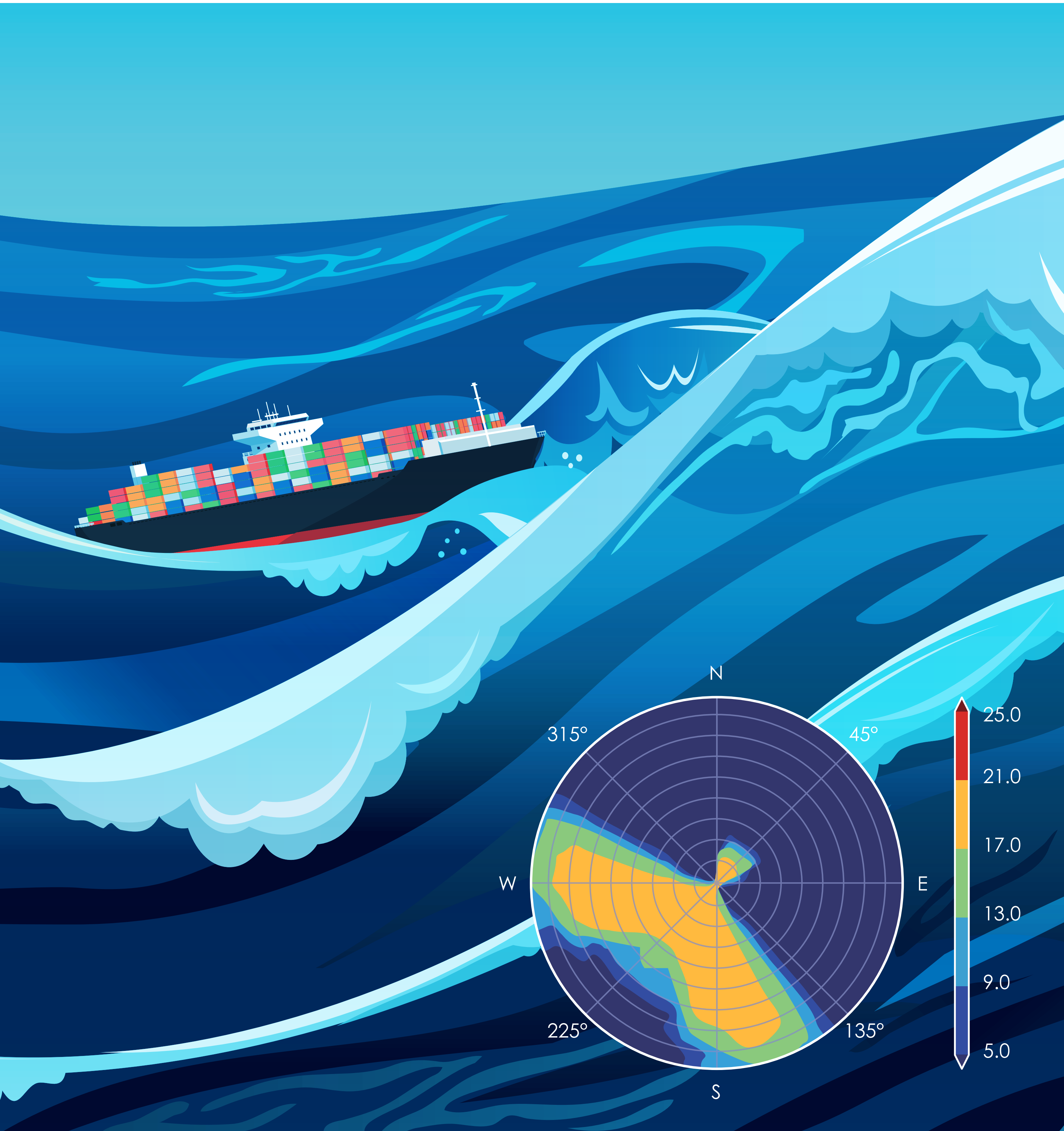
CHARTING THE FUTURE

ClassNK

Guidelines on Preventive Measures against Parametric Rolling (Edition 1.0)

[English]



Introduction

In recent years, cargo collapse accidents that are thought to have been caused by parametric rolling have occurred successively in large containerships and car carriers, including an accident in which more than 2,000 containers were lost or damaged. In response to this situation, various organizations, institutions and groups have issued alerts and proposed numerous measures related to parametric rolling.

The International Maritime Organization (IMO) issued "*Interim Guidelines on the Second Generation Intact Stability Criteria"* – MSC.1/Circ.1627 (hereinafter, SGISc), which specifies criteria for assessing vulnerability to parametric rolling. A variety of measures for avoiding parametric rolling have also been developed and recommended, including preparation of tables and polar charts of predicted parametric roll response, installation of rolling reduction devices, such as anti-roll tanks, and introduction of parametric rolling alert systems.

With this background, Nippon Kaiji Kyokai (ClassNK; hereinafter, "the Society") decided to publish these Guidelines, which summarize the requirements to affix the related notations to classification characters of ships that take effective measures against parametric rolling, together with the related requirements. The Appendices of the Guidelines also provide a fundamental knowledge of the mechanism, features and points to note in connection with parametric rolling, an outline of the parametric roll response calculation, an introduction to devices and techniques for preventive measures against parametric rolling and the method for preparing polar charts.

We hope that these Guidelines will encourage preventive measures against parametric rolling and contribute to reducing accidents due to parametric rolling.

February 2023
Nippon Kaiji Kyokai (ClassNK)

Guidelines on Preventive Measures against Parametric Rolling

CONTENTS

Chapter 1 GENERAL PROVISIONS

1.1 General

1.1.1 Application

These "Guidelines on Preventive Measures against Parametric Rolling" (hereinafter, "Guidelines") apply to ships registered with Nippon Kaiji Kyokai (ClassNK, hereinafter, "the Society") that adopt preventive measures against parametric rolling (hereinafter, "preventive measures") and submit an application for the class notation to classification characters.

1.1.2 Class Notations

-1. The class notation "*Parametric Roll Preventive Measure (XX)*" (abbreviated *PRPM (XX)*) is to be affixed to classification characters of ships that adopt applicable preventive measures in accordance with these Guidelines. An outline of the relevant measure is described in "*XX.*" (E.g., "*Parametric Roll Preventive Measure (Device)*" (abbreviated *PRPM (Device)*) is affixed to classification characters when a ship is equipped with devices for prevention and reduction of parametric rolling as specified in the Guidelines.)

-2. Where a ship adopts a preventive measure which is not specified in the Guidelines, an indication to that effect may be affixed to classification characters upon application for the said notation and approval of its effectiveness by the Society.

1.1.3 Termination of Class Notation

The Society will delete the relevant class notation if the ship does not appropriately maintain the relevant preventive measure in accordance with these Guidelines. However, compliance with the Guidelines is optional, and is not a condition for maintaining class registration.

Chapter 2 SURVEYS

2.1 General

2.1.1 Types of Surveys

The types of surveys are specified in the following (1) to (3).

(1) Initial Survey
(2) Periodical Surveys
(3) Occasional Surveys

2.1.2 Implementation and Timing of Surveys

The timing of the implementation of surveys is as specified in the following (1) to (3).

(1) An Initial Survey is to be conducted when an application for an initial survey is made.
(2) Periodical Surveys are to be carried out at the times of Annual Surveys, Intermediate Surveys and Special Surveys for Classification (e.g., the times given in 1.1.3-1 (1) to (3), Part B of the Rules for the Survey and Construction of Steel Ships).
(3) Occasional Surveys are to be carried out under any of the following conditions at times other than the Initial Survey or Periodical Surveys.
    (a) When preventive measures are changed or replaced.
    (b) When modifications affecting the preventive measure are carried out.
    (c) When an application for a survey is submitted by the Owner.
    (d) At other occasions when considered necessary.

2.1.3 Advance Implementation and Postponement of Periodical Surveys

The requirements for advance implementation or postponement of a Periodical Survey are to be in accordance with the requirements for Periodical Surveys for Classification (e.g., 1.1.4 or 1.1.5, Part B of the Rules for the Survey and Construction of Steel Ships).

2.1.4 Ships Laid-up

Ships laid-up are not subject to the Periodical Survey specified in 2.1.1 (2).

2.1.5 Preparation for Surveys and Other Related Issues

-1. In cases where ships are to be surveyed in accordance with these Guidelines, it is the responsibility of the Owner to notify the Surveyors of the locations where the survey should be conducted. The Surveyors are to be advised of the survey in advance so that the survey can be carried out at the proper time.

-2. Preparations that are required to enable a proper survey, corresponding to the type of survey to be received, are to be made by the survey applicant for the survey items specified in the Guidelines and for other items indicated by the Surveyors when necessary based on the provisions of the Guidelines.

-3. The survey applicant is to understand and accept the survey items when receiving the survey and provide the necessary support to the Surveyors by having the person who supervises the preparations for the survey witness the survey.

-4. Surveys may be suspended when the necessary preparations have not been made, a witnessing person is not present, or the Surveyors judge that the conditions are dangerous.

-5. When repairs are deemed necessary as the result of a survey, the Surveyors notify the survey applicant to that effect. When the survey applicant receives this notification, the applicant is to receive confirmation from the Surveyors after carrying out the necessary repairs.

-6. Surveys and documents that are not applicable to the type of preventive measures or its performance are not required to be performed or submitted.

2.2 Initial Survey

2.2.1 General

During an Initial Survey, the preventive measures are to be examined and investigated to ascertain that they conform to the relevant requirements of the Guidelines.

2.2.2 Submission of Documents

-1. For ships that are to undergo an Initial Survey, the relevant plans and documents specified below are to be submitted to the Society for confirmation that they conform to the relevant provisions of **Chapter 3**.

(1) Documents specifying the outline and specifications of the measure adopted
(2) Drawings related to the equipment itself and system configuration diagrams
(3) Drawings showing the locations of installation
(4) Documents and related calculations showing the parametric rolling prevention effect
(5) Documents (data) and test plans for confirmation of accuracy
(6) Operational guidance
(7) Operation manuals

-2. The Society may require additional documents as deemed necessary.

2.2.3 Survey Items

During the Initial Survey, the following items are to be confirmed:

(1) The relevant equipment, devices and systems are installed properly.
(2) If applicable, the preventive measure is to pass tests based on plans reviewed in advance, including confirmation of accuracy.
(3) The relevant documents, including operational guidance and operation manuals, are to be provided onboard the ship.

2.3 Periodical Surveys

2.3.1 General

During Periodical Surveys, preventive measures are to be examined and investigated to ascertain that they are being maintained in conformity with the relevant provisions of the Guidelines.

2.3.2 Confirmation of Current Condition

Proper maintenance and management of the following systems, equipment and related documents is confirmed.

(1) Equipment, devices and systems related to the preventive measure
(2) Related documents, including operational guidance and operation manuals

2.3.3 Confirmation of Effectiveness

-1. Effective functioning of the preventive measure is confirmed by interviews with the captain and crew and examination of retained data and records, etc.
-2. If deemed necessary by the Surveyor, operation tests of the related devices and systems and accuracy checks may be required.

2.4 Occasional Surveys

In cases where the machinery and equipment related to the preventive measures of a ship are modified or repaired, confirmation is to be received in an Occasional Survey. An Occasional Survey is conducted to confirm that the said modification or repair conforms to the provisions of the Guidelines. On-site surveys may be omitted when deemed appropriate by the Society.

Chapter 3 FUNCTIONAL REQUIREMENTS

3.1 General

3.1.1 Types of Preventive Measures

-1. These Guidelines apply to the following preventive measures. The class notation is affixed to classification characters of ships complying with the related requirements.

(1) Complying with SGISc
"Parametric Roll Preventive Measure (Design)" (abbreviated *PRPM (Design)*)

(2) Installation of devices and systems for prevention and reduction of parametric rolling
"Parametric Roll Preventive Measure (Device)" (abbreviated *PRPM (Device)*)

(3) Operational measures to avoid parametric rolling
"Parametric Roll Preventive Measure (Operation)" (abbreviated *PRPM (Operation)*)

-2. Any measures not mentioned in the above may be surveyed and the relevant class notations may be affixed to the class character of the ship in accordance with the provisions of these Guidelines if deemed appropriate by the Society.

3.1.2 Ensuring Stability

-1. In principle, requirements related to ship stability are not reduced in consideration of the effects of equipment or devices installed or operational methods adopted as preventive measures for parametric rolling.

-2. If the equipment, etc. adopted as preventive measures may affect the stability of the ship, due consideration is to be given to ensure the stability.

3.1.3 Complying with SGISc

-1. In principle, assessments in accordance with SGISc are to be conducted for all possible loading and navigation conditions.

-2. In cases where an evaluation is conducted for conditions limited to a certain range of draft, metacentric height (*GM*), etc., the limitation on the loading and navigation conditions is to be described in the relevant loading manual, stability documents and operational guidance.

-3. When applying the Level 2-*C*2 evaluation criterion, in principle, if the design roll angle of the ship, i.e., the roll angle assumed as a limit condition for evaluation of the strength of stowage and securing arrangements for cargos or other operational conditions, is less than 25°, a threshold roll angle not more than the design roll angle is to be used in place of the standard threshold roll angle (normally 25°) in the evaluation. The threshold roll angle used in the evaluation is to be described in a descriptive note to the relevant class notation. (Example of note: "*with threshold roll angle of 20 degree*")

-4. The following adopted criterion are to be described in a descriptive note to the ship's class notation, e.g. as follows:

(1) Level 1: "*Adopted Criterion for Parametric Roll Preventive Measure: SGISc Level 1*"

(2) Level 2-*C*1: "*Adopted Criterion for Parametric Roll Preventive Measure: SGSIc Level 2-C1*"

(3) Level 2-*C*2: "*Adopted Criterion for Parametric Roll Preventive Measure: SGISc Level 2-C2, with threshold roll angle of XX degree*"

(4) Level 3: "*Adopted Criterion for Parametric Roll Preventive Measure: SGISc Level 3*"

3.1.4 Installation of Devices and Systems for Prevention and Reduction of Parametric Rolling

-1. In cases where devices such as fin stabilizers and anti-roll tanks are installed, documents that can verify their effectiveness in preventing or reducing parametric rolling are to be submitted.

-2. Devices for prevention and reduction of parametric rolling are to comply with the applicable class rule requirements.

-3. The following adopted devices and systems for prevention and reduction of parametric rolling are to be described in a descriptive note to the ship's class notation, e.g. as follows:

(1) Fin stabilizer: "*Adopted Device for Parametric Roll Preventive Measure: Fin-Stabilizer*"

(2) Anti-roll tank: "*Adopted Device for Parametric Roll Preventive Measure: Anti-Roll Tank*"

(3) Rudder roll stabilization control system: "*Adopted Device for Parametric Roll Preventive Measure: Rudder Roll Control System*"

3.1.5 Operational measures to avoid parametric rolling

-1. In cases where operational measures are adopted, documents that can verify their effectiveness in avoiding parametric rolling are to be submitted, for example, materials on the method for predicting the occurrence of parametric rolling and estimating roll angles, etc.

-2. Operational guidance showing instructions to the captain (with associated charts), related manuals and other explanatory materials are to be submitted.

-3. In cases where monitoring systems are adopted, they are to comply with applicable requirements in the related rules, if necessary.

-4. In preparing a chart for avoiding parametric rolling, a method based on Appendix-6 of these Guidelines or a method deemed appropriate by the Society based on parametric roll response calculations is to be used.

-5. The following adopted operational measures are to be described in a descriptive note to the ship's class notation, e.g. as follows:

(1) Operational guidance using charts: "*Adopted Operational Measure for Parametric Roll Preventive Measure: Operational Guidance - Chart*"

(2) Weather services: "*Adopted Operational Measure for Parametric Roll Preventive Measure: Weather Service*"

(3) Monitoring and Alert Systems: "*Adopted Operational Measure for Parametric Roll Preventive Measure: Monitoring and Alert System*"

Appendix-1 Mechanism and Features of Parametric Rolling

This Appendix explains the mechanism of parametric rolling in an easy-to-understand manner and presents an overview of the features of parametric rolling.

-1. Mechanism of parametric rolling

Parametric rolling is a kind of resonant phenomena, but its generating mechanism differs significantly from that of ordinary resonance. Damage caused by vibration is sometimes seen in stiffeners, girders, supports of ladders and pipes, etc. in engine rooms or in cargo tanks and deep tanks located aft, but in many cases, this damage is induced by resonance in which the natural frequency of the damaged structural element is similar to one of higher orders of the frequency of the exciting force induced by the main engine or propellers.

Synchronous rolling is a similar resonant phenomenon in ship roll motion that occurs when the natural roll period of the ship coincides with the encounter period of beam seas. In particular, there is a danger of capsizing if synchronous rolling occurs in a dead ship condition. The basic principle of these resonant phenomena is that the amplitude increases when the natural frequency of the object structure or body is similar to the frequency (or its higher orders) of an external force such as the exciting force of the main engine or propellers or the heeling moment of a beam sea.

Parametric rolling is also caused by effect of waves but is not a roll motion by external wave-induced forces. Rather, it is a resonant phenomenon induced by periodical changes in the stability or righting moment of the ship itself when navigating in head seas or following seas and alternately encountering wave crests and troughs. In engineering terms, this phenomenon is categorized as self-excited oscillation.

In a containership or car carrier with large flares at the bow and stern, which has a fine hull form but a deck width that does not change significantly over the ship length, the waterplane area in a wave trough is larger than that in still water. Conversely, it becomes smaller in a wave crest. (See Fig. A1-1)

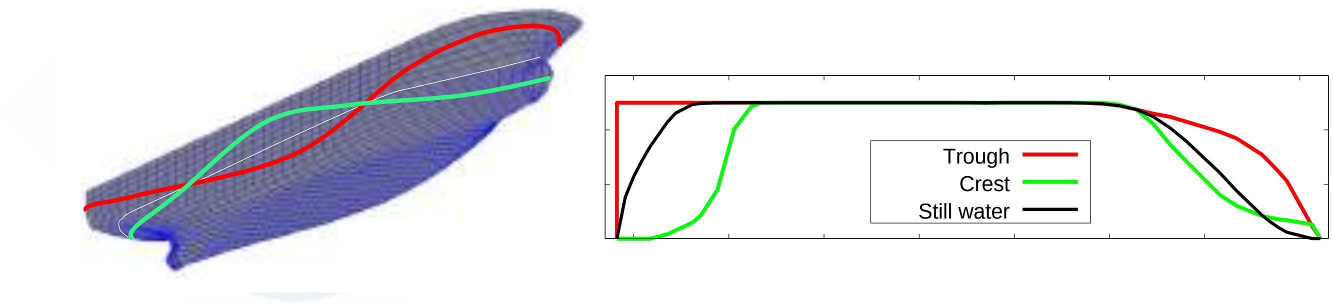


Fig. A1-1 Waterplane area in wave trough and crest

Due to this change in the waterplane area, the metacentric height (*GM*), that is, the stability of the ship, changes as follows:

In wave trough: Waterplane area increases ➡ Stability increases (*GM*)
In wave crest: Waterplane area decreases ➡ Stability decreases (*GM*)

Ships navigating at sea usually encounter irregular waves generated by a combination of wind waves and swells, which are composed of various wave elements having different periods, heights and directions. It is not rare, however, to encounter sea states dominated by regular waves from a single direction, like swells with a long wavelength induced by typhoons or hurricanes.

Here, let us consider a hypothetical situation in which a ship is navigating in a sea state with swells of regular waves from the bow or stern direction. The ship would pitch and heave but would not roll without winds or other external forces from the transverse direction.

Now, suppose that the ship suddenly suffers a lateral gust or wave and heels over to the port or starboard side. If such a gust or wave is temporary and no other transverse force is applied to the ship, it would roll with its natural roll period but the amplitude of that rolling would decrease gradually due to the damping effects of viscous friction and wave making resistance, etc. Here, however, to simplify the discussion, we assume that no damping effect occurs and steady-state rolling with the ship's natural roll period continues.

As mentioned above, a ship's *GM* or stability changes with the movement of the positions of the wave crest and trough while a swell is passing the ship. If the trough of the swell passes near the midship position of the ship in phase (1) in Fig. A1-2, where the ship is returning to the upright position from a heeled condition, this change increases its stability and accelerates the righting motion, which results in a larger angular velocity at the upright position. Whereas, if the crest of the swell passes near the midship position in phase (2) in Fig. A1-2, where the ship is going toward the heeled condition, it decreases the ship's stability and discourages deceleration of the rolling motion, resulting in a larger roll angle on the opposite side compared to the steady-state rolling condition. When this process occurs repeatedly, the ship's roll amplitude becomes larger and larger, finally causing parametric rolling with an excessive roll angle.

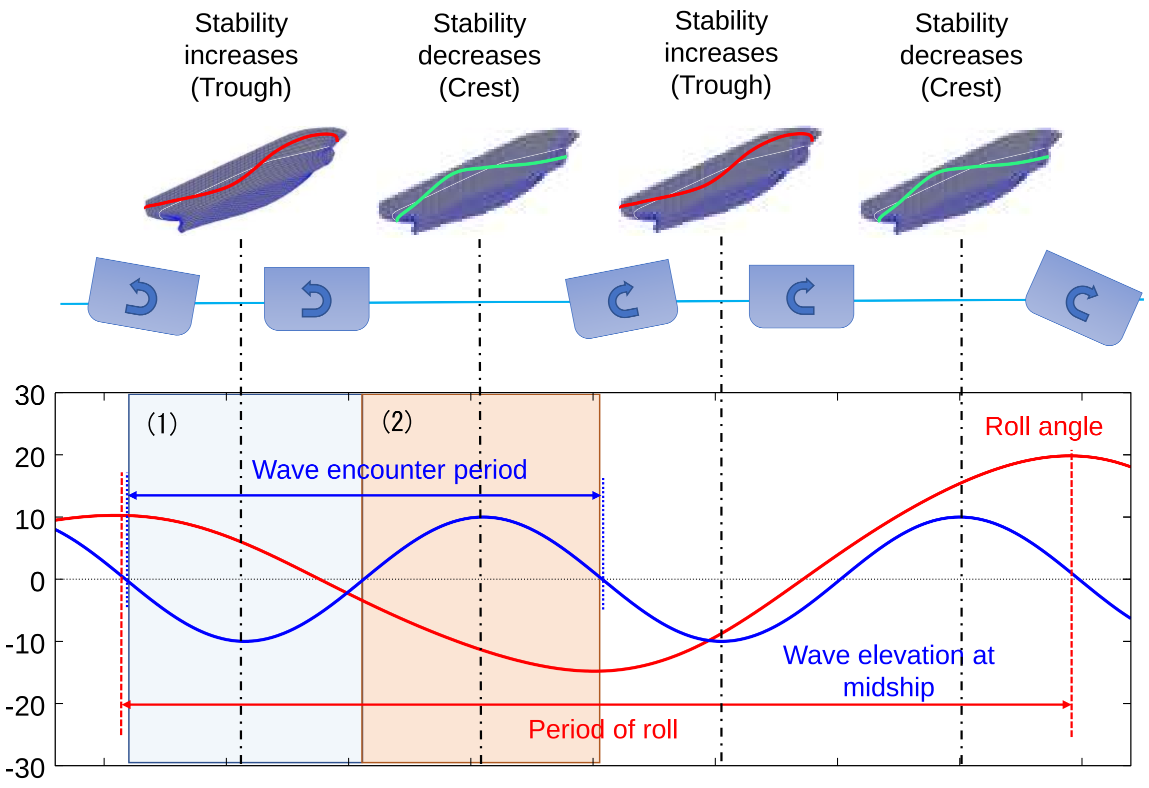


Fig. A1-2 Development of parametric rolling

As shown in Fig. A1-2, the ship encounters two crests and troughs respectively during one roll cycle. One condition for the occurrence of parametric rolling is that the ship is to encounter swells from the bow or stern direction whose wave period T_e is approximately half of the ship's natural roll period T_R.

$$i.e.\ \ T_R \fallingdotseq 2 \times T_e \quad (s)$$

Theoretically, parametric rolling may possibly occur under the condition $T_R : T_e \fallingdotseq 2 : n\ (n = 1, 2, 3\ldots)$. In general, however, only the period ratio 2 : 1 is examined. (Although parametric rolling may occur in some cases when $n = 2$, *i.e.*, 2 : 2, $n > 2$ causes no problem at all.)

Another condition for parametric rolling is that roll motion amplifying effect induced by the change in stability at the wave crest and trough is to overcome the damping effect of the ship.

Although the damping effect has been neglected up to this point for simplicity, ship roll motion is affected by various damping effects such as friction and wave making. When the variation of stability does not exceed a certain threshold, ship roll motion cannot be amplified and the parametric rolling phenomenon does not occur. This point is explained more in detail in the following -2.

-2. Features of parametric rolling

As described in -1., the conditions for generating parametric rolling can be summarized as follows.

(1) The ship is navigating in swells from the bow or aft direction.

(2) The wave encounter period (relative wave period to ship speed) is about half of the ship's natural roll

period.

(3) The variation of stability exceeds a certain threshold in relation to damping effects.

Although the theoretical explanation is omitted here, the above-mentioned condition (3) can be given by the following relational expression.

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

GM_{max}: Maximum (at trough) value of *GM* during a single wavelength of a swell passing the ship, in *m*

GM_{min}: Minimum (at crest) value of *GM* during a single wavelength of a swell passing the ship, in *m*

$\overline{GM}(= (GM_{max} - GM_{min})/2)$: Mean *GM*, in *m*

α: Linear roll damping coefficient

$\omega_0(= 2\pi/T_R)$: Natural roll frequency, in *rad./s*

This relational expression means that parametric rolling occurs when the capacity index for roll amplification, which is obtained by dividing the amplitude of *GM* variation [$(GM_{max}–GM_{min})/2$] by the averaged *GM*, becomes greater than the threshold of damping effects, and indicates the following features of parametric rolling.

- Parametric rolling is more unlikely to occur as *GM* (averaged *GM*) becomes larger.
- Parametric rolling is more likely to occur as the variation of *GM* increases.
- The possibility of parametric rolling can be reduced by installing devices which increase damping effects, such as an enlarged bilge keel and anti-rolling tanks.

In general, a larger wave height increases the variation of *GM*. At the same wave height, a swell whose wavelength is close to the ship's length causes the maximum variation of *GM*. Therefore, the possibility of parametric rolling increases when the ship encounters swells whose wave height is larger and whose wavelength is close to the ship's length. Although a larger wave height usually causes a larger parametric roll amplitude, it is possible that a larger wave height (wave steepness) exceeding a certain limit might produce a lesser roll angle and an even larger wave might not even cause parametric rolling.

When a ship completely meets the conditions for the occurrence of parametric rolling, it would theoretically suffer extraordinary roll angles exceeding 30° during a few times of rolling, and in this case, it would be almost impossible to take any action such as changing course or speed after recognizing that parametric rolling is occurring. It is unlikely, however, that a ship will suddenly encounter all the conditions for parametric rolling; rather, the ship might approach the dangerous region gradually, first passing through yellow and red zones from the safe state. The statements from captains and crews that encountered parametric rolling also suggest that the ships suffered several severe roll motions prior to and possibly presaging fatal parametric rolling that caused their accidents. Hence, it is essential to take the necessary actions to avoid fatal parametric rolling in the earlier stages. In any case, it is important to remember that parametric rolling is an essentially dangerous phenomenon that can cause fatal rolling suddenly and in a very short time.

Appendix-2 Key Points for Avoiding Parametric Rolling

This Appendix provides a general explanation of the key points for avoiding parametric rolling. Parametric rolling is a dangerous phenomenon in which a ship suddenly makes a heavy roll while navigating in a head sea, following sea or oblique sea. When a ship encounters a resonant condition that induces parametric rolling, extraordinarily large roll angles can occur in a very short time, and it is almost impossible to take any action. In addition, since the common and ingrained operation of the crew for heaving to in rough seas may possibly trigger parametric rolling, the usual and ordinary precautions, practices and measures against heavy weather conditions cannot always apply to parametric rolling.

Precautions and effective measures against parametric rolling, including early avoidance of danger zones and immediate course change on detecting any advance signs of parametric rolling, are important for preventing parametric rolling and the consequent accidents and damage. This section gives a brief explanation and basic knowledge on the following matters, which should be useful for such purposes.

(1) Determine the natural roll period of the ship
(2) Pay due attention to the direction and encounter period of swells
(3) Know the estimated roll angle of the ship (especially for large ships)
(4) Be familiar with the ship's vulnerability to parametric rolling and the available operational guidance

-1. Estimation of natural roll period

Parametric rolling is a phenomenon induced by synchronicity of a ship's natural roll period and the temporal variation of stability in head seas or following seas. Therefore, it is essential to determine the natural roll period of the ship, although this is not necessarily a simple matter.

The natural roll period is defined as the roll period in a calm water condition which is not influenced by winds and waves. Observed roll periods at sea, however, always change due to the influence of winds and waves, and do not coincide with the natural roll period of the ship. Although the natural roll period of small ships can be measured by rolling period tests, these tests are unrealistic for large ships. Hence, the natural roll period is usually estimated by using experimental formulas.

The natural roll period can be obtained theoretically according to the following expression.

$$T_R = 2\pi K/\sqrt{gGM} \quad (s)$$

The coefficient K means the roll radius of gyration considering the effect of added mass, which is difficult to obtain by theoretical calculations but is usually determined by experimental formulas. The major classification societies have proposed their own methods, and while there are some differences between the societies, most give a relationship of approximately $K = 0.39B$ to $0.41B$. Accordingly, the natural roll period of a ship can be estimated by the following formula.

$$T_R \cong 0.8B/\sqrt{GM} \quad (s)$$

Although this formula does not depend on the type of ship and can be used for most conventional vessels, there are some reports that this formula and other similar methods may underestimate the natural roll periods of large containerships. When a ship has a reliable onboard monitoring system to directly estimate the natural roll period, the output of the system should be used instead of experimental estimation.

The following expression for estimation of the natural roll period is given in the 2008 IS Code (*International Code on Intact Stability, 2008*), which is usually referenced in materials on stability and the loading manual provided onboard.

$$T_R = \frac{2 * C * B}{\sqrt{GM}} \quad (s), \qquad C = 0.373 + 0.023\left(\frac{B}{d}\right) - 0.043\left(\frac{L_{wl}}{100}\right)$$

However, this formula was derived from the measured roll periods of rather small vessels such as passenger ships, cargo ships and fishing boats up to the 1980s, and it is widely acknowledged that it can no longer be applied to modern merchant vessels, and particularly large containerships. It should be noted that any results given by this formula cannot be considered reliable. While most onboard loading computers and stability computers give natural roll periods calculated by this formula in the 2008 IS Code, it should not be used to obtain the natural roll period of modern merchant ships for any examination and calculation purposes, and especially not for parametric rolling.

All formulas for estimation of the natural roll period require the ship's *GM* as a parameter, and it is essential to use an accurate value of *GM* for this purpose. *GM* is defined as shown below as a fundamental relation in naval architecture.

$$GM = KB + BM - KG$$

The height of buoyancy *KB* and the metacentric radius *BM* can be calculated accurately by the loading computer and stability computer, provided ship type with the draft and trim is given correctly. The height of the center of gravity *KG* is also calculated by the loading computer, but needs correct inputs for the loaded cargoes, fuels, ballast water and free surface effect. Although it is essential to correctly comprehend the weights and positions of the loaded cargoes, this procedure is not easy and may be troublesome. It is not unusual that improper *KG* and *GM* are given due to incorrect inputs of the weights and positions of loaded cargoes. Moreover, it should be noted that improper estimation of *KG* may magnify the error of *GM*. There is a possibility, for example, that a 10 % error in the *KG* estimation may cause a 50 % error in *GM*.

The natural roll period is the most essential parameter for discussion and examination of parametric rolling. It is necessary to comprehend and input the weights and positions of loaded cargoes correctly in order to obtain the correct *KG*.

- ✓ Obtain the accurate *KG* by correctly determining the weights and positions of loaded cargoes.
- ✓ Estimate the natural roll period based on the accurate *GM* after loading. ($T_R \cong 0.8B/\sqrt{GM}$)
- ✓ DO NOT use the natural roll period given by the 2008 IS Code.

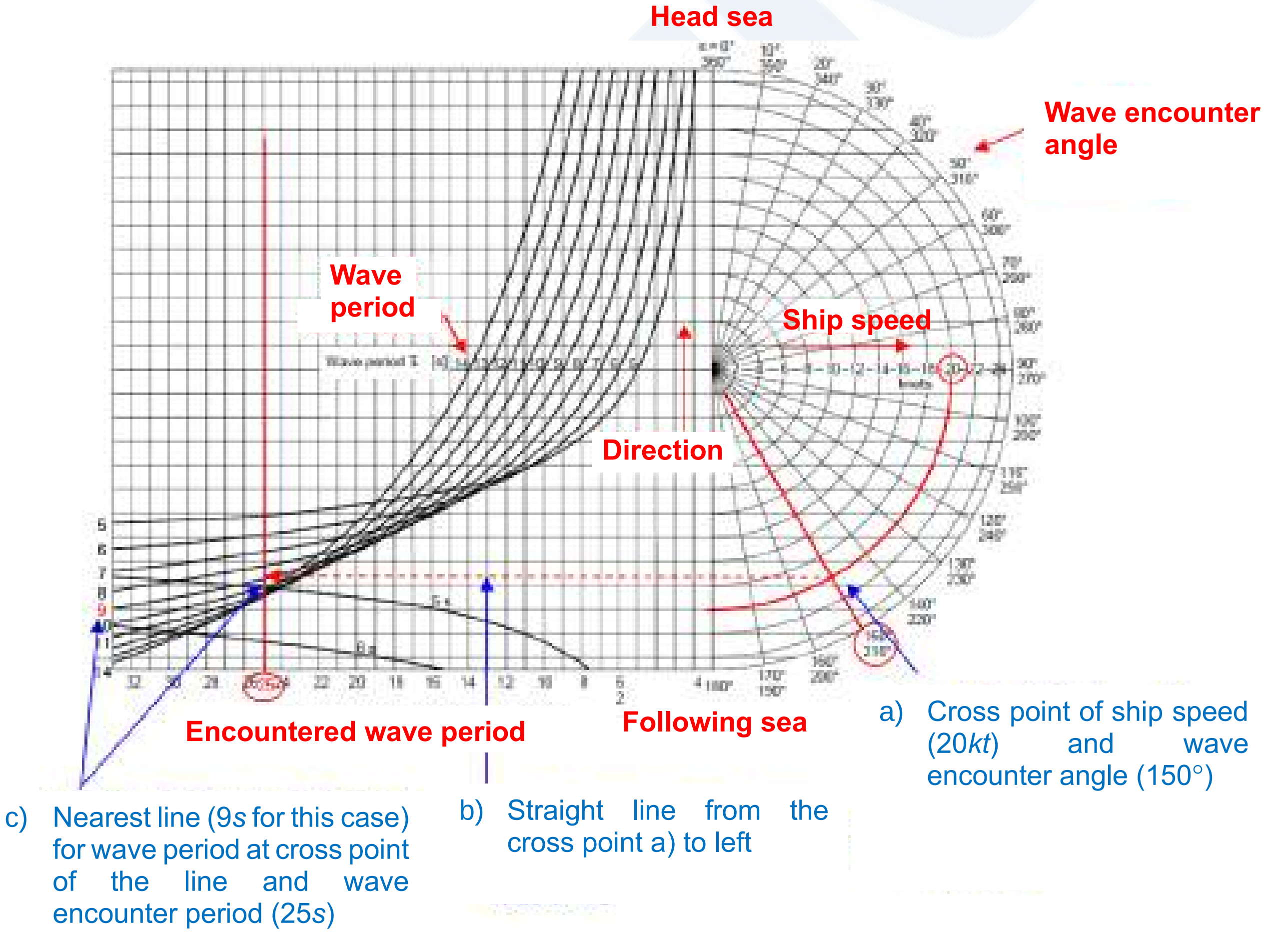
-2. Direction and encounter period of swells

Parametric rolling occurs when a ship is navigating in head or following seas with swells whose encounter period is close to half of the natural roll period of the ship. Therefore, when the ship encounters large swells, it is necessary to pay due attention to the direction and the encounter period of those swells.

Swells from the bow or aft direction and within the range of approximately 60° on both sides of the centerline have a high possibility of causing parametric rolling, and the range of approximately 40° on either side requires special attention. The encounter period of swells is usually obtained by visual measurement, but information provided by available weather services can be useful for determining it. Onboard wave radars, if available, give valuable information on the direction, wave period and height of swells.

Swell wavelengths which are equivalent to 0.6 times or longer a ship's length are the worst case for parametric rolling. Although it is not easy to determine the wavelength of swells, it can be grasped by the following method.

(1) Obtain the wave period of swells from the encounter period, wave encounter angle and ship speed by using the following chart. As shown in Fig. A2-1, the definition of the wave encounter angle in these Guidelines is 0° as a head sea and 180° as a following sea.



a) Cross point of ship speed (20*kt*) and wave encounter angle (150°)

b) Straight line from the cross point a) to left

c) Nearest line (9*s* for this case) for wave period at cross point of the line and wave encounter period (25*s*)

Fig. A2-1 Determination of the wave encounter period

(Source: Notice from Japanese Gov. (MLIT) in line with MSC.1/Circ.1228)

The example of Fig. A2-1 shows that the encounter period of 25s, the wave encounter angle of 150° and ship speed of 20kt result in a wave period of 9s.

(2) Estimate the wave length λ from the obtained wave period T_e according to the following relation.

$$\lambda = 1.56 \times T_e^2 \quad (m)$$

In the example of Fig. A2-1, the wave length is estimated as 126m with the wave period of 9s. When a ship encounters long swells and the measured encounter period is close to half of the natural roll period, appropriate action such as a change of course or speed should be taken. If the wave length obtained by the above method is equivalent to 0.6 times or longer the ship's length, an immediate turn should be conducted.

- ✓ Pay due attention to the direction and encounter period of swells.
- ✓ Change course or speed if the ship encounters swells from the bow or aft direction (within 60° on both sides of the ship) whose encounter period is close to half of ship's natural roll period.
- ✓ Turn immediately if the wave length of such swells is equivalent to 0.6 times or longer the ship's length.

-3. Roll angle in heavy weather

In heavy weather, roll angles exceeding 20° or even 30° are not unusual for small- and medium-sized ships. However, large containerships with a breadth exceeding 50m rarely experience roll angles of more than 10°. If a large roll motion of this size occurs suddenly, there is a high possibility that it is caused by parametric rolling.

As this suggests, an advance grasp of the estimated roll angles of the ship in heavy weather is helpful for grasping the signs of parametric rolling and avoiding potentially dangerous situations as soon as possible, especially in the case of large containerships.

The anticipated roll angles in storms of various intensity levels can be learned from previous logbooks, recorded data and actual shipboard experience. It is also desirable to know the estimated maximum roll angles in the worst heavy weather conditions for the service life of ships. The maximum roll angles are usually obtained from estimation formulas proposed by classification societies or by ship motion analyses with short-term and long-term predictions, but can also be estimated roughly by the following formula:

$$\phi \approx \frac{2.6 \times 10^3}{\sqrt{L_{PP}B}} \quad (deg.)$$

For example, the estimated maximum roll angles would be approximately 22° for 8,000TEU class containerships with L=300m and B=45m, 20° for 14,000 TEU class with L=350m and B=50m and 17° for 20,000TEU class mega containerships with L=400m and B=60m. While container ships of the Panamax class or smaller sizes often suffer roll angles of more than 30° in heavy weather, the possible roll angles of large ships with breadths of more than 50m are much smaller than expected. It is particularly rare that mega containerships with a breadth of about 60m experience a roll of more than 10°. Thus, if a mega containership suffers a heavy roll with a roll angle of more than 10°, parametric rolling is conceivable, and immediate evasive action should be taken.

As described above, when parametric rolling is not considered, the maximum roll angles which large containerships might suffer in their service lives are actually small and are much less than imagined, and the design roll angle for lashing and securing arrangements for on-deck containers is usually set as 20° or less. However, parametric rolling can cause excessive roll angles of more than 25° or 30°, and might result in damage and collapse of on-deck containers.

As mentioned repeatedly, if a mega containership experiences a spontaneous roll with a roll angle of more than 10° or other unusual behavior in rough seas, especially when encountering long swells from the fore or aft direction, the possibility that parametric rolling has occurred should be considered. This kind of behavior may mean that the ship is approaching a danger zone for parametric rolling, and may suffer a fatal parametric roll if it maintains its current course and speed. Moreover, the design roll angles for lashing and securing on-deck containers are usually 20° or less in mega containerships, which is not sufficient for possible parametric rolling. It is easy to imagine that parametric rolling of this magnitude would cause severe damages and collapse of on-deck containers.

- ✓ Grasp the roll angles that normally occur in the ship in heavy weather. The maximum roll angle in a ship's service life can be estimated roughly by the following formula.

$$\phi \approx \frac{2.6 \times 10^3}{\sqrt{L_{PP}B}} \quad (deg.)$$

- ✓ Take appropriate action, such as changing course or speed, if the ship experiences excessive rolling greater than expected or other abnormal behavior in swells from the bow or stern direction, as the ship might have suffered parametric rolling.
- ✓ If a roll angle exceeding 10° occurs in mega containerships, there is a high possibility that the ship is entering a parametric rolling danger zone. Take action to avoid parametric rolling, such as changing course or speed, as the lashing arrangements of large containerships are vulnerable to the large roll angles.

-4. Ship's vulnerability to parametric rolling and operational guidance

SGISc (Second Generation Intact Stability Criteria) provides several methods for evaluating a ship's vulnerability to parametric rolling. Among those methods, the Level 2-*C*2 criterion is practical in terms of accuracy and difficulty, and provides the basic principles for numerical calculations on parametric rolling. The calculation process for this criterion produces a table that shows the predicted roll angle corresponding to each sea state, in combination with the wave period and effective wave height given in the wave scatter table. This is a useful tool for grasping the maximum roll angle that may possibly be induced by parametric rolling when the ship encounters the corresponding sea state.

However, because SGISc was developed to prevent accidents related to stability for ships in a seaway, such as capsizing and water ingress, its Level 2-*C*2 criterion accepts parametric rolling of up to 25°. It should be noted that this is inconsistent with the design roll angles for lashing and securing arrangements on large containerships, which are usually set to less than 25°.

As of 2023, when the present Guidelines were published, SGISc is not a mandatory code or convention, and there are few ships that are subject to application of this interim guidelines. It is expected, however, that SGISc will attract attention as part of measures against parametric rolling, and the number of ships adopting SGISc will increase. When any evaluation results for vulnerability to parametric rolling or materials according to SGISc are presented, their meaning and methods of use should be well understood.

Various theories, methods and systems for calculating the possible response values of parametric rolling have been established and developed, including the SGISc method for Level 2-*C*2. Such methods and systems can be utilized for preventive measures against parametric rolling.

For example, it is possible to specify the dangerous conditions of sea states and operation for parametric rolling by calculation of the predicted amplitudes for various parameters such as wave height, wave direction, draft, *GM*, ship speed, heading angle, etc. Polar charts or other visual indications of danger zones based on such calculations are useful to avoid parametric rolling. Fig. A2-2 is an example of such charts. In the charts shown here, 0° is the head sea and 180° is the following sea.

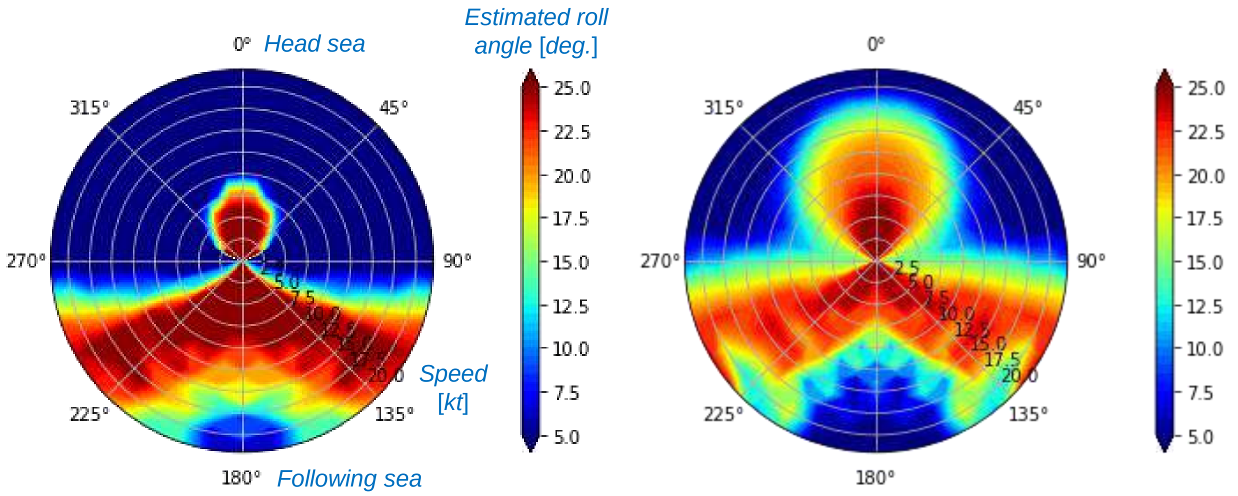


Fig. A2-2 Sample chart showing possible parametric roll angles

Although some weather services already provide information related to parametric rolling, it is expected that more services and systems that are useful for avoiding parametric rolling will be developed and widely used. If a service or system of this type is used on a ship or is to be introduced in the future, it must be used correctly after fully mastering its method of use.

- ✓ Understand the meaning of the vulnerability or characteristics of the ship related to parametric rolling, such as the estimated maximum roll angles, if provided and available.
- ✓ Be familiar with the charts and operational guidance for avoiding parametric rolling, if provided and available onboard the ship.
- ✓ Be familiar with weather services and preventive systems, if introduced and available onboard the ship.

Appendix-3. Outline of SGISc Evaluation Criteria

This Appendix provides an overview of the evaluation criteria for parametric rolling provided in SGISc.

-1. SGISc evaluation criteria

SGISc provides three criteria, Level 1, Level 2 and Level 3, with different degrees of difficulty for vulnerabilities that can occur in dynamic stability, such as the dead ship condition, surf-riding, pure loss of stability and parametric rolling.

Level 1 has the advantage that vulnerabilities can be evaluated by a comparatively simple formula, but in many cases, Level 1 may impose significant restrictions on ship operation conditions, as this criterion is based on a large safety margin corresponding to its simplicity. Level 2 is technically more sophisticated and requires complex calculations, but operational restrictions are reduced because a smaller safety margin can be set, corresponding to its improved estimation accuracy. Level 3 is intended to avoid risk by reproducing the ship's response characteristics with high accuracy by simulation calculations of the most advanced level.

The following is an overview of the evaluation criteria for parametric rolling provided in SGISc. However, since priority is given to easy understanding, the explanation of some conditions and formula has been omitted. Thus, it should be noted that this is not a comprehensive description of all requitements of SGISc and may contain some inaccuracies.

-2. Level 1 criterion

In -2 of Appendix-1, the following relational expression is given as the condition for occurrence of parametric rolling. This means that parametric rolling will occur when the variation in *GM* exceeds the threshold related to damping.

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

The following assumptions and conditions are introduced in this relational expression.

- Take the wave height (variation of draft) as h=0.0167L (wave steepness of 0.0167). (For L=300m, the wave height is approximately 5m.)
- Define the transverse moment of inertia of the waterplane area at the draft of $d+h/2$ as $I_{max.}$
- Define the transverse moment of inertia of the waterplane area at the draft of $d–h/2$ as I_{min}.
- Assume that the variation of *GM*, i.e. $GM_{max}–GM_{min}$ can be represented by $(I_{max}–I_{min})/\nabla$ (∇: volume displacement of the ship.) and is defined as $2\delta GM_1$. (δGM_1 is the amplitude, and is half of the total amount of variation.
- The linear damping coefficient α can be calculated by an approximate formula using the bilge keel area and midship section coefficient as parameters.

By adopting these assumptions and conditions, the above-mentioned relational expression can be replaced with the following formula, which is the basis of the Level 1 criterion.

$$\frac{\delta GM_1}{GM} \leq R_{PR}$$

Here, R_{PR} is the threshold for the Level 1 criterion, which is based on the linear rolling damping coefficient and is calculated using the principal dimensions, bilge keel area and midship section coefficient, but the concrete formulas for its calculation are omitted here.

-3. Level 2-*C*1 criterion

For parametric rolling, SGISc specifies two evaluation criteria as Level 2. The first, *C*1, provides a more accurate estimate of the possibility of parametric rolling than the Level 1 criterion in -2. above by introducing more realistic assumptions and conditions than those used in Level 1.

- Consider 16 cases of swells (i=1, 2, . . . 16) with different wave heights and wavelengths, considering the wave scatter table (IACS Rec.34).
- Change the position of the wave crest for each swell (i=1, 2, . . . 16) at intervals of $0.1L$ along ship's length, and calculate GM in the equilibrium state considering the changes in draft and trim. The maximum and minimum GM are defined as GM_{max} and GM_{min}, respectively.
- Conduct the same evaluation as in Level 1 using the GM_{max} and GM_{min} obtained above in place of δGM_1. Set C_i=0 when the criterion is satisfied and C_i=1 if the criterion is not satisfied.
- Multiply C_i under the various wave conditions calculated above by the weighting coefficient Wi, which corresponds to the probability of occurrence of each wave state, and obtain *C*1 as the sum of all wave states.

Based on the results of an examination of past accidents due to parametric rolling, it is judged that a ship is not vulnerable to parametric rolling if the obtained *C*1 is not more than 0.06. That is, the Level 2-*C*1 evaluation criterion is defined by the following conditional expression.

$$C1 = \sum_{i=1}^{16} W_i \, C_i \leq 0.06$$

-4. Level 2-*C*2 criterion

The *C*2 criterion, which is the other Level 2 evaluation criterion, is premised on a numerical calculation of the following equation for one degree of freedom of parametric rolling.

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

*C*2 is obtained from the results of calculations for various wave conditions and ship speeds by a variety of statistical methods, which include estimation of the response value of parametric rolling in various sea states in the wave scatter table of IACS Rec.34.

As the calculation procedures for the Level 2-*C*2 criterion are quite complex, a detailed explanation will be omitted here. However, the general procedure is as follows.

(1) Calculate the parametric roll response under various conditions.

Perform calculations for the target loading condition (draft, *GM*) for 10 cases of wave heights and 26 cases of ship speeds.

- Wave length (m): $\lambda = L$ (equivalent to the ship's length)
- Wave period (s): $T_w = \sqrt{\frac{2\pi\lambda}{g}}$ (deep-water waves)
- Wave height (m): $H_w = 0.01L \sim 0.1L$, 10 cases
- Ship speed (kt): $\{1.0, 0.991, 0.996, 0.924, 0.866, 0.793, 0.707, 0.609, 0.5, 0.383, 0.259, 0.131, 0\} \times V_s$ (Velocity component at intervals of 7.5° for each direction of head and following waves, 26 cases)
- V_s: Service speed (kt)

(2) Estimate the roll angles for the sea states in the IACS wave scatter table for each ship speed

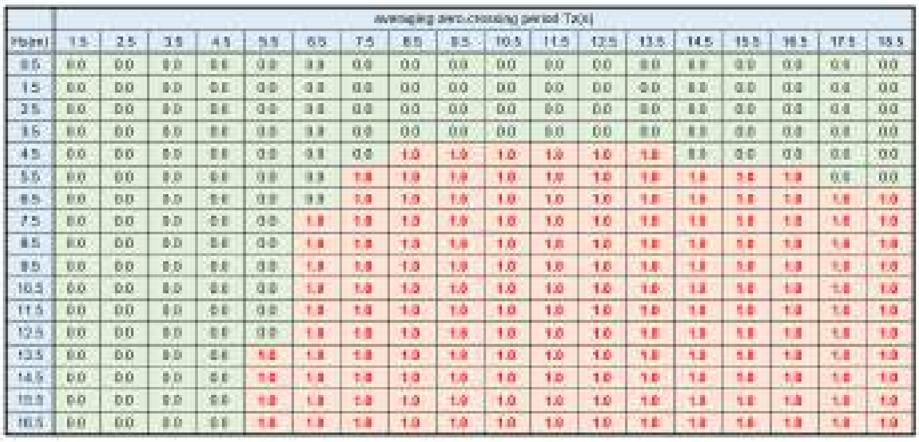
- Calculate the representative wave height corresponding to each sea state in the wave scatter table provided in IACS Rec.34. (This method is based on the theory of Grim's effective wave. Details are omitted here.)
- Calculate the parametric roll response corresponding to the sea state by linear interpolation of the calculation results in (1).
- Prepare a table summarizing the maximum roll angles by entering the response values in the corresponding cells of the wave scatter table. (see Fig. A3-1)

Fig. A3-1 Predicted maximum roll angles corresponding to wave states in wave scatter table

(3) Calculate *C*2 by multiplying the number of sea states with roll angles exceeding 25° by the probability of occurrence of those sea states.

- In the table prepared in (2), replace the value with "1" if the roll angle exceeds 25° and with "0" if it is not more than 25°. (Fig. A3-2)

- Multiply this table (Fig. A3-2) by the table (Fig. A3-3) of the probability of occurrence of the sea states in the wave scatter table to create another table (Fig. A3-4), and obtain *C*2(*Fn, β*) as the sum of the entire table. (*C*2(*Fn, β*) is obtained for a total of 26 cases, as values are calculated for 26 different ship speeds.)
- *C*2 is obtained as the average value of *C*2(*Fn, β*).



	averaging zero-crossing period Tz(s)																	
Hs(m)	1.5	2.5	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	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0
5.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0
6.5	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
7.5	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
8.5	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
9.5	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
10.5	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
11.5	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
12.5	0.0	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
13.5	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
14.5	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
15.5	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
16.5	0.0	0.0	0.0	0.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Fig. A3-2 Table showing “1” for roll angles exceeding 25° and “0” otherwise

Fig. A3-3 Table showing probability of occurrence of sea states in wave scatter table

Fig. A3-4 Table obtained by multiplying tables in Fig. A3-2 and Fig. A3-3

The key point of the SGISc Level 2-$C2$ evaluation criterion is that the risk of parametric rolling is judged to be within the permissible range if $C2 \leqq 0.025$ is satisfied. The threshold 0.025 was determined based on the results of an examination of past accidents due to parametric rolling.

It should be noted that the $C2$ evaluation criterion in the current SGISc is based on the premise that parametric roll angles of up to 25° are acceptable. However, this inconsistent with the fact that the lashing and securing arrangements for large-scale container carriers, etc. are generally assessed by using roll angles of less than 25°. Although the $C2$ criterion is thought to provide a considerable margin, it is desirable to revise the threshold of 25° for parametric rolling in the above-mentioned calculations to no more than the design roll angle used in calculations of the strength of stowage and securing arrangements.

-5. Level 3 criterion

The Level 3 evaluation for parametric rolling is premised on a ship motion simulation with 6 degrees of freedom which can directly reproduce stability changes with respect to the target operating conditions. However, those calculations require an extremely advanced level of technology and analysis tools and a huge amount of calculation time. Since use of the Level 3 evaluation criterion to evaluate the parametric rolling vulnerability of a ship or to prepare operational guidance cannot be considered realistic, the explanation of this technique will be omitted here. If necessary, the reader may refer to the relevant portions of SGISc and the Explanatory Notes (EN).

Appendix-4 Methods and Measures for Avoidance of Parametric Rolling

This Appendix introduces various measures for preventing parametric rolling or reducing the risk thereof.

-1. Devices for prevention and reduction of parametric rolling

Parametric rolling can be prevented or reduced by installing devices such as fin stabilizers or anti-roll tanks.

(1) Fin stabilizers

Fin stabilizers are a type of oscillation reduction (anti-motion) device that is widely used in passenger ships and the like. They offer excellent performance in reducing rolling during navigation and are also effective against parametric rolling. Even the fixed type has a large damping effect and is considered useful in preventing parametric rolling, but the active type is more effective. As a drawback, fin stabilizers function effectively at high speeds, but their effect decreases at lower speeds.

(2) Anti-roll tanks

Anti-roll tanks are also anti-motion devices that suppress ship rolling by utilizing the phase difference obtained by moving liquid between the right and left side tanks when ship rolling occurs. A large parametric rolling prevention effect can also be expected.

(3) Rudder roll stabilization control systems

Rudder roll stabilization control systems reduce a ship's roll motion by using adaptive control of the existing rudders corresponding to the rolling angle and utilizing the rolling moment of the rudder force. They are also effective in reducing parametric rolling. While the oscillation reduction effect of such systems is generally inferior to that of fin stabilizers, they have the advantages of low cost and effectiveness even at low speed.

(4) Enlarged bilge keels

Bilge keels are common arrangements that are widely adopted in general merchant ships to reduce rolling. Bilge keels with larger areas are expected to prevent or reduce parametric rolling to some degree due to their increased damping force. Similar effects can be expected by installation of appendages with a shape like the skegs of yachts.

-2. Operational guidance and weather services

(1) Operational guidance

Using the parametric roll response calculation method of SGISc Level 2-*C*2 or Level 3 or a similar method makes it possible to estimate the maximum roll angle due to parametric rolling for sea states that a ship may encounter under its intended navigation conditions. By carrying out series calculations of the predicted parametric roll response (roll angles) for various navigation conditions and sea states, it is possible to prepare materials such as polar charts showing the degree of danger of parametric rolling. Together with these charts, if the captain is provided with operational guidance indicating the action to be taken upon encountering danger of a certain degree or larger, this is expected to contribute to appropriate action for avoiding parametric rolling.

(2) Weather services

Various weather services provide advice for avoiding heavy weather and optimizing fuel efficiency based on forecasted meteorological/hydrographic data. Recently, some services also provide information related to parametric rolling. At present, highly accurate prediction of the risk of parametric rolling is still not possible, but it appears that reliable services that combine forecasted meteorological/hydrographic data and ship operating characteristics related to parametric rolling can be expected in the near future.

-3. Parametric rolling monitoring and alert systems

In order to predict the occurrence of parametric rolling and take appropriate action to avoid it, a proper understanding of the natural roll period of the vessel and the sea states encountered is necessary. For this reason, the development and introduction of devices that can measure these data accurately are desirable. Some of these devices are already in practical use. However, in addition to the further development and practical application of monitoring systems, development of systems that can accurately predict the occurrence of parametric rolling and issue alerts in combination with those monitoring devices is expected. As examples, the following monitoring and alerts system are conceivable.

(1) Natural roll period measurement system

A ship’s natural roll period is one of the most important parameters for predicting the occurrence parametric rolling or calculating its response value. As mentioned previously, since it is particularly difficult to measure the natural period of a large ship directly, the general practice is calculation using estimation formulas based on available data. It has also been reported that the natural roll periods of large container ships are larger than those obtained by such estimation formulas. Thus, the introduction of systems that enable accurate measurement of the natural roll period is desired.

(2) Wave radar

Wave radar is a technology that is already used practically, and the number of ships with wave radars installed onboard has increased in recent years. Wave radars can accurately observe the direction, period and wave height of waves and swells and are especially effective at night, when waves cannot be observed visually. Although there are still few cases in which wave radar is used as a preventive measure for parametric rolling, it is hoped that the use of wave radars will spread rapidly in the future.

(3) Integrated alert system combining wave radar and polar charts

Systems that combine the wave radar in (2) above and polar charts showing the degree of danger of parametric rolling referred to in -2 (1), and issue an alert when the ship encounters a sea state in which parametric rolling is possible are conceivable, and development and study aiming at introduction on actual ships are progressing. Moreover, even higher prediction and estimation accuracy is expected if systems of this type are combined with the natural roll period measurement system in mentioned above in (1).

(4) Real-time simulation system

Many of the systems and methods mentioned above as preventive measures for parametric rolling utilize a database that performed series calculations of the parametric roll response for various operational conditions and sea states in advance. However, it is also considered feasible to implement a system that performs real-time simulations onboard the vessel or ashore and judges the necessity of a change of course or speed.

(5) Alert system using ship motion data analysis

Methods for detecting the occurrence of parametric rolling as quickly as possible by analysis of time-series data related to the rolling, pitching and heaving behavior of a ship have been proposed. If systems that detect the occurrence of parametric rolling in an early stage and issue alerts are introduced on ships, such systems are expected to encourage quick action such as changes in the ship's speed or course, making it possible to avoid large roll motions due to parametric rolling. The development of systems that enable early detection of the signs of parametric rolling by AI-based analysis of ship motion data, etc. and issue alerts when danger is detected are also considered a possibility in the future.

Appendix-5 Basic Principles for Parametric Roll Response Calculation

This Appendix provides an overview of the basic principles of the governing equations, calculation methods and calculation conditions of parametric roll response calculations.[1]。

When applying these Guidelines, in principle, the related calculations are to be performed according to the principles described herein. However, this does not apply to the Level 3 simulation calculations stipulated in SGISc and other calculation methods deemed appropriate by the Society.

-1. Governing equation

Basically, the parametric roll response is to be obtained by a time domain simulation for the following equation of a ship's roll motion.

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

Φ : Roll angle

α, γ : Linear and cubic damping coefficients

ω_0 : Natural roll frequency

$f(\Phi, t)$: Term of nonlinear restoring force

Notwithstanding the above, except for the calculations related to Chapter 3, 3.1.3 of these Guidelines, the parametric roll response can be calculated by other calculation methods deemed appropriate by the Society. For example, the following governing equation, or so-called averaging method, may be used.

$$\ddot{\phi} + 2\alpha\dot{\phi} + \gamma\dot{\phi}^3 + \omega_0{}^2\left(\frac{GM_{mean}}{GM} + \frac{GM_{amp}}{GM}\cos\omega_e t\right)\left\{\phi - \left(1/\pi^2\right)\phi^3\right\} + \omega_0{}^2(\phi + l_3\phi^3 + l_5\phi^5) = 0$$

GM_{mean}: Difference between mean value of GM variation in waves and GM in calm-water

GM_{amp}: Amplitude of GM variation in waves

l_3, l_5: Third and fifth order coefficients on stability

ω_e: Wave encounter frequency

-2. Conditions of calculation and handling of response value

In principle, the following conditions are to be used in the governing equations shown in -1 above to obtain response values of parametric rolling.

- Assume a cosine wave with a wavelength equal to the ship length L_{PP}. Although wave periods are usually obtained from the formula for deep-water waves, the wave periods used for calculations related to polar charts are to be obtained by the methods specified in Appendix-6.

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[1] In Appendix-5 and -6 different unit systems are used without clear distinction, e.g. *deg*. (°) and *rad*. for roll angles, *kt* and *m/s* for ship speeds. Distinguishing the proper units as appropriate is requested.

- Conduct time domain simulations considering the variation of stability in waves. When using the averaging method, variation of stability can be considered by calculating *GM* values by moving the position of the wave crest at the interval of 0.1 L_{PP} from A.P. to F.P. Pitch and heave motions in waves are to be considered to keep the equilibrium condition.
- Set a 5° heel as the initial condition. (Initial heel angle: 5°)
- Conduct time domain simulations for 500 seconds or more with a time step of 1 second or less.
- Adopt the converged roll angle as the response value of the simulations. When the roll angles do not converge, the number of calculation steps is to be increased as necessary. If the simulation results diverge, the maximum value in the simulations or an appropriate roll angle of 45° or more is to be taken as the response value of the simulations.

Notwithstanding the above, the relevant requirements of SGISc are, in principle, to be followed in the calculations related to Chapter 3, 3.1.3.

-3. Definition of damping coefficients

The damping coefficients α, γ in the governing equations given above are obtained by the following procedure.

- Calculate the damping coefficients a (1) and a (25) at heel angles of 1° and 25°, respectively.
- Define α and γ, i.e., the first and third order damping coefficients, by the following relations.

$$\alpha = \frac{a(1) \cdot \omega_0}{\pi} \quad , \quad \gamma = c\frac{8}{3\pi\omega_0}\left(\frac{180}{\pi}\right)^2 \quad , \quad c = \frac{a(25) - a(1)}{25^2}$$

The calculations should consider the damping components of skin-friction, wave-making, eddy-making, bilge keel and lift and, in principle, be based on the simplified Ikeda method.

-4. Definition of coefficients for *GZ*-curve approximation

The polynomial coefficients of approximation for the calm-water *GZ* (righting lever) curve used in the averaging method are obtained by the following procedure.

- Calculate *GZ* values of the ship at heel angles from 0° to 40° at intervals of 5°or less.
- Define the 3rd and 5th order coefficients, l_3 and l_5, of polynomials of the approximation by the least square method based on the *GZ* values obtained above.

$$GZ = (\phi + l_3\phi^3 + l_5\phi^5)GM$$

-5. Susceptibility discriminant

The governing equation specified in the above -1. can be transformed into a so-called “Mathieu-type equation.” Mathieu-type equations have special mathematical features that can predict if their solutions converge or diverge without actually solving the differential equations. By using these mathematical features, it is theoretically possible to discriminate the susceptibility or possibility of parametric rolling by rather simple calculations.

The following relational expression given in Appendix-1 and Appendix-2 as the condition for the occurrence of parametric rolling is one such susceptibility discriminant method.

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

Although this expression is simple and is the basis of the SGISc Level 1 and Level 2 criteria, it is not practicable to discriminate susceptibility by this expression. Instead, another relational expression of the susceptibility discriminant for parametric rolling is given below. If this relational expression is satisfied, it is judged that parametric rolling will not occur under the intended conditions, and the related response calculations can be omitted.

$$M < 2\sqrt{\left\{(1+F) - \frac{1}{4}\left(\frac{\omega_e}{\omega_0}\right)^2\right\}^2 + \left(\frac{\alpha}{\omega_0}\right)^2\left(\frac{\omega_e}{\omega_0}\right)^2}$$

$$F = \frac{(GM_{max} + GM_{min}) - GM}{GM}, \quad M = \frac{(GM_{max} - GM_{min})}{GM}$$

-6. Accuracy of calculation programs

The calculation programs, software and tools used in assessments and other calculations related to parametric rolling should be able to perform the related calculations with appropriate accuracy and to demonstrate similar calculations for the standard ship (C11 class containership) presented in the explanatory notes[2] to SGISc within the allowable error of +5% and -3%. Irrespective of this standard of accuracy, the calculation programs used for Level 3 direct stability assessment should comply with the relevant requirements[3] for validation specified in SGISc. The calculation software and programs related to these Guidelines should be approved or accepted by the Society.

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[2] Refer to EN Appendix 2 *"Examples of assessments using vulnerability criteria according to the second generation Intact stability criteria".*

[3] Refer to SGISc *3.4 "Requirements for validation of software for numerical simulation of ship motions"* and related EN (Appendix 4).

Appendix-6 Calculations and Procedures for Polar Charts

This Appendix provides the standard conditions of calculations and related procedures for preparing polar charts which show the estimated roll angles of possible parametric rolling for various loading conditions and sea conditions, and are utilized as part of operational guidance against parametric rolling.

These calculations and procedures are generally based on those of the SGISc Level 2-*C*2 criterion but are enhanced for practical and reasonable operational guidance. Although this Appendix assumes that the necessary response calculations are performed with 1 degree of freedom (1-DOF) governing equations such as those specified in Appendix-5, direct calculations for SGISc Level 3 criterion or other appropriate calculation methods deemed appropriate by the Society can be used for preparing polar charts.

The standard loading and calculation conditions should be and can be changed as necessary and proper.

-1. Standard loading conditions

- Mean draft: At each draft from ballast draft to full draft, at intervals of $1m$
- Trim: Normally, even trim
- GM (GM_0): Possible range of GM during normal operations ($0.5m$ interval is recommended)

Although consideration of trim for ballast conditions is recommended, another approach is to prepare polar charts for ballast conditions separately.

-2. Effective wave heights and effective wave encounter periods

(1) Effective wave heights

Effective wave heights H_{eff} are calculated for each sea state by the combination of the significant wave height H_S and the average wave period T_Z in the wave scatter table according to formulas which are based on Grim's theory and given below, and are summarized in a table format (See Fig. A6-1). As the effective wave heights change depending on the wave encounter angle, this type of table of effective wave heights is prepared for each wave encounter angle (normally every 10°). Effective wave heights for sea states whose frequency of occurrence is less than 1 in the wave scatter table are treated as zero.

$$H_{eff} = 4.0043\sqrt{\int_{\alpha=-\pi/2}^{\alpha=\pi/2}\int_{\omega=0}^{\omega=\infty} S\eta_{eff}\left(\omega, L_{pp}, \alpha\right)d\omega d\alpha}$$

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

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

$\bar{\chi}$: Ship heading angle from main wave direction $\quad \chi = \bar{\chi} - \alpha$

As in SGISc, the Bretschneider spectrum recommended for the North Atlantic is given hereto, but other proper spectra can be used to prepare polar charts for ships intended to navigate in particular areas and routes.

Effective Wave Height (m)		Average Wave Period (s)																	
		1.5	2.5	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
Significant Wave Height (m)	0.5	0.00	0.00	0.09	0.12	0.15	0.20	0.26	0.30	0.33	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1.5	0.00	0.00	0.00	0.35	0.46	0.61	0.77	0.91	0.98	1.00	0.99	0.95	0.89	0.00	0.00	0.00	0.00	0.00
	2.5	0.00	0.00	0.00	0.59	0.77	1.02	1.29	1.51	1.64	1.67	1.65	1.58	1.49	1.39	1.29	0.00	0.00	0.00
	3.5	0.00	0.00	0.00	0.00	1.08	1.42	1.81	2.12	2.29	2.34	2.30	2.21	2.08	1.95	1.81	0.00	0.00	0.00
	4.5	0.00	0.00	0.00	0.00	1.39	1.83	2.32	2.72	2.95	3.01	2.96	2.84	2.68	2.50	2.32	2.15	0.00	0.00
	5.5	0.00	0.00	0.00	0.00	1.70	2.23	2.84	3.33	3.60	3.68	3.62	3.47	3.27	3.06	2.84	2.62	0.00	0.00
	6.5	0.00	0.00	0.00	0.00	0.00	2.64	3.36	3.93	4.26	4.35	4.28	4.10	3.87	3.61	3.35	3.10	0.00	0.00
	7.5	0.00	0.00	0.00	0.00	0.00	3.05	3.87	4.54	4.91	5.02	4.94	4.73	4.46	4.17	3.87	3.58	0.00	0.00
	8.5	0.00	0.00	0.00	0.00	0.00	0.00	4.39	5.14	5.57	5.69	5.59	5.36	5.06	4.72	4.38	4.05	0.00	0.00
	9.5	0.00	0.00	0.00	0.00	0.00	0.00	4.90	5.75	6.22	6.36	6.25	5.99	5.65	5.28	4.90	4.53	0.00	0.00
	10.5	0.00	0.00	0.00	0.00	0.00	0.00	5.42	6.35	6.88	7.03	6.91	6.62	6.25	5.84	5.42	5.01	0.00	0.00
	11.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.95	7.53	7.70	7.57	7.26	6.84	6.39	5.93	0.00	0.00	0.00
	12.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.56	8.19	8.37	8.23	7.89	7.44	6.95	6.45	0.00	0.00	0.00
	13.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.84	9.04	8.88	8.52	8.03	7.50	0.00	0.00	0.00	0.00
	14.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.71	9.54	9.15	8.63	0.00	0.00	0.00	0.00	0.00
	15.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	16.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Fig. A6-1 Table of effective wave heights (depending on wave encounter angle)

(2) Effective wave encounter period (frequency)

Effective wave encounter frequencies $\overline{\omega}_e$ or effective wave encounter periods $\overline{T}_e$ are obtained from the following equations based on the spectrum of the effective wave $S\eta_{eff}(\omega, L_{pp}, \alpha)$ defined in the above (1), the ship's speed U and the wave encounter angle χ. Note that 0° is defined here as the head sea and 180° as the following sea, which differs from the definition of the wave encounter angle and the positive and negative signs in the formula in the attached reprinted paper. The effective wave encounter frequency $\overline{\omega}_e$ does not depend on the significant wave height but on the wave encounter angle. It is necessary to calculate the effective wave encounter period (frequency) corresponding to each combination of ship speed and mean wave period on the wave scatter table, at every wave encounter angle. (See Fig. A6-2)

$$\overline{\omega}_e = \sqrt{\frac{\int_{\alpha=-\frac{\pi}{2}}^{\alpha=\frac{\pi}{2}} \int_{\omega=0}^{\omega=\infty} \left(\omega + \frac{\omega^2}{g} U\cos\chi\right)^2 S_{\eta_{eff}}(\omega, L_{pp}, \chi)\, d\omega\, d\alpha}{\int_{\alpha=-\frac{\pi}{2}}^{\alpha=\frac{\pi}{2}} \int_{\omega=0}^{\omega=\infty} S_{\eta_{eff}}(\omega, L_{pp}, \chi)\, d\omega\, d\alpha}}, \quad \overline{T}_e = \frac{2\pi}{\overline{\omega}_e}$$

Encounter Wave Period (s)		Average Wave Period (s)																	
		1.5	2.5	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
Ship speed (kt)	0.0	1.67	2.59	3.63	4.72	5.88	7.14	8.30	9.18	9.83	10.33	10.72	11.05	11.32	11.55	11.75	11.92	12.07	12.20
	2.0	1.68	2.61	3.68	4.82	6.04	7.37	8.61	9.55	10.23	10.75	11.17	11.50	11.78	12.02	12.22	12.40	12.55	12.68
	4.0	1.68	2.63	3.74	4.92	6.21	7.62	8.94	9.94	10.67	11.21	11.64	11.99	12.28	12.52	12.73	12.91	13.07	13.20
	6.0	1.69	2.65	3.78	5.01	6.37	7.88	9.29	10.36	11.13	11.71	12.16	12.52	12.82	13.07	13.28	13.47	13.63	13.76
	8.0	1.69	2.66	3.83	5.11	6.54	8.15	9.67	10.82	11.64	12.25	12.72	13.10	13.41	13.66	13.88	14.07	14.23	14.37
	10.0	1.69	2.68	3.86	5.20	6.71	8.43	10.07	11.31	12.19	12.84	13.33	13.72	14.04	14.31	14.54	14.73	14.89	15.04
	12.0	1.69	2.68	3.90	5.28	6.88	8.72	10.49	11.84	12.79	13.48	14.00	14.41	14.74	15.02	15.25	15.45	15.62	15.76
	14.0	1.69	2.69	3.93	5.36	7.05	9.02	10.94	12.42	13.45	14.18	14.73	15.16	15.51	15.79	16.03	16.23	16.41	16.56
	16.0	1.68	2.69	3.95	5.44	7.21	9.33	11.42	13.04	14.16	14.95	15.54	15.99	16.35	16.65	16.89	17.10	17.27	17.43
	18.0	1.68	2.69	3.97	5.50	7.37	9.65	11.93	13.71	14.94	15.80	16.43	16.90	17.28	17.59	17.84	18.05	18.23	18.39
	20.0	1.67	2.68	3.98	5.56	7.53	9.96	12.47	14.43	15.79	16.73	17.41	17.92	18.31	18.63	18.89	19.10	19.29	19.45
	22.0	1.66	2.67	3.99	5.61	7.67	10.28	13.03	15.21	16.73	17.76	18.50	19.04	19.45	19.78	20.05	20.27	20.46	20.62
	24.0	1.65	2.66	3.99	5.65	7.81	10.60	13.61	16.05	17.75	18.90	19.70	20.28	20.72	21.07	21.34	21.57	21.76	21.92

Fig. A6-2 Table of effective wave encounter periods (depending on wave encounter angle)

-3. Response calculation and conversion for effective wave heights

(1) Response calculations of parametric rolling

For each combination of draft and *GM* given in the standard loading conditions specified in the above -1, the necessary series calculations are carried out and the response values obtained thereby are arranged in a table for each combination of ship speed and wave encounter angle. The calculated response for a certain wave height should not be smaller than the responses for smaller wave heights. (See Fig. A6-3)

The standard conditions for the series calculations are given below.

・ Wave length:	$\lambda = L_{PP}$ (equal to the length between perpendiculars)
・ Wave height:	1.5*m* to 12*m*, in steps of 1.5*m*
・ Wave direction:	0 to 350°, in steps of 10°
・ Ship speed:	Up to service speed, in steps of 2*kt*
・ Wave encounter period:	As obtained according to the above -2.(2)

Response Angle (°)		Average Wave Period (s)																	
		1.5	2.5	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
Calc Wave Height (m)	1.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.59	9.61	2.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.92	16.64	12.65	8.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	4.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.68	18.71	14.87	11.15	7.31	0.71	0.00	0.00	0.00	0.00	0.00
	6	0.00	0.00	0.00	0.00	0.00	0.00	21.63	23.47	20.28	16.57	13.19	10.05	6.83	2.20	0.00	0.00	0.00	0.00
	7.5	0.00	0.00	0.00	0.00	0.00	0.00	23.65	24.81	21.69	18.16	15.04	12.31	9.78	7.27	4.37	0.00	0.00	0.00
	9	0.00	0.00	0.00	0.00	0.00	0.00	25.22	26.23	23.30	19.98	17.11	14.68	12.57	10.67	8.88	7.13	5.28	2.97
	10.5	0.00	0.00	0.00	0.00	0.00	0.00	25.22	26.23	23.30	19.98	17.11	14.68	12.57	10.67	8.88	7.13	5.28	2.97
	12	0.00	0.00	0.00	0.00	0.00	0.00	25.22	26.23	23.30	19.98	17.11	14.68	12.57	10.67	8.88	7.13	5.28	2.97

Fig. A6-3 Table of calculated responses of parametric rolling
(depending on ship speed and wave encounter angle)

(2) Parametric roll angle corresponding to effective wave height

Parametric roll angles corresponding to the effective wave heights defined in -2.(1) are obtained by linear interpolation by using the calculated responses obtained in the above (1) (see Fig. A6-4), and are arranged in a table format for parametric roll angles to effective wave heights (see Fig. A6-5).

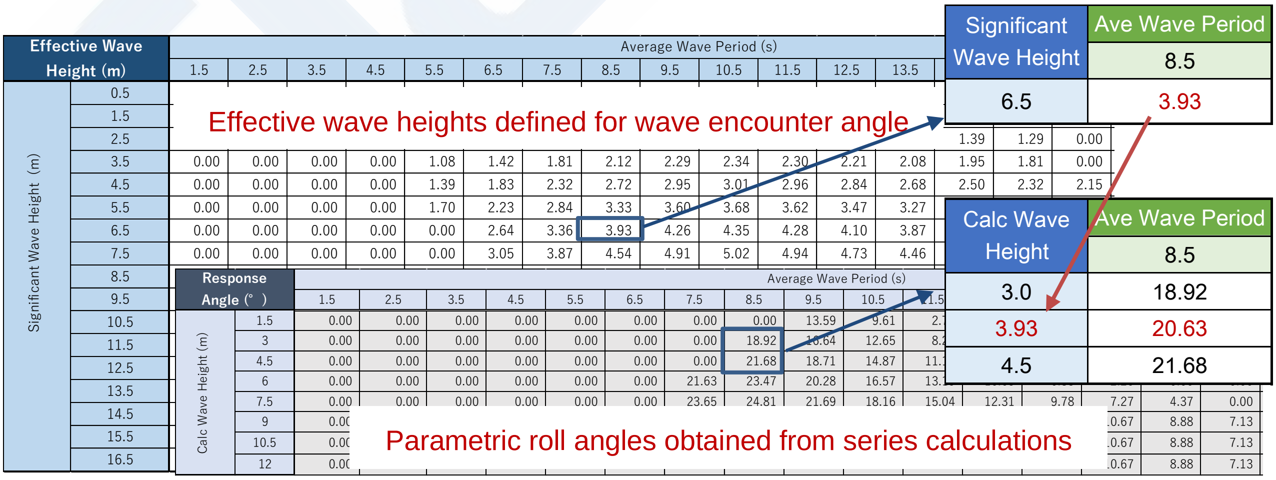


Fig. A6-4 Linear interpolation for parametric roll angles to effective wave height

Response angle (°)		Average Wave Period																	
		1.5	2.5	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	Max
Significant Wave Height (m)	0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.97	2.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.97
	1.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.90	6.44	1.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.90
	2.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	13.87	9.97	3.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.87
	3.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.78	15.20	11.32	5.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.20
	4.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.41	16.53	12.67	8.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.53
	5.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.52	17.47	13.66	9.44	2.29	0.13	0.00	0.00	0.00	0.00	0.00	19.52
	6.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	20.63	18.37	14.65	10.72	5.37	0.41	0.00	0.00	0.00	0.00	0.00	20.63
	7.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.72	19.14	15.46	11.74	7.74	0.69	0.00	0.00	0.00	0.00	0.00	21.72
	8.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.44	19.82	16.22	12.64	8.89	2.99	0.33	0.00	0.00	0.00	0.00	22.44
	9.5	0.00	0.00	0.00	0.00	0.00	0.00	5.83	23.16	20.49	16.95	13.50	10.04	5.42	1.15	0.00	0.00	0.00	0.00	23.16
	10.5	0.00	0.00	0.00	0.00	0.00	0.00	13.27	23.78	21.10	17.66	14.31	10.99	7.32	1.96	0.00	0.00	0.00	0.00	23.78
	11.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24.32	21.72	18.40	15.14	11.94	8.49	3.53	0.00	0.00	0.00	0.00	24.32
	12.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	24.87	22.43	19.21	16.05	12.92	9.66	5.40	1.30	0.00	0.00	0.00	24.87
	13.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	23.13	19.98	16.95	13.92	10.78	7.28	0.00	0.00	0.00	0.00	23.13
	14.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	19.98	17.11	14.68	11.88	0.00	0.00	0.00	0.00	0.00	19.98
	15.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	16.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Fig. A6-5 Examples of parametric roll angles to effective wave heights

The maximum response among those for all average wave periods is taken as the parametric roll angle corresponding to that significant wave height. The table of anticipated parametric roll angles for the intended loading condition and ship speed, as shown in Fig. A6-6, can be obtained by performing similar operations for all wave encounter angles. If polar charts are prepared for particular average wave periods, this procedure (maximum response for all average wave periods) is not applicable.

Estimated roll angle (°)		Significant Wave Height											
		1.5m	2.5m	3.5m	4.5m	5.5m	6.5m	7.5m	8.5m	9.5m	10.5m	11.5m	12.5m
Wave Encounter Angle	0°	6.9	11.4	12.6	13.8	14.9	18.8	19.5	20.3	20.9	21.5	19.0	19.6
	10°	7.6	12.5	13.6	14.8	15.8	19.2	20.1	20.9	21.6	22.2	19.9	20.5
	20°	8.6	14.2	15.6	16.9	18.0	18.9	19.7	20.4	22.1	22.8	22.2	22.7
	30°	8.9	13.9	15.2	16.5	19.5	20.6	21.7	22.4	23.2	23.8	24.3	24.9
	40°	8.8	14.0	15.3	17.3	19.7	20.8	21.7	22.5	23.2	23.8	24.4	25.0
	50°	8.5	14.1	15.7	17.2	19.6	20.8	21.8	22.5	23.5	24.2	24.8	25.4
	60°	0.0	10.7	14.3	15.3	18.4	19.8	21.1	22.2	23.0	23.7	24.3	24.8
	70°	0.0	0.0	0.0	4.8	9.9	15.0	18.5	19.6	20.7	22.0	22.7	23.5
	80°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	6.5	6.9	12.5
	90°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	100°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	110°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	120°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	130°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	140°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	150°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	160°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	170°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	180°	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig. A6-6 Table of anticipated parametric roll angles

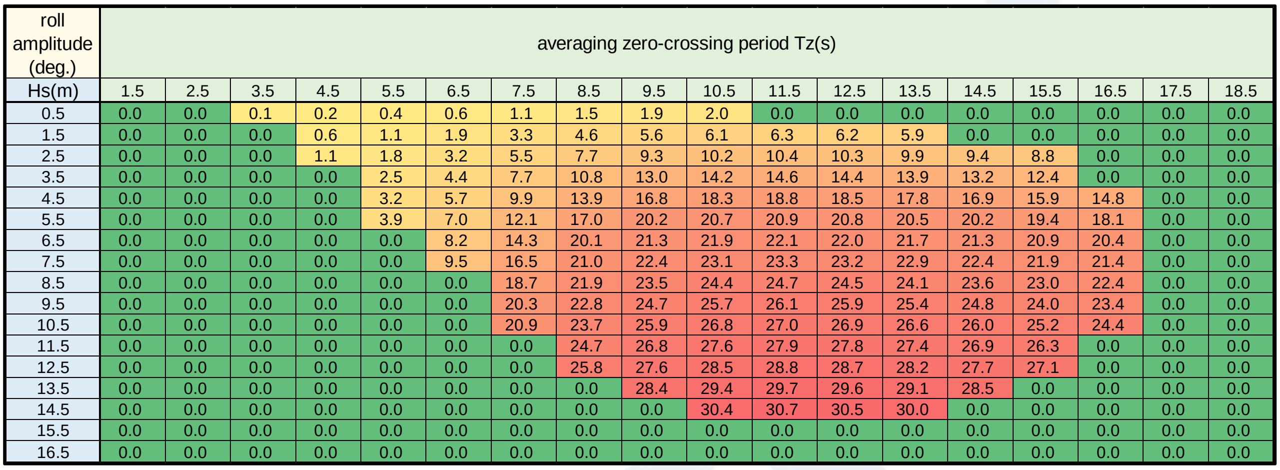
-4. Charts for operational guidance

The anticipated parametric roll angles for various loading conditions and sea conditions can be obtained through the process of calculations and procedures shown above. Charts for operational guidance are prepared by using these values, and some examples are given below.

(1) Table of maximum roll angles

In the process of calculations for the SGISc Level 2-*C*2 criterion, it is possible to obtain tables such as Fig.

A6-7, which give the anticipated parametric roll angles for possible sea states (combinations of significant wave heights and average wave periods) under the intended loading. However, the calculation procedure explained in the above -3. can also produce similar tables that provide more rational and reliable results. For reference, the table in Fig. A6-7 gives zero response as the anticipated parametric roll angle for sea state conditions whose numbers of occurrence are less than 1. Such tables can give necessary information and instructions to captains with regard to dangerous sea states which should be avoided to prevent parametric rolling under the intended loading and navigating conditions.



roll amplitude (deg.)	averaging zero-crossing period Tz(s)																	
Hs(m)	1.5	2.5	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	0.0	0.0	0.1	0.2	0.4	0.6	1.1	1.5	1.9	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5	0.0	0.0	0.0	0.6	1.1	1.9	3.3	4.6	5.6	6.1	6.3	6.2	5.9	0.0	0.0	0.0	0.0	0.0
2.5	0.0	0.0	0.0	1.1	1.8	3.2	5.5	7.7	9.3	10.2	10.4	10.3	9.9	9.4	8.8	0.0	0.0	0.0
3.5	0.0	0.0	0.0	0.0	2.5	4.4	7.7	10.8	13.0	14.2	14.6	14.4	13.9	13.2	12.4	0.0	0.0	0.0
4.5	0.0	0.0	0.0	0.0	3.2	5.7	9.9	13.9	16.8	18.3	18.8	18.5	17.8	16.9	15.9	14.8	0.0	0.0
5.5	0.0	0.0	0.0	0.0	3.9	7.0	12.1	17.0	20.2	20.7	20.9	20.8	20.5	20.2	19.4	18.1	0.0	0.0
6.5	0.0	0.0	0.0	0.0	0.0	8.2	14.3	20.1	21.3	21.9	22.1	22.0	21.7	21.3	20.9	20.4	0.0	0.0
7.5	0.0	0.0	0.0	0.0	0.0	9.5	16.5	21.0	22.4	23.1	23.3	23.2	22.9	22.4	21.9	21.4	0.0	0.0
8.5	0.0	0.0	0.0	0.0	0.0	0.0	18.7	21.9	23.5	24.4	24.7	24.5	24.1	23.6	23.0	22.4	0.0	0.0
9.5	0.0	0.0	0.0	0.0	0.0	0.0	20.3	22.8	24.7	25.7	26.1	25.9	25.4	24.8	24.0	23.4	0.0	0.0
10.5	0.0	0.0	0.0	0.0	0.0	0.0	20.9	23.7	25.9	26.8	27.0	26.9	26.6	26.0	25.2	24.4	0.0	0.0
11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.7	26.8	27.6	27.9	27.8	27.4	26.9	26.3	0.0	0.0	0.0
12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.8	27.6	28.5	28.8	28.7	28.2	27.7	27.1	0.0	0.0	0.0
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.4	29.4	29.7	29.6	29.1	28.5	0.0	0.0	0.0	0.0
14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.4	30.7	30.5	30.0	0.0	0.0	0.0	0.0	0.0
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Fig. A6-7 Table showing anticipated roll angles for various sea states

(2) Polar charts

Polar charts, which show anticipated roll angles based on various parameters of sea conditions and navigation conditions, can be utilized to predict the maximum roll angles of possible parametric rolling and to judge the necessity of changