Introduction of “Guidelines on Preventive Measures against Parametric Rolling”

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1. INTRODUCTION

In response to a series of stack collapse accidents that are thought to have been caused by parametric rolling in large container carriers and other vessels [1)-4)], parametric rolling has attracted considerable attention in recent years, and preventive measures have also become an urgent issue.

In 2020, the International Maritime Organization (IMO) released Interim Guidelines on the Second Generation Intact Stability Criteria – MSC.1/Circ.1627 (hereinafter, SGISc), which specify assessment criteria for dynamic stability failure modes including parametric rolling. In addition, SGISc has made recommendations on a method for simulating parametric rolling and appropriate operational guidance for avoiding parametric rolling. [5)] At the same time, related industries are also implementing a variety of practical measures for avoiding parametric rolling by utilizing wave radar or weather services, reducing excessive roll by installing anti-roll tanks, and others.

Based on this background, ClassNK (hereinafter, the Society) issued “Guidelines on Preventive Measures against Parametric Rolling” (hereinafter, Guidelines; see Fig. 1) in February 2023 to encourage wide adoption of avoidance and preventive measures against parametric rolling [6)].

2. OVERVIEW OF GUIDELINES

The Society affixes the class notation to the classification characters of ships with effective measures against parametric rolling. The intentions of this Guidelines are to identify ships that take parametric rolling measures, improve the added value of ships and encourage adoption of parametric rolling measures. The Guidelines specifies the types of parametric rolling measures which the Society deems effective, and the class notation affixed to the ship’s classification characters (Table 1), together with the necessary documentation, surveys and functional requirements to be applied.

Although the mechanism of parametric rolling has been known from an early date and research has also progressed rapidly in recent years, in the future, it will be important to encourage an adequate recognition of parametric rolling and wide adoption of effective measures against this phenomenon. Therefore, the Appendices of the Guidelines describe useful content for the captain, the crew and other related parties, such as the mechanism of parametric rolling and basic precautions for avoidance.

The Appendices also present an outline of the procedure for calculating the response of parametric rolling and methods for preparing polar charts showing the dangerous area where parametric rolling may occur. When it comes to preparing polar charts, the Appendices also explain the detailed procedure, which is based on the theory proposed by Umeda *et al*. [7) 8)]. This method is an extension of Grim’s effective wave theory [9) 10)], which has been adopted in the Level 2-C2 criterion of SGISc, and enables us to estimate the roll response in short-crested irregular waves. Use of this method makes it possible to prepare polar charts in a relatively short time for all required sea states and loading conditions.

Table 1 Class notations affixed to ship’s classification characters

Types of preventive measures	Abbreviation
(1) Compliance with SGISc (Second Generation Intact Stability Criteria)	PRPM (Design)
(2) Installation of devices and systems for prevention and reduction of parametric rolling, such as anti-roll tanks, etc.	PRPM (Device)
(3) Operational measures to avoid parametric rolling, such as polar charts, etc.	PRPM (Operation)

PRPM: Parametric Roll Preventive Measure

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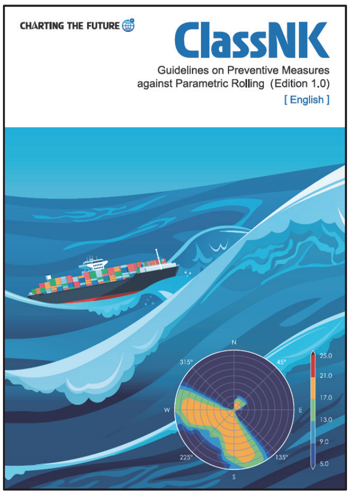

Fig. 1 Guidelines on preventive measures against parametric rolling [6)]

3. PARAMETRIC ROLLING

3.1 Mechanism

Although parametric rolling is a type of resonance phenomenon, the mechanism is different from that of ordinary synchronous rolling. Synchronous rolling is a resonance phenomenon that occurs when the ship's natural roll period coincides with the wave encounter period, and its amplitude is increased due to forced oscillation of waves.

While parametric rolling is also a resonance phenomenon caused by waves, it is not caused by forced oscillation of waves. Rather, resonance occurs due to periodical changes in the righting moment of the ship when navigating in head seas, following seas or quartering seas. Parametric rolling occurs easily in ships with a slender hull form with large flairs around the bow and stern, such as container carriers and pure car carriers.

