in Equation (19), should be calculated by filtering waves equal to the ship length. This means that the hydrodynamic coefficients are calculated using H_s and T_z of Table 3 as input variables in the equation of motion of Equation (18). Therefore, for determining the maximum roll angle of parametric rolling, each environmental condition (H_s, T_z) is substituted by a representative wave [19,20]. In particular, since the spectral density of sea wave elevation in Equation (21) represents a long-term characterization, the representative wave height can be expressed through the effective RAO_{Heff} in Equation (22). The RAO_{Heff} is shown in Figure 4 as the main factor of the wave number (k_w), which implies the wave frequency. The roll added mass (A_{44}) and damping coefficient (B_{44}), which are hydrodynamic coefficients in Equation (18), were calculated by the representative wave height and period through an in-house code based on potential flow with reference to previous studies [23–26].

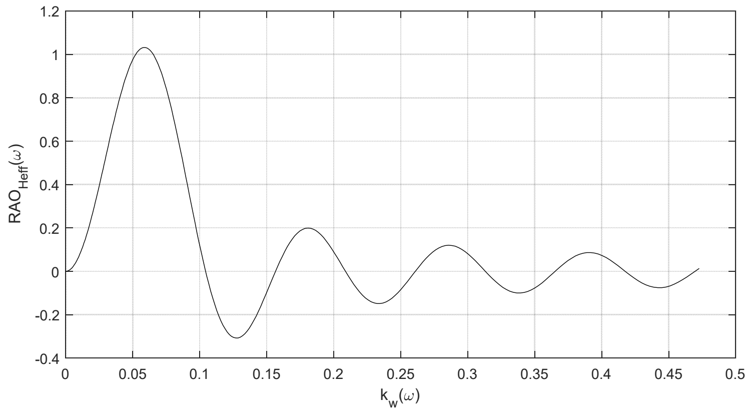

Figure 4. Response Amplitude Operator (RAO) according to wave number k_W in deep water condition.

The equation of motion completed by obtaining each coefficient is a nonlinear equation with the roll angle as an unknown. Numerical calculation was performed using the 4th order Runge-Kutta method to obtain the roll angle. Figure 5 is the simulation result of the equation of roll motion in the time domain at H = 9.5 (m) and T = 12.57 (s). The response is not expected to look like a decaying sine function because of both the parametric excitation and nonlinearity of the equation of motion. $C_{S,i}$ in Equation (16) was determined in each environmental condition in the manner described so far, and Equation (15), which is the overall Level 2B vulnerability criterion assessment, was calculated.

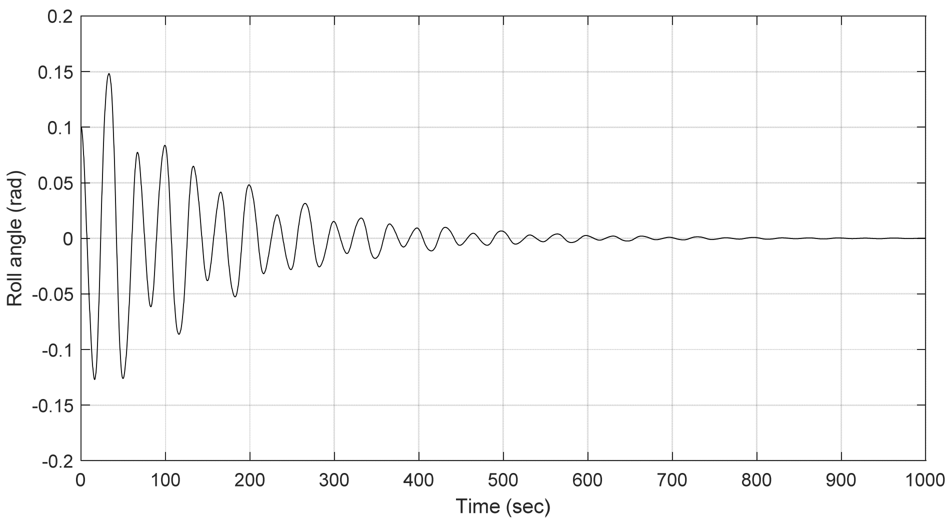

Figure 5. Time domain simulation of the Response in parametric roll (H = 9.5 (m), T = 12.57 (s)).

As a result of the calculation, as shown in Table 9, the Level 2B vulnerability criterion was not satisfied. Level 1, Level 2A, and Level 2B of parametric roll vulnerability criteria performed in this paper are all unsatisfied. Therefore, it can be confirmed that a direct stability assessment, which is DSA, corresponding to Level 3 is necessary. This research topic will be carried out in a future study.

Table 9. Evaluation of Level 2B vulnerability criterion of 13K chemical tanker.

