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Comprehensive calculation and safety assessment of parametric roll of very large container ship

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Abstract: As the significant variation of *GM* in waves for very large container ships, strict demands are raised for this ship type in the evaluation and safety assessment of parametric roll. Targeting a 10 000 TEU container ship sailing in head sea, this study conducts a series of calculations and evaluations on parametric roll motion in which each loading condition is calculated step-by-step. Direct calculation is conducted if neither Level 1 nor Level 2 is satisfied. In this paper, an independently developed time-domain simulation is conducted for loading conditions that fail to match the Level 2 criteria, which is based on a typical 3-DOF weakly nonlinear numerical model. Ship velocity and wave conditions are taken into consideration to explore sensible conditions concerning parametric roll. Finally, according to the results, corresponding safety assessments and several avoidance measures are proposed, such as reducing the height of the center of gravity and raising the speed moderately. In addition, if wave predictions can be detected in advance, the circumstance of the natural rolling period being twice as great as the encountering period should be avoided, which is the most sensible factor for inducing parametric roll. Comprehensive calculation and checking for the 10 000 TEU ship can instruct the general design and improve safety for very large container ships; as a result, remarkable engineering applications and reference value can be recognized.

Key words: very large container ship; parametric roll; direct calculation; safety assessment

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0 Introduction

The International Maritime Organization (IMO) is formulating the second generation of intact stability rules [1] including five kinds of stability failure modes, i.e. parametric roll, pure stability loss, surf-riding/broaching, dead ship stability and excessive acceleration. As an important part of the second generation of intact stability criterion, the formulation and implementation of parametric roll criterion will have a significant impact on the performance and design of ship [2]. For ships navigating in longitudinal waves, when the natural period of rolling is close to two times the encountering period, and the incident wavelength range is close to the range of ship length, area of waterplane will have large fluctuations with the changes of relative position of the waves and the hull, causing variation of the metacentric height *GM*. At this point, if the roll damping of the ship is small, large-amplitude rolling will occur in the case of small initial lateral disturbances, i.e., parametric roll phenomenon occurs [3-5]. This kind of circumstance happens in fishing boat, ro-ro passenger ship and large container ship [6].

According to the research results of parametric roll and considering the convenience of engineering

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application, IMO divides the criterion into three levels, that is, the first level criterion, the second level criterion, and direct calculation criterion. The three levels of criteria are designed to predict parametric roll from simple empirical formula to the single Degree of Freedom (DOF) nonlinear mechanics method, until by means of complex numerical simulation of the 3-DOF and above motion, in ascending order of the complexity and the prediction accuracy [7]. In the real design of a ship, calculation of a higher level criterion is needed only when the design scheme fails to pass through the lower level criterion.

Large container ships are more sensitive to parametric roll. It can be found in the investigation reports on a number of ship accidents including APL CHINA (C11 container ship) that [5], casualties and property losses caused by large-amplitude rolling and even capsizing will be more disastrous. Combined with the first two level criteria of the second generation intact stability parametric roll and the software platform for stability evaluation developed by China Ship Scientific Research Center, Fu et al. [8] analyzed the sensitive factors of the bilge keel area and the height of the center of gravity on parametric roll of the C11 container ship, and the molded lines of ship bow and stern were improved to improve the parametric roll. But there is not much work on comprehensive check of the three levels for such ships. Therefore, at contemporary era when the navigational safety of oceangoing freighter is paid more attention, the significance of the safety assessment of 10 000 TEU container ship is particularly prominent, which also can better guide the overall design of very large container ship, providing more fundamental research for the improvement of safety level.

The IMO intact stability rule of the second generation of parametric roll is expected to be finalized in 2019, in which the first and second level criteria have almost matured, and the formula system has gradually been recognized by many research institutions. Umeda et al. [9] simplified the parametric roll into a single DOF roll motion model, where the nonlinear restoring force was expressed by nonlinear functions associated with wave steepness. Liang et al. [2] calculated the restoring force coefficient in still water by using multivariate linear regression method based on parametric roll criterion, and used the dichotomy to solve the amplitude of roll. According to the calculation results of a fisheries administration ship, it provides operational guidance for the safety of navigation. However, for the third level criterion, there are many proposals for different calculation methods and models, and they are still in the stage of sample ship calculation. A systematic and complete criterion framework has not been formed yet. Therefore, it is of great research value to enrich the information and check data of sample ships of the third level criterion before they are finalized.

For this, considering the impact of pitching and heaving obtained by calculation of hydrostatic force on parametric roll, Bulian [10] proposed a model of 1.5 DOFs, and obtained an accurate time-domain simulation method of parametric roll. Spanos and Papanikolaou [11] carried out numerical simulation of fishing boats and ro-ro ships by using a six-DOF model based on the impulse response function method, and the results show that rolling and pitching were coupled, and nonlinear restoring force has great influence on the calculation results of parametric roll. Sadat-Hosseini et al. [12] studied the parametric roll of a surface ship by CFD method and found that, the simulated results were in good agreement with the experimental results in head sea, but the use of CFD for calculation was time-consuming.

In this paper, according to the loading and the stability calculation sheet of a 10 000 TEU container ship navigating in head sea, the loading conditions were calculated one by one. The first level criterion was judged first. If the requirements were not met, the 1st check and 2nd check of the second level criterion were needed. In view of the strong nonlinearity of parametric roll, it was greatly influenced by the roll damping and nonlinear restoring force calculation. Considering that the practical problems in engineering calculation are relatively simple and practical, a typical 3-DOF (rolling, pitching and heaving) weakly nonlinear model was proposed and developed independently, so as to perform parametric roll simulation of regular waves in head sea in time domain for the loading conditions that did not meet the requirements of the second level criterion. Finally, parametric roll was simulated for the 10 000 TEU container ship at different speeds, wave heights and wave frequencies, and the characteristics of sensitive conditions were analyzed to conduct evaluation of navigation safety and propose measures for avoiding risks.