This section presents a simple explanation of the mechanism by which the roll of a ship is amplified by parametric rolling. As shown in Fig. 2, when a ship navigating in head seas or following seas enters the trough of a wave in the phase where it returns from a heeled condition to the upright position (Fig. 2 (1)), the waterplane area increases and the metacentric height *GM* becomes higher. When this happens, the righting moment also increases, causing the ship to roll at a large angular velocity in comparison with the ordinary rolling. Conversely, if the ship also enters the crest of a wave while rolling from the upright position to the opposite side (Fig. 2 (2)), the waterplane area decreases, reducing the ship's righting moment, causing the ship to roll to the opposite side with a larger angle than in the ordinary rolling. As this cycle is repeated, the amplitude of rolling increases, causing heavy rolling.

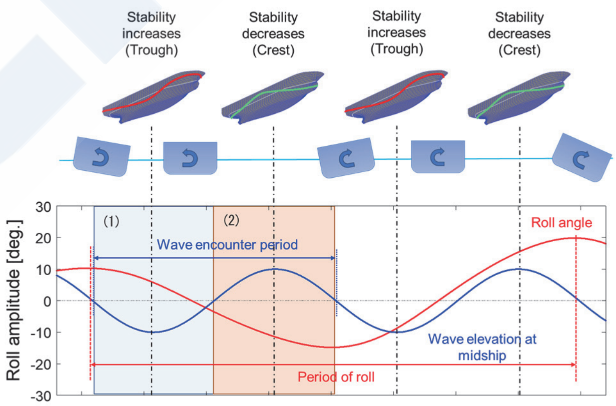

Fig. 2 Development of parametric rolling

As shown in Fig. 2, the ship encounters two crests and two troughs in one roll period. As is well known, one of the conditions causing parametric rolling is that the wave encounter period T_E is approximately half of the ship’s natural roll period T_R ($T_R \fallingdotseq 2T_E$). Theoretically, parametric rolling may occur under conditions that satisfy $T_R : T_E \fallingdotseq 2 : n$ ($n = 1,2,3 \ldots$), but only the condition $n = 1$ should be generally considered.

Another condition is that the amplifying effect due to changes in the righting moment exceeds the reducing effect of damping forces. This can be expressed as shown in Eq. (1). This theory is the basis for the Level 1 criterion of SGISc [10].

$$\frac{GM_{max} - GM_{min}}{2\overline{GM}} > \frac{4\alpha}{\omega_0} \qquad (1)$$

GM_{max}: Maximum (at trough) value of *GM* (m)
GM_{min}: Minimum (at crest) value of *GM* (m)
$\overline{GM}(= (GM_{max} + GM_{min})/2)$: Mean *GM* (m)
α: Linear roll damping coefficient
$\omega_0(= 2\pi/T_R)$: Natural roll circular frequency (rad/s)

From the Eq. (1), it can be said that parametric rolling occurs more easily as *GM* becomes smaller and its variation becomes larger. Generally, the variation of *GM* increases as the wave height becomes larger. At the same wave height, *GM* has the largest variation when the wavelength is equal to the ship length. In other words, when a ship encounters swells with a high wave height and a long wavelength equivalent to the length of the ship, there is an increased risk of parametric rolling.

3.2 Key Points for Avoiding Parametric Rolling

As mentioned previously, parametric rolling is a unique phenomenon that occurs suddenly when navigating in a head sea, following sea or quartering sea in sea states with large swells. If a ship encounters sea states conditions that can cause parametric rolling, heavy roll may occur in a short time. Then it would be almost impossible to take any action. For this reason, advance preparation, bearing in mind the possibility of parametric rolling, is essential. Early action should be taken to avoid dangerous areas with a high possibility of parametric rolling, and appropriate operation, i.e., immediate changes in the ship speed and course, must be made when advance signs of parametric rolling are detected. Therefore, the following describes the precautions and preparations which are considered important for avoiding parametric rolling.

(1) Natural roll period of the ship

Because parametric rolling is a phenomenon in which the periodic change of a ship’s righting moment and the natural roll period are related, it is extremely important to determine the ship’s natural roll period. The natural roll period T_R can be obtained theoretically by the following Eq. (2).

$$T_R = \frac{2\pi K}{\sqrt{gGM}} \qquad (2)$$

where, g is acceleration of gravity and K is the roll radius of gyration considering the effect of added mass. The Guidelines provide the simplified equation shown as Eq. (3), in which *K* is set empirically to $K \fallingdotseq 0.4B$ (B: breadth of the ship).

$$T_R \approx \frac{0.8B}{\sqrt{GM}} \qquad (3)$$

In estimation of the natural roll period from roll monitoring data rather than by the simplified equation, the use of data is effective after considering the applicable range and reliability of the estimation. However, it is important to remember that the roll periods observed during navigation change constantly due to the effects of waves and wind force, and are not necessarily identical with the actual natural roll period. In addition, it is considered necessary to collect measured data for a long period of time in order to estimate the natural roll period from roll monitoring data with high reliability.

The International Code on Intact Stability, 2008 (2008 IS Code) [11], which is cited in materials on ship stability and loading manuals, defines the following Eq. (4). Many onboard stability computers and loading computers output the natural roll period based on Eq. (4). However, because these are based on actual data acquired with relatively small vessels such as passenger ships, cargo ships and fishing boats until 1980s, there have been warnings to the effect that they should not be applied to general merchant ships built in recent years [12]. Thus, the natural roll periods based on the 2008 IS Code should not be used as reference.

$$T_R = \frac{2 \times C \times B}{\sqrt{GM}}$$

$$C = 0.373 + 0.023\left(\frac{B}{d}\right) - 0.043\left(\frac{L_{wl}}{100}\right) \tag{4}$$

where, d is draft and L_{wl} is the length of water line of a ship.

(2) Direction and encounter period of swells

As conditions for parametric rolling, there is generally a high probability of parametric rolling when a ship encounters large swells with a length equal to or longer than the ship length within a range of approximately 60° to the right or left of the bow or stern, and the wave encounter period is also close to half of the ship's natural roll period. When wave radar is installed on the ship and can directly measure the wavelength, direction, period and wave height of swells, those measured values are used, but a rough estimate of the wavelength is also possible by a method using the chart in Fig. 3 [14]. In the example in Fig. 3, when a ship encounters swells with a wave encounter period of 25 s and a quarter direction of 30° from the stern side (quartering sea) while navigating at a speed of 20 knots, the chart shows that the actual wave period is approximately 9 s. The wavelength of the swell can be found in a simple manner by multiplying 1.56 by the square of the wave period, and is estimated at 126m in the example in Fig. 3.

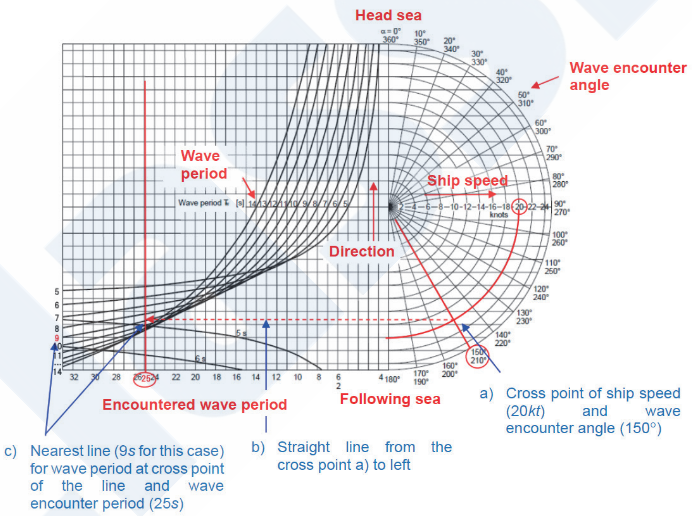

Fig. 3 Determination of the wave period (Source: Notice from Japanese Gov. (MLIT) [14] based on MSC.1/Circ.1228 [13])

(3) Ship's vulnerability to parametric rolling and operational guidance

SGISc (Second Generation Intact Stability Criteria) issued by the IMO specifies three evaluation levels (Level 1 to Level 3) respectively for dynamic stability failure modes, such as the dead ship condition, surf-riding, pure loss of stability and parametric rolling. When it comes to vulnerability to parametric rolling, Level 2-C2, which applies Grim's effective wave theory, is a practical method in terms of both evaluation accuracy and difficulty.

Although SGISs is not a mandatory code (as of July 2023), it is expected to attract attention in the future as part of measures against parametric rolling. Furthermore, when a ship does not comply with the vulnerability criteria, SGISc specifies application of operational guidance such as polar charts. When polar charts are provided for a ship, a good understanding of their content and method of use is important.

4. PREPARATION OF POLAR CHARTS

4.1 Overview of Polar Charts

The above-mentioned polar chart is one of the effective tools for avoiding parametric rolling, and it can visually represent the estimated roll angle or frequency of occurrence of rolling exceeding a certain threshold value for various loading and sea state conditions. For example, the polar chart in Fig. 4 shows the estimated maximum roll angles in a range of wave encounter angles and ship speeds, which are shown in the radius vector direction. Here, “head sea” and “following sea” are defined as 0° and 180°, respectively, and the ship’s heading is fixed at 0°. The dangerous area where parametric rolling can occur is shown in an easily-understood form by a contour display of the estimated maximum roll angles.

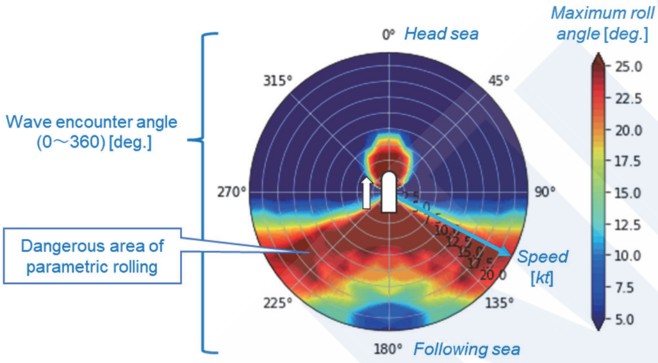

Fig. 4 Example of chart of estimated parametric rolling angles

4.2 Calculation of Parametric Roll Response

The governing equation with one degree of freedom (1-DOF) for obtaining the response values of parametric rolling can be expressed by Eq. (5).

$$\ddot{\phi} + 2\alpha\dot{\phi} + \gamma\dot{\phi}^3 + \omega_0^2 f(\phi, t) = 0 \qquad (5)$$

where, ϕ is the roll angle, α and γ are linear and cubic damping coefficients, respectively, and $f(\phi, t)$ is a nonlinear righting moment term and includes variation components of *GM* and righting arm *GZ*. Basically, the response of parametric rolling is determined by carrying out a numerical simulation based on the following conditions.

- As the wavelength λ, assume a sine wave having a length equal to the length between perpendiculars L_{PP} of the ship.
- Consider the variation of righting moment due to movement of waves.
- Assume a 5° heel condition of the ship as the initial condition.
- Carry out the calculation of the simulation for a sufficient time.
- Adopt the converged value of the roll angle amplitude in the calculation time domain as the response value. If the calculation does not converge, increase the number of calculation steps as necessary.

4.3 Polar Chart Preparation Procedure

Several methods for preparing polar charts are available. However, in the Guidelines, a preparation procedure based on the method proposed by Umeda *et al.* [7) 8)] is described. This method makes it possible to prepare polar charts that consider the response in quartering seas even in calculations using a simulation code with one degree of freedom. Fig. 5 shows a procedure for preparing the polar chart.

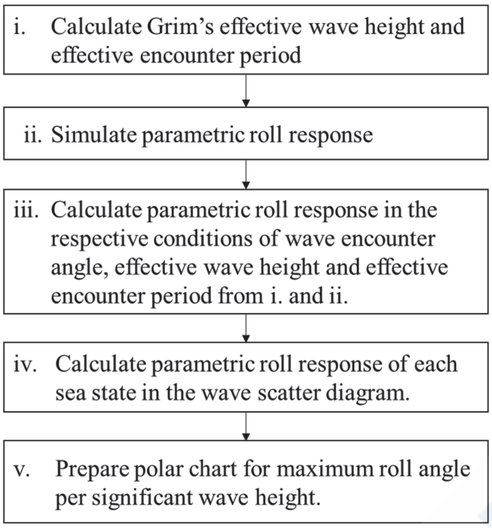

Fig. 5 Polar chart preparation procedure

First, using Eqs. (6) and (7), Grim's effective wave height H_{eff} can be obtained for each sea state, as defined by combinations of the significant wave height H_S and zero-crossing mean wave period T_Z in the wave scatter diagram, and each wave encounter angle. Although IACS Rec. 34 was revised in 2022 [15], the Guidelines refer to the Pierson-Moskowitz (P-M) type wave spectrum (Eq. (8)) and wave scatter diagram in the 2001 edition of IACS Rec. 34 [16], as well as SGISc. IACS Rec. 34 corresponds to sea states in the North Atlantic Ocean, and it is possible to use a different wave spectrum when preparing polar charts for designated sea areas or routes.

$$H_{eff} = 4.0043\sqrt{\int_{-\pi/2}^{\pi/2}\int_{-\infty}^{\infty} S\eta_{eff}(\omega, L_{PP}, \alpha)\, d\omega d\alpha} \quad (6)$$

$$S\eta_{eff}(\omega, L_{PP}, \alpha) = \left[\frac{\frac{\omega^2}{g} L_{PP}\cos\chi \sin\left(\frac{\omega^2}{2g} L_{PP}\cos\chi\right)}{\pi^2 - \left(\frac{\omega^2}{2g} L_{PP}\cos\chi\right)^2}\right]^2 S(\omega, \alpha) \quad (7)$$

$$S(\omega, \alpha) = \frac{H_S^2}{4\pi}\left(\frac{2\pi}{T_Z}\right)^4 \omega^{-5} \exp\left[-\frac{1}{\pi}\left(\frac{2\pi}{T_Z}\right)^4 \omega^{-4}\right] k\cos^2\alpha$$
$$k = 1/\int_{-\pi/2}^{\pi/2} \cos^2\alpha\, d\alpha \quad (8)$$

where, $S\eta_{eff}$ is the spectrum of the effective wave, ω is the circular frequency and χ is the wave encounter angle.

Next, from the effective wave spectrum, the ship speed U and the wave encounter angle, the effective circular encounter frequency $\overline{\omega}_e$ and effective encounter frequency $\overline{T}_e$ can be obtained using Eq. (9). As mentioned previously, in this paper, head seas and following seas are defined as 0° and 180°, respectively, but it should be noted that the definitions of the wave directions and the sign in the equations in the references [7) 8)] are different from those in this paper. Here, although the effective encounter period does not depend on the significant wave height, it is necessary to calculate parametric roll response for each encounter angle, ship speed and zero-crossing mean wave period.

$$\overline{\omega}_e = \sqrt{\frac{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_{-\infty}^{\infty}\left(\omega + \frac{\omega^2}{g} U\cos\chi\right)^2 S\eta_{eff}\, d\omega d\alpha}{\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_{-\infty}^{\infty} S\eta_{eff}\, d\omega d\alpha}} \quad (9)$$

$$\bar{T}_e = \frac{2\pi}{\bar{\omega}_e}$$

If the effective wave height and the effective encounter period can be calculated, the estimated maximum roll angle for each sea state in the wave scatter diagram can be found by combining those results with parametric roll response. In the Guidelines procedure, the estimated roll angle of polar chart shows the maximum roll angle for a certain significant wave height, and not the results for each zero-crossing mean wave period.

4.4 Examples of Polar Charts

Fig. 6 shows examples of polar charts prepared by the procedure in the Guidelines. Here, we used the ship size and principal particulars [17] of the ClassNK’s original 14 000 TEU container carrier (Table 2).

Table 2 Principal particulars of the ClassNK’s original container carrier used in trial calculation [17]

Length (L_{pp})	352.0m
Breadth	50.0m
Draft	15.0m
C_b	0.676
Bilge keel (length)	From S.S.3.95 to S.S.6.0
Bilge keel (width)	0.4m

The natural roll period is a value which was obtained by a simple estimation from $0.77B/\sqrt{GM}$. Fig. 6 shows that when *GM* = 1.5 m ($T_R = 31.4s$), parametric rolling will occur under a following sea even in a sea state with a relatively small significant wave height. Especially in the case of quartering seas, the area where heavy roll occur shows almost no dependence on the ship speed. When *GM* becomes large and the natural roll period is 25 s or less, parametric rolling tends to occur even in a head sea. Furthermore, parametric rolling hardly occurs when *GM* is 4.5 m and the natural roll period is approximately 18 s. In large container carriers with small *GM*s, it is necessary to pay attention to the range from following seas to quartering seas. Thus, by preparing polar charts, the area where parametric rolling occurs at various *GM*s can be found in advance.

Fig. 6 shows examples of polar charts for significant wave heights which were prepared by the procedure in the Guidelines. That is, the figure shows the maximum roll angles at all zero-crossing mean wave periods for various significant wave heights. On the other hand, Fig. 7 shows polar charts for a condition of *GM* = 1.5 m for zero-crossing mean wave periods of 6.5 s, 8.5 s, 10.5 s and 12.5 s. Because the parametric rolling is related to the natural roll period of a ship and the wave encounter period, the area of parametric rolling can be narrowed as shown in Fig. 7 if the zero-crossing mean wave period can be identified. In actual operation, it is also possible to show polar charts reflecting the real sea state on a ship by linking with wave radar or weather routing, which is expected to be used for more practical operation support.

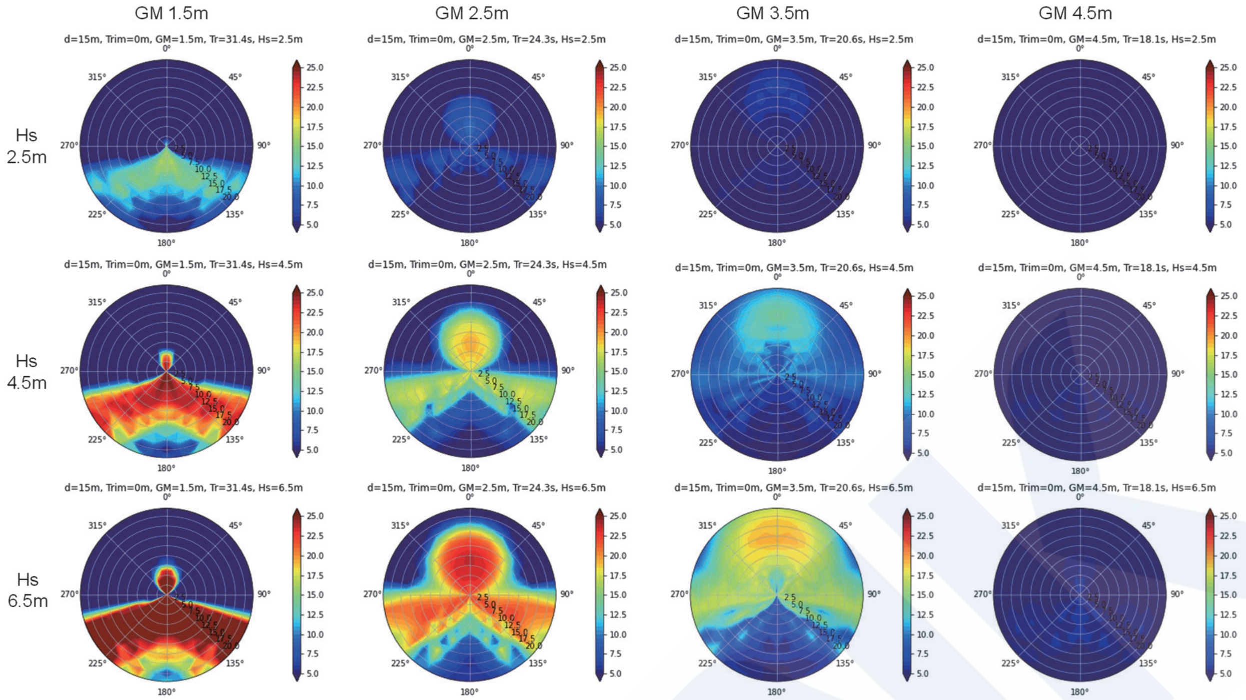

Fig. 6 Examples of polar charts for various *GM*s and significant wave heights
(*GM*: 1.5 m, 2.5 m, 3.5 m, 4.5 m / Significant wave height H_S: 2.5 m, 4.5 m, 6.5 m)

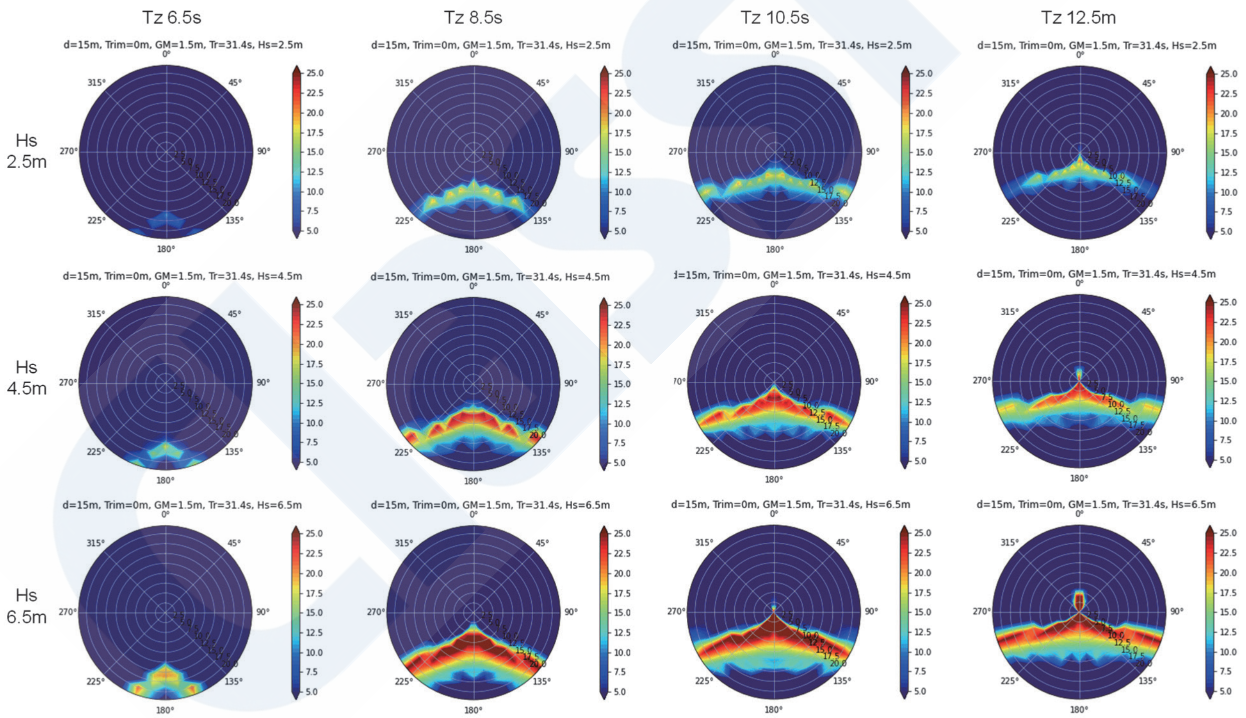

Fig. 7 Examples of polar charts for various significant wave heights and zero-crossing mean wave periods for GM = 1.5 m
(Zero-crossing mean wave period T_Z : 6.5 s, 8.5 s, 10.5s, 12.5 s / Significant wave height H_S : 2.5 m, 4.5 m, 6.5 m)

5. CONCLUSION

In response to a heightened recognition of the need for preventive measures against parametric rolling, the Society issued Guidelines, and has announced the related requirements and the class notations to be affixed to ship classification characters, and also presented a basic commentary on avoidance of parametric rolling. A method that expands the Level 2-2C criterion of SGISc to short-crested irregular waves was adopted, and a practical procedure for preparing polar charts was described. This method enables us to prepare polar charts for various assumed sea states and loading conditions in a relatively short time, without a long-term simulation for irregular wave conditions.

If ships are equipped with wave radar and have access to a weather service, polar charts corresponding to the actual encountered sea states can be displayed on board and it is expected to be utilized for more practical support for ship operation, for example, weather routing considering parametric rolling. Although not described in this paper, anti-roll tanks have also attracted attention as one of the measures against parametric rolling, and installation on ships have also increased in recent years.

The Society will continue to grapple with measures against parametric rolling in the future through various activities such as research and development of various measures, including anti-roll tanks, establishment of the related evaluation criteria, and technical support for preparation of polar charts.

ACKNOWLEDGEMENT

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