Evaluation of Level 2B Vulnerability Criterion	
$C2 = \left[\sum_{i=1}^{12} C2(F_{n_i}, \beta_h) + \frac{1}{2}\left\{C2(0, \beta_h) + C2\left(0, \beta_f\right)\right\} + \sum_{i=1}^{12} C2\left(F_{n_i}, \beta_f\right)\right]/25$ $\rightarrow 0.11249 > R_{PR2}(=0.025)$	**Unsatisfied**

7. Conclusions

In this study, IMO second generation intact stability was evaluated in the parametric roll mode, one of the five vulnerability criteria presented by IMO (International Maritime Organization). Parametric rolling is caused by changes in stability that occur in certain rolling period of large-sized vessels, including container ships and cargo ships. This is a resonance phenomenon that occurs when the frequency of a wave incident on the hull is twice natural frequency, and it can be seen that it is distinguished from general rolling resonance. Previous researchers have conducted studies using relatively widely known container ship data [12–15]. However, in this paper, the second-generation intact stability criteria evaluation of the parametric roll mode was performed based on the specific ship (13K chemical tanker) designed and built in Korea. This ship is the size of a medium-sized ship, and the verification of the vulnerability criteria was expanded by applying the criteria that were previously used for stability evaluation mainly on large ships. The second generation stability evaluation consists of three stages, except for the proposal of the operational guidance. In this study, evaluation was conducted up to Level 1 and Level 2A and 2B. The most notable difference from the previous stability evaluation is that dynamic stability is considered by including wave conditions as a major factor. We described the evaluation procedure in as much detail as possible considering that the second-generation stability evaluation criteria are not yet widespread.

In Level 1 evaluation, it was confirmed that the ship's dimensional specifications, bilge keel area, and midship section coefficient were the main factors, and that it was relatively easy to check and change in the design stage. However, this ship satisfied GM's change ratio, but did not satisfy other conditions, which are displacement related factors, so it had to finally go to Level 2 evaluation. In the Level 2 evaluation, it is divided into 2A and 2B steps. First, in Level 2A, under the condition that the ship speed is 15 knots, the probability calculation including the weighting function under the condition of 16 different wave conditions was not satisfied because the standard value was 0.2087, which is greater than 0.06. In Level 2B, which was performed subsequently, we evaluated the maximum roll angle based on the equation of roll motion through simulation calculation in the time domain. By estimating each hydrodynamic coefficient, the complete equation of motion was constructed, and numerical analysis was performed under given wave conditions, including representative waves, to obtain the response to the parametric roll angle of the ship. As a result of the Level 2B evaluation, the value of 0.11249, which is greater than the standard value of 0.025, was not satisfied. Therefore, in this study, it was concluded that the 13K chemical tanker did not satisfy the vulnerability criteria of Level 1, Level 2A, and 2B in parametric roll mode. Considering that the IMO second generation intact stability criteria were recently established, there were few papers detailing the process of calculating Level 1 and Level 2 for the parametric roll mode. In addition, the 13K chemical tanker should be carried out the direct stability assessment, which is the Level 3 evaluation. Nevertheless, since the calculation process of Level 2B was not described in detail in the draft, it is considered that this study has value as a detailed description of the evaluation process. Level 3 evaluation, that is, direct stability assessment, will be evaluated as a future research topic when specific standards are arranged. When evaluating Level 3, that is, the DSA level, the difficulty in predicting the parametric roll is the influence of the hydrodynamic coefficient in the equation of motion. In particular, damping occurs in parametric rolling due to various causes, and it is very difficult to accurately predict each of these factors. In the future, we plan to systematically analyze the cause of each coefficient in the equation of motion for parametric rolls and continue research to mathematically express its quantitative size to come up with a more practical formula. Applying a more realistic model has the advantage of reducing the design margin because the behavior of the solution can be more accurately estimated even if the mathematical model is complex. Therefore, the results of this study are expected to prepare a ship design response strategy that can reduce the vulnerability to parametric roll mode.

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Abbreviations

Symbols	Definition	Symbols	Definition
L	length of the ship	M	mass of the ship
B	moulded breadth of the ship	GM	metacentric height
D	moulded depth	T_r	natural roll period
V_s	service speed	ω_r	natural roll frequency
Fn	Froude number = $V_s/\sqrt{Lg}$	Λ	wavelength
A_k	total overall area of the bilge keels	H	wave height
∇	volume of displacement	H_s	significant wave height for the short-term environmental condition
g	density of salt water	T_z	mean zero-crossing period for the short-term environmental condition
ρ	acceleration due to gravity	S_{zz}	wave elevation energy spectrum
d	mean draft	Ω	circular frequency
C_B	block coefficient	K	wave number = $2\pi/\lambda$
A_W	waterplane area at the draft	N_s	number of simulations
I_{xx}	roll moment of inertia		

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