1 IMO first level vulnerability criterion of parametric roll

The first level criterion is based on the empirical formula [7]. If a ship meets the following condition, it can be determined that the ship is not sensitive to parametric roll:

$$\frac{\Delta GM}{GM} \leqslant R_{\mathrm{PR}} \tag{1}$$

where ΔGM is the variation range of metacentric height of the ship when the waves pass through the hull; GM is the metacentric height of the loading conditions of the ship calculated under hydrostatic conditions; the R_{PR} is the standard value and the specific formula is as follows:

$$R_{\mathrm{PR}} = \begin{cases} 0.17 + 0.425 \cdot \dfrac{100A_{\mathrm{BK}}}{L_{\mathrm{pp}}B}, & C_{\mathrm{m}} > 0.96 \\ 0.17 + \left(10.625C_{\mathrm{m}} - 9.775\right) \cdot \dfrac{100A_{\mathrm{BK}}}{L_{\mathrm{pp}}B}, & 0.94 < C_{\mathrm{m}} < 0.96 \\ 0.17 + 0.212\,5 \cdot \dfrac{100A_{\mathrm{BK}}}{L_{\mathrm{pp}}B}, & C_{\mathrm{m}} < 0.94 \end{cases} \tag{2}$$

where C_{m} is the cross section coefficient of midship; A_{BK} is the sum of lateral projection area of bilge keel that is not included in the appendage, m^2.

The main dimensions of the 10 000 TEU container ship are shown in Table 1.

Table 1 Main dimensions of 10 000 TEU container ship

Parameters	Values
Length between perpendiculars L_{pp}/m	320.00
Molded breadth B/m	48.20
Molded depth D/m	27.20
Design draft d_{f}/m	13.00
Scantling draft d_{a}/m	15.50

The check calculation results are shown in Fig. 1 and Fig. 2. By contrast, it can be seen that, for an empty ship with smaller draft (d < 10 m) and ballast condition under various conditions, the height of the center of gravity was far lower than that under the loading conditions. The value of GM was larger (GM > 12 m), and the calculation value of $\Delta GM/GM$ was smaller, which passed the criterion more easily.

For loading conditions of a larger draft d, the value of GM depends mainly on the height of the center of gravity G, i.e., the storey height of the container load on deck. Research shows that the lower storey height of the container layout, the lower center of gravity of the whole ship, the greater GM, the smaller calculation value of $\Delta GM/GM$, and the higher passing rate of the first level criterion of parametric roll. Without changing the layout of the container, the center of gravity of the whole ship can be lowered by loading the heavy containers as many as possible into the cargo compartment and loading the light containers onto the deck.

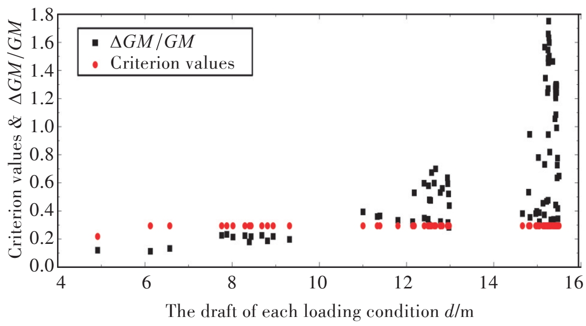


Fig.1 The first level criterion results of parametric roll

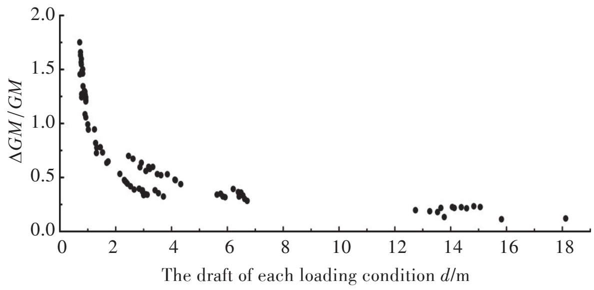


Fig.2 Variation of $\Delta GM/GM$ with GM

After calculation and verification, in the 89 loading conditions of the 10 000 TEU container ship, 14 loading conditions passed the first level vulnerability criterion of parametric roll, and the remaining 75 loading conditions did not pass the criterion, which require the second level criterion.

2 IMO second level vulnerability criterion of parametric roll

According to the draft of parametric roll [7], the irregular wave scatter diagram recommended by the International Association of Classification Societies (IACS) was used for the incident wave conditions of ship sensitivity forecast, and all the sea conditions will be converted to the equivalent regular waves by using the equivalent wave theory of Grim [13]. The second level was stricter than the first level. If a ship satisfies any of the following conditions, it is assumed that no parametric roll will occur:

1) The value of C_1 calculated by 1$^{\mathrm{st}}$ check is less than R_{PR0};

2) The value of C_1 calculated by 1$^{\mathrm{st}}$ check is greater than R_{PR0}, and the value of C_2 obtained by 2$^{\mathrm{nd}}$ check is less than R_{PR1}.

2.1 1$^{\mathrm{st}}$ check algorithm

The 1$^{\mathrm{st}}$ check algorithm determines the sensitivity index of ship to parametric rollby expanding the incident wave condition of the first level criterion, and by weighted calculation of several equivalent regular incident waves.

$$C_1 < R_{\mathrm{PR0}}\ ,\ R_{\mathrm{PR0}} = 0.06 \tag{3}$$

where C_1 is the sensitivity index; R_{PR0} is the standard value of 1st check. When the condition of Formula (3) was satisfied, it can be considered that the ship can meet the requirements of 1st check, and the specific calculation procedure refers to Ref. [9].

2.2 2nd check algorithm

2nd check uses a 1-DOF roll motion equation based on nonlinear mechanics method, which is used for the prediction of amplitude of parametric roll, and sensitivity analysis was carried out on the basis of this method. The equation of motion is

$$\ddot{\varphi} + 2\alpha\dot{\varphi} + \gamma\dot{\varphi}^3 + \omega_\varphi^2 \frac{GZ}{GM} = 0 \tag{4}$$

where:

$$GZ = GM\left(\varphi + \sum_{k=1}^{n} l_{2k+1}\varphi^{2k+1}\right) + \left(GM_{\mathrm{mean}} + GM_{\mathrm{amp}}\cos\omega_{\mathrm{e}}t\right)\left[1 - \left(\frac{\varphi}{\pi}\right)^2\right]\varphi \tag{5}$$

where φ is the rolling angle of the ship; GM_{mean} is the mean value of metacentric height in waves; GM_{amp} is the amplitude value of metacentric height variation in waves; ω_φ is a natural circular rolling frequency; ω_{e} is the encountering frequency; l_{2k+1} is the fitting coefficient obtained by GZ curve fitting in static water using the least squares, where k is the fitting order; α and γ are linear and third-order roll damping coefficient, which can be calculated by the simplified Ikeda method [14] in the case of lacking results of roll decay test.

For different Froude numbers Fr, in head sea condition, the probability that the rolling angle of the ship exceeds 25° was calculated, and the average value of the probability was taken so that the sensitivity index C_2 was obtained. If

$$C_2 < R_{\mathrm{PR1}}\ ,\ R_{\mathrm{PR1}} = 0.06 \tag{6}$$

It is concluded that the loading condition of ship check was not sensitive to parametric roll.

The formula for C_2 is

$$C_2 = \frac{1}{2N+1}\left[\sum_{i=1}^{N} C_{2\mathrm{h}}(Fr_i) + C_{2\mathrm{h}}(0) + \sum_{i=1}^{N} C_{2\mathrm{f}}(Fr_i)\right] \tag{7}$$

where $C_{2\mathrm{h}}(Fr_i)$ and $C_{2\mathrm{f}}(Fr_i)$ are the components of C_2 navigating by Fr_i in head sea and following seas. Wherein, Fr_i is taken as follows:

$$Fr_i = \frac{V_{\mathrm{s}}}{\sqrt{Lg}}\cos\left[\frac{(i-1)\pi}{2N}\right];\quad i = 1, 2, \cdots, N \tag{8}$$

where L is the ship length; g is gravitational acceleration; V_{s} is service speed; N is wave spacing number, and the latest recommendation by IMO is $N = 3$ [15].

2.3 Check results

After checking and screening the first level vulnerability criterion, the 75 remaining loading conditions, which did not pass the first level criterion, went through the second level criterion, and the calculations of 1st check and 2nd check were carried out respectively.

The check calculation results of 1st check are shown in Fig. 3. The distribution of the results basically showed that, the larger the GM value, the greater the calculation value C_1.

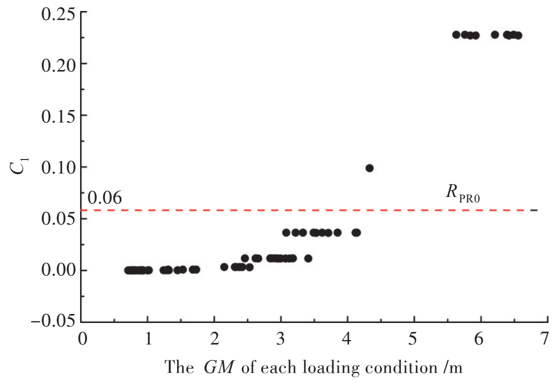


Fig.3 The second level criterion 1st check results of parametric roll

The check calculation results of 2nd check are shown in Fig. 4. The results showed that the sensitivity index C_2 of 75 loading conditions was less than $R_{\mathrm{PR1}} = 0.06$.

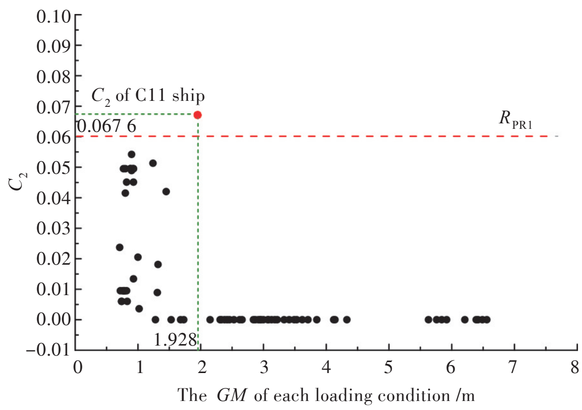


Fig.4 The second level criterion 2nd check results of parametric roll

For the 10 loading conditions whose metacentric height was greater than 4.33 m, the calculation in Fig. 3 shows that, although they did not pass the 1st check criterion, their sensitivity index C_2 was 0 in the check calculation of 2nd check. Thus they are considered not sensitive to the parametric roll.

Besides, due to a severe parametric roll accident in the commercial operations of the APL CHINA (C11 container ship) in the Pacific [5], C11 ship became the only standard sample ship for developing the criterion failure mode of parametric roll by IMO. In this paper, we selected the results C_2 (C_2 = 0.067 6) of C11 ship under design draft loading condition (draft d = 11.5 m, GM = 1.928 m) to compare with the check results of this ship (Fig. 4), and found that values of C_2 of this ship under various loading conditions was less than the corresponding results of C11 ship.

For the GZ curve fitting in still water (Formula (5)), the fitting range was the part from upright floating to heeling angle of 30°. GZ curve was calculated at a spacing of 2°, and the fitting error should be less than the larger value of 5% and 0.005 m [15]. However, calculation showed that the GZ curve under the loading condition of 14TAS (14T/TEU Arrival at Scantling Draft) in still water had fitting errors of 5.98%, 5.51% and 5.43% in 6°, 8°, 10° respectively, which did not meet the accuracy requirements, so the loading condition did not pass the second level criterion of parametric roll and needed direct calculation. Meanwhile, because the loading condition was close to full load, GM = 1.24 m, C_2 = 0.051 3 which was closer to the criterion value of 0.06 and was slightly dangerous, it is necessary to carry out direct calculation criterion.

3 The related theory of direct calculation of parametric roll

At present, IMO has not formulated the rules for direct calculation criterion of parametric roll, but only provided preliminary requirements guidelines for direct calculation criterion of motion [16].

In this section, a 3-DOF weakly nonlinear motion prediction model in time domain based on potential flow theory was adopted as the check method for direct calculation criterion. The method uses the impulse response function theory based on potential flow method in 3D frequency domain, and uses the 3D pressure integral method to consider the nonlinear effect of the Froude-Krylov force and restoring force caused by the instantaneous wetted surface area of hull. The equation of motion [17] is as follows:

$$\begin{aligned}&\left(\boldsymbol{M}+\boldsymbol{\mu}_{33}\right)\ddot{\eta}_3+\int_0^t \boldsymbol{K}_{33}(t-\tau)\dot{\eta}_3\mathrm{d}\tau+\boldsymbol{\mu}_{35}\ddot{\eta}_5+\boldsymbol{b}_{35}\dot{\eta}_5+\\&\int_0^t \boldsymbol{K}_{35}(t-\tau)\dot{\eta}_5\mathrm{d}\tau=\boldsymbol{F}_3^{\mathrm{IS}}+\boldsymbol{F}_3^{\mathrm{D}}-\boldsymbol{M}g\\&\left(\boldsymbol{I}_{xx}+\boldsymbol{\mu}_{44}\right)\ddot{\eta}_4+\int_0^t \boldsymbol{K}_{44}(t-\tau)\dot{\eta}_4\mathrm{d}\tau-\boldsymbol{F}_4^{v}=\boldsymbol{F}_4^{\mathrm{IS}}+\boldsymbol{F}_4^{\mathrm{D}}\\&\left(\boldsymbol{I}_{yy}+\boldsymbol{\mu}_{55}\right)\ddot{\eta}_5+\int_0^t \boldsymbol{K}_{55}(t-\tau)\dot{\eta}_5\mathrm{d}\tau+c_{55}\eta_5+\boldsymbol{\mu}_{53}\ddot{\eta}_3+\\&\boldsymbol{b}_{53}\dot{\eta}_3+\int_0^t \boldsymbol{K}_{53}(t-\tau)\dot{\eta}_3\mathrm{d}\tau=\boldsymbol{F}_5^{\mathrm{IS}}+\boldsymbol{F}_5^{\mathrm{D}}\end{aligned} \tag{9}$$

where $\boldsymbol{M}$ and $\boldsymbol{I}_{xx}, \boldsymbol{I}_{yy}$ are ship mass and moment of inertia, respectively; η_3, η_4, η_5 are the ship's vertical displacement, rolling angle and pitch angle, respectively; c_{55} is restoring force coefficient of pitch; g is the acceleration of gravity; t is time; τ is the time integrated parameter; $\boldsymbol{\mu}_{jk}$(j, k = 1, 2, 3, representing the vertical, horizontal and vertical directions, respectively) is additional mass and additional moment of inertia, which was obtained by solving the 3D boundary problem under the average wet surface; $\boldsymbol{F}_4^{v}$ is viscous damping torque of rolling, which is calculated using Ikeda method [14]; $\boldsymbol{F}^{\mathrm{IS}}$ is the resultant force of Froude-Krylov force and the restoring force, which is calculated based on 3D pressure integral method, and the nonlinear effect caused by the instantaneous wetted surface area of the hull was considered; calculation of radiometric force (integral term) and diffraction force $\boldsymbol{F}^{\mathrm{D}}$ was based on 3D frequency-domain linear hydrodynamic method. The calculation of $\boldsymbol{K}_{jk}$ in the radiometric force was based on the theory of impulse response function, so as to take into account the time delay effect.

$$\boldsymbol{K}_{jk}(\tau)=\frac{2}{\pi}\int_0^{\infty}\left[\boldsymbol{B}_{jk}(\omega_{\mathrm{e}})-\boldsymbol{b}_{jk}\right]\cos\omega_{\mathrm{e}}\tau\mathrm{d}\omega_{\mathrm{e}} \tag{10}$$

where $\boldsymbol{B}_{jk}(\omega_{\mathrm{e}})$ is the theoretically calculated wave-making damping in frequency domain; $\boldsymbol{b}_{jk}$ is the damping term caused by the impulse response function theory for the radiometric force.

4 Calculated loading condition and working condition

4.1 Calculated loading

By the end of section 2, it has been mentioned that, because the fitting precision of GZ curve of 14TAS loading condition did not meet the requirement of the second level criterion, and the calculated value of sensitivity index C_2 was close to the criterion value, it was slightly dangerous. Therefore, the direct calculation of the third level was needed. The associated floating information for this loading condition is shown in Table 2.

Table 2 Floating information about loading condition 14TAS

Parameters	Values
Draft/m	14.824
Trim/m	−1.190
GM/m	1.24
Transverse metacentric height/m	23.97
Height of C.G./m	22.71
Longitudinal position of C.G./m	150.91

4.2 Calculating parameter and working condition setting

Among the calculating parameters, Fr was set as 0.05, 0.1 and 0.218 (the corresponding V_s =23.75 kn) in ascending order. For incident regular waves, three forms were taken into account when the wavelength was selected:

1) The wavelength was equal to the ship length ($\lambda = L_{pp}$), and wave steepness was selected by reference to the first and second level criteria of parametric roll [7], corresponding to conditions 1–2 at each speed.

2) The wavelength was obtained according to the conversion of the sufficient condition of parametric roll occurrence (the natural rolling period of the ship was approximately two times the wave encountering period $T_\varphi \approx 2T_i$) and wave dispersion relation ($\omega^2_{\mathrm{wave}} = gk^2_{\mathrm{wave}}$, where ω_{wave} is wave frequency, and k_{wave} is wavenumber). Wave steepness was selected by reference to the first and second level criteria of parametric roll [7], corresponding to conditions 3–6 at each speed.

3) Regular wave (λ =287.931 m, H=4.031 m) with the maximum weight proportion (the probability of occurrence of different wave conditions shown according to the North Atlantic wave statistics) in equivalent incident wave table of Grim [13] corresponds to condition 7 at each speed.

5 Direct calculation results and discussion

5.1 Integration program verification of instantaneous wet surface

In this study, the numerical simulation program of parametric roll uses the instantaneous wet surface pressure integral method based on the NURBS surface to calculate the nonlinear restoring force and the Froude–Krylov force.

The variation of ship's waterplane area in waves is an important cause of parametric roll, which is mainly due to the change of GM . Therefore, in this paper, the GM value of the 10 000 TEU container ship at different relative positions of hull and waves was calculated using the program under the loading condition of 14TAS, which was compared with the calculation result of general software NAPA, as shown in Fig. 5. It is shown in the figure that the results of the two are of little difference, and the accuracy and effectiveness of the instantaneous wet surface pressure integration program based on NURBS surface was further verified.

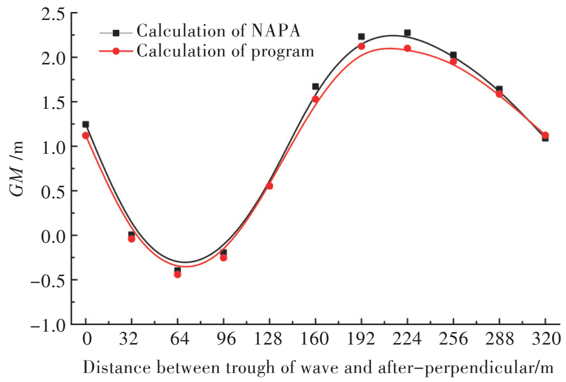


Fig.5 Variation of GM with hull and waves' relative position

5.2 Check results and analysis

Numerical simulation and analysis were carried out by the combination of the above wave conditions and the speed setting under typical conditions. The 3-DOF (heaving, rolling and pitching) time history curve was output. The rolling angle of initial disturbance was given as 0.2°, and the simulation time length was 1 200 s. Table 3 shows the calculation results of parametric roll under different conditions, in which the "capsizing" of several examples was defined as a rolling angle of more than 90° at some moment.

For the conditions of I–1, I–2, II–1, II–2, III–1 and III–2 with the wavelength equal to the ship length ($\lambda = L_{pp} = 320$ m), the value of wave steepness was reasonable. Only in two conditions (I–1, I–2) at low speed of Fr = 0.05, slight parametric roll appeared. The 3-DOF time-domain simulation curve under the condition I–2 is shown in Fig. 6. It can be seen that at 400 s, rolling begins to appear and gradually increases. After 600 s, the parametric roll, heaving and pitching oscillate stably in a small range when they tend to the steady amplitude (2.98°).

When the natural period of rolling was approximately equal to two times the encountering period of

Table 3 Parametric roll results of different conditions in regular waves

Fr	Condition	Wave length λ/m	Wave steepness S_W	Wave height *H*/m	T_φ/T_i	Rolling amplitude/(°)
0.05	Ⅰ-1	320	0.016 7	5.344	2.15	2.40
	Ⅰ-2		0.02	6.4		2.98
	Ⅰ-3	365.747	0.006 6	2.4	2	5.88
	Ⅰ-4		0.01	3.66		9.72
	Ⅰ-5		0.016 7	6.1		21.36
	Ⅰ-6		0.02	7.31		Capsizing
	Ⅰ-7	287.931	0.014	4.03	2.28	0
0.1	Ⅱ-1	320	0.016 7	5.344	2.21	0
	Ⅱ-2		0.02	6.4		0.36
	Ⅱ-3	432.92	0.01	4.33	2	1.91
	Ⅱ-4		0.016 7	7.23		14.32
	Ⅱ-5		0.018	7.79		26.53
	Ⅱ-6		0.02	8.66		Capsizing
	Ⅱ-7	287.931	0.014	4.03	2.55	0
0.218	Ⅲ-1	320	0.016 7	5.344	2.96	0
	Ⅲ-2		0.02	6.4		0.13
	Ⅲ-3	579.43	0.006 9	4	2	0.20
	Ⅲ-4		0.011	6.37		2.52
	Ⅲ-5		0.016 7	9.68		Capsizing
	Ⅲ-6		0.02	11.59		Capsizing
	Ⅲ-7	287.931	0.014	4.03	3.18	0

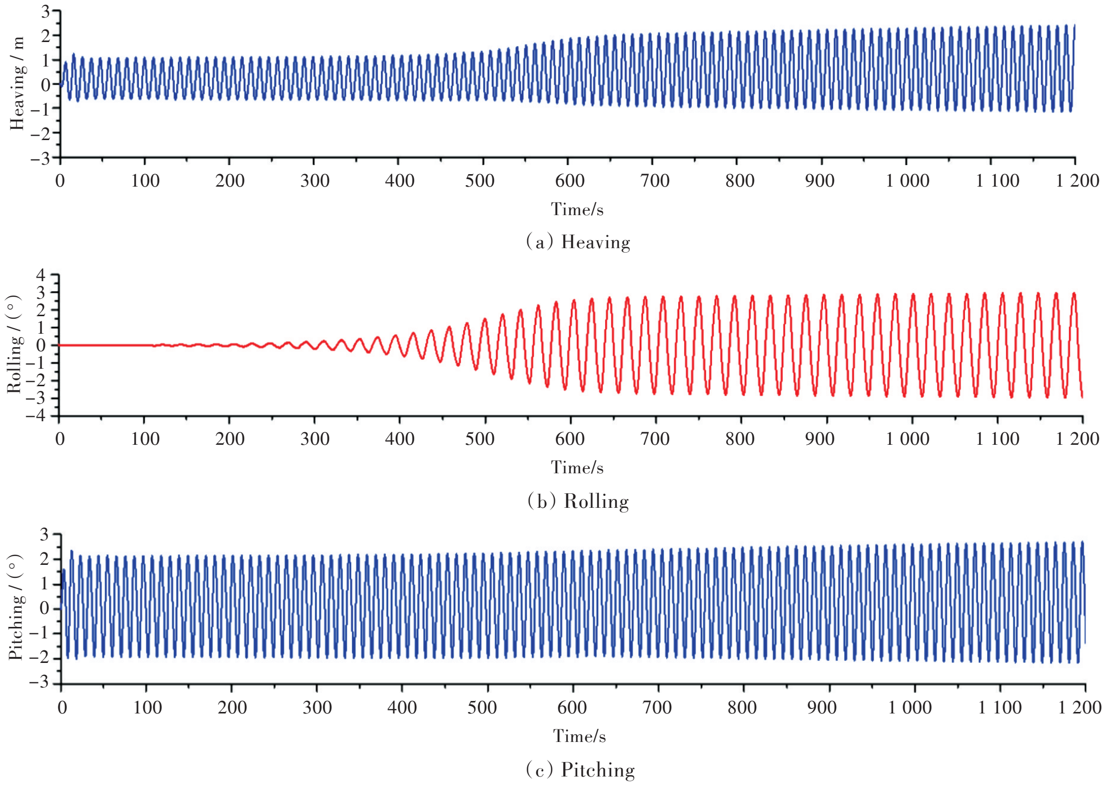
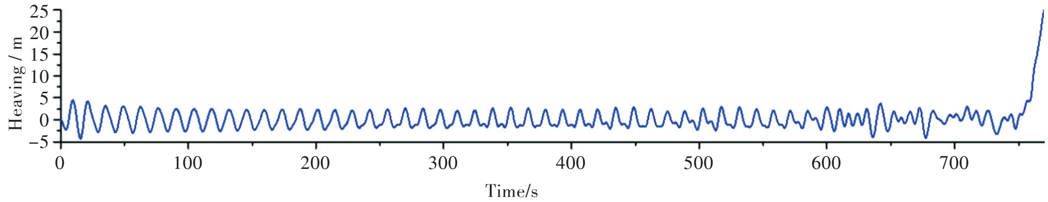
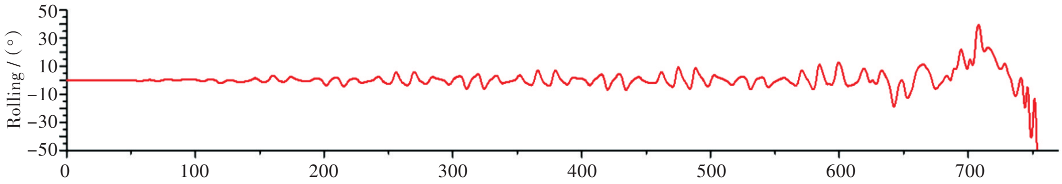


Fig.6 Time history curves of heaving, rolling and pitching at condition Ⅰ-2

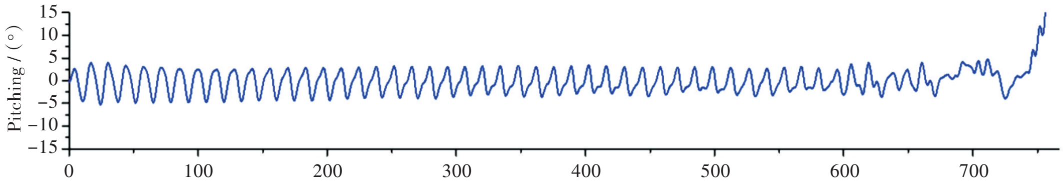
waves, parametric roll was more prone to happen, and the amplitude of rolling was much larger than the wave condition of $\lambda = L_{pp}$ at similar wave height. Fig. 7 shows the 3-DOF time-domain simulation curve under the condition of II-6. It can be seen that in the early and middle stages of time-domain simulation, heaving and pitching were more violent, and rolling was weak, under the combined excitation of frequency doubling relation and larger wave height, after 600 s, heaving and pitching began to show strong nonlinear effects, and rolling also increased, until capsizing appeared after 800 s. For these two conditions (I-2 and II-6), the time of occurrence of significant parametric roll was later.



(a) Heaving



(b) Rolling



(c) Pitching

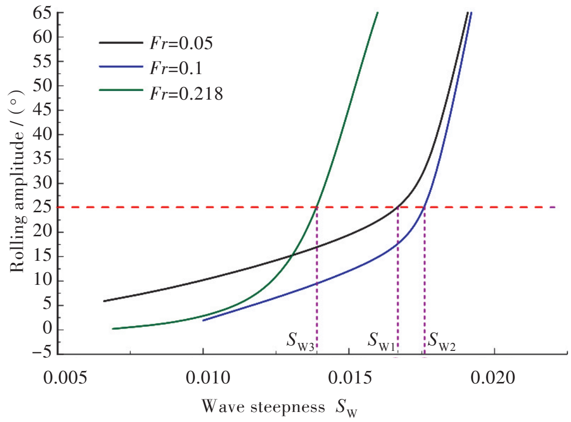
Fig.7 Time history curves of heaving, rolling and pitching at condition Ⅱ-6

5.3 Analysis of the characteristics of dangerous conditions in the direct calculation criterion

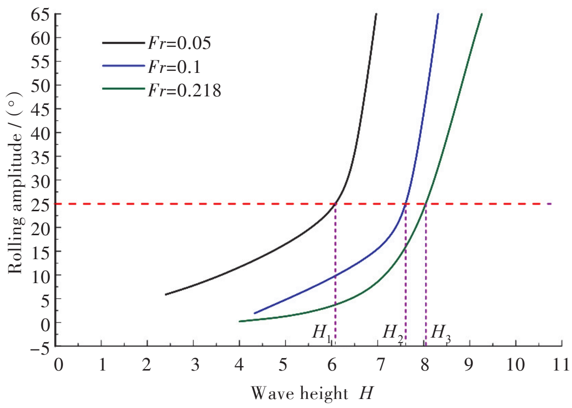
It is not difficult to find that according to the calculation results in Table 3, when the ship navigates in regular waves of head sea, and the wavelength of regular wave meets $\lambda = L_{pp}$, 10 000 TEU container ship was not sensitive to parametric roll at three speeds in ascending order; and when the wavelength of regular wave meets that the natural period of rolling was approximately two times the encountering period of waves, the occurrence of parametric roll was the most obvious. In fact, this is also one of the conditions for parametric roll.

Fig. 8 shows the variation of the rolling amplitude at the occurrence of parametric roll with the wave steepness and wave height at different speeds when the incident wave satisfies the frequency doubling relation. For the direct calculation of parametric roll, generally, in the time-domain simulation of a longer period of time, the ship rolling angle exceeding 25° means that parametric roll occurs [17], so Fig. 8 gives the critical wave steepness and critical wave height for the occurrence of parametric roll at different speeds.

From the figure it can be found that, when the critical wave steepness was used as the standard to ana-



(a) Critical wave steepness of regular wave



(b) Critical wave height of regular wave

Fig.8 Variation of amplitude of rolling with wave steepness and wave height at different speeds($T_\varphi \approx 2T_i$)

lyze the sensitivity of parametric roll at different operational conditions, distribution of critical wave steepness values at different speeds lacks of rules; and when the critical wave height was used as the standard for analysis, the distribution of critical wave height and speed has good correlation. Therefore, the wave height conditions should be used as selection criteria of the dangerous working conditions for very large container ship when calculating parametric roll criteria. When the ship is in a low speed (Fr = 0.05), critical wave height for the occurrence of parametric roll was relatively small (H = 6.2 m), which belongs to the relatively dangerous conditions, and compared with other speeds, the corresponding incident wavelength was the closest to the regular wave of the largest weight proportion in the equivalent incident wave table of Grim [13], which means closer to the real sea conditions.

5.4 Evaluation of navigation safety in real sea

Based on the 3-DOF weakly nonlinear motion prediction model in time domain, for 10 000 TEU container ships, low speed is more sensitive to parametric roll. In the actual navigation process, in the case of continuous regular surge with long wavelength and high amplitude, it is necessary to increase the speed and avoid the frequency doubling range, so as to keep navigating in longitudinal waves with small transverse interference and avoid large-amplitude rolling.

In fact, the risk assessment of parametric roll of 14TAS loading condition is relatively conservative. First of all, the calculated sensitive conditions almost satisfy the frequency doubling condition; secondly, only when the speed is lower and the wave height is higher than the critical wave height can parametric roll occur. If such bad sea conditions appear in the actual navigation, the driver needs to change the heading to head sea. When necessary, corresponding measures such as deceleration to stop the ship and firmly seizing the containers need to be taken to avoid instability or capsizing.

The phenomenon of large-amplitude parametric roll in dangerous conditions almost occurs in the late stage of time-domain simulation, and the phenomenon of rolling increase has gradually appeared in the early and middle stages. At this point, in view of the parametric roll, the driver needs to take corresponding measures to avoid the further increase of rolling according to the navigation manual and operation instructions. And parametric roll can be avoided effectively by reducing the height of the center of gravity, increasing the speed of the ship properly, and avoiding the satisfaction of the wave frequency doubling as much as possible.

6 Conclusion

In view of the higher requirements of very large container ship for parametric roll safety assessment, the significance of check is prominent. A 10 000 TEU container ship was taken as the research object in this paper. The comprehensive check calculation of parametric roll vulnerability of the second generation IMO intact stability was carried out under various loading conditions, and the following conclusions are drawn:

1) According to the results of the first level criterion, reducing the height of the ship's center of gravity can significantly reduce the variation amplitude of metacentric height in waves, improving the parametric roll obviously.

2) According to the result of the second level criterion, the larger the GM of the loading condition, the greater the sensitivity index C_1; for the loading condition with a larger sensitivity index C_2, distribution of GM value was beyond about 1 m.

3) With the increase of wave steepness, the amplitude of parametric roll became larger due to the great change of restoring force in waves. For the dangerous wave condition satisfying frequency doubling relation, it is necessary to select the critical wave height at different speeds for a particular ship as the calculation value of the check.

4) Speed has a great influence on parametric roll. According to the direct calculation results, the speed increase can restrain the parametric roll to a certain extent.

5) The equivalent incident wave table of Grim [13] is based on the statistical data of the North Atlantic waves. In head sea condition, for the regular waves with the largest weight proportion, 10 000 TEU container ship was insensitive to parametric roll at the three speeds.

References

[1] International Maritime Organization (IMO). Development of second generation intact stability criteria[C]// Sub-committee on stability and load lines and on fishing vessels safety (SLF) 55th session. London: International Maritime Organization, 2013.

[2] LIANG H B, MA K. Research of navigation safety

based on parametric roll[J]. Shipbuilding of China, 2015,56(Supp 1):185-192 (in Chinese).

[3] DALLINGA R P, BLOCK J J, LUTH H R. Excessive rolling of cruise ships in head and following waves[C]// RINA International Conference on Ship Motions & Maneuverability. London, UK:[s.n.], 1998.

[4] CHU J L, WU C S, LU J, et al. Study on a 3D time-domain method to predict parametric rolling of a ship in regular head seas[J]. Journal of Ship Mechanics, 2016(12): 1513-1522.

[5] FRANCE W N, LEVADOU M, TREAKLE T W, et al. An investigation of head-sea parametric rolling and its influence on container lashing systems [J]. Marine Technology, 2003, 40(1):1-19.

[6] LEVADOU M, VEER R V. Parametric roll and ship design: contemporary ideas on ship stability and capsizing in waves [M]. Netherlands: Springer, 2011: 307-330.

[7] International Maritime Organization (IMO). SDC 1/INF.8. Information collected by the correspondence group on intact stability regarding the second generation intact stability criteria development[C]//Ship Design and Construction (SDC) 1st Session. London: International Maritime Organization, 2013.

[8] FU C, MA S, DUAN W Y, et al. Research on the analysis and improvement measures of the parametric roll sensitivity factor of C11 container ship [C]//Collected papers of the National Academic Symposium on Ship Stability 2014. Wuxi: Chinese shipbuilding engineering society, 2015 (in Chinese).

[9] UMEDA N, HASHIMOTO H, VASSALOS D, et al. Nonlinear dynamics on parametric roll resonance with realistic numerical modelling[J]. International Shipbuilding Progress, 2004, 51(2/3):205-220.

[10] BULIAN G. Nonlinear parametric rolling in regular waves—a general procedure for the analytical approximation of the *GZ* curve and its use in time domain simulations[J]. Ocean Engineering, 2005, 32(3/4): 309-330.

[11] SPANOS D, PAPANIKOLAOU A. Numerical simulation of parametric roll in head seas[J]. International Shipbuilding Progress, 2007, 54(4):249-267.

[12] SADAT-HOSSEINI H, STERN F, OLIVIERI A, et al. Head-wave parametric rolling of a surface combatant [J]. Ocean Engineering, 2010, 37(10):859-878.

[13] GRIM O. Beitragzudem problem der sicherheit des schiffesimseegang [J]. Shiff und Hafen, 1961, 6: 490-497 (in German).

[14] KAWAHARA Y, MAEKAWA K, IKEDA Y. A simple prediction formula of roll damping of conventional cargo ships on the basis of Ikeda's method and its limitation[C]//Proceedings of the 10th International Conference on Stability of Ships and Ocean Vehicles. Netherlands: Springer, 2009:387-398.

[15] International Maritime Organization (IMO). Finalization of second generation intact stability criteria, amendments to Part B of the 2008 IS code on towing, lifting and anchor handling operations[C]//Ship Design and Construction (SDC) 3rd session. London: International Maritime Organization, 2016.

[16] International Maritime Organization (IMO). Information collected by the correspondence group on intact stability regarding the second generation intact stability criteria development [C]//Ship Design and Construction (SDC) 1st session. London: Internation Maritime Organization, 2014.

[17] ZHOU Y H, MA N, GU X C. Effect of calculation methods of roll moment of inertia on sensitivity prediction of parametric rolling for container ships[J]. Shipbuilding of China, 2013, 54(3):11-20 (in Chinese).

超大型集装箱船参数横摇全面校核与安全评估

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摘　要:[**目的**] 由于超大型集装箱船在波浪中稳性高的变化较为显著,对其参数横摇校核与安全评估要求较高,因此,[**方法**] 基于参数横摇模式,针对在迎浪中航行的某10 000 TEU集装箱船,对其各个装载状况逐一并逐级进行计算。自主开发基于典型弱非线性三自由度模型的数值预报方法,对不满足第2层衡准要求的载况进行时域模拟,并综合考虑航速、波况的影响,全面探索其可能发生参数横摇的工况。[**结果**] 根据衡准结果,得出相应的安全性评估与规避措施:降低重心高度、适当提高航速、尽量避免船舶横摇固有周期约等于2倍遭遇周期等均能有效避免参数横摇的发生。[**结论**] 对10 000 TEU集装箱船进行的参数横摇全面校核评估能够更好地指导超大型集装箱船的总体设计,提高安全水平,具有较高的工程应用及参考价值。

关键词:超大型集装箱船; 参数横摇; 直接计算; 安全性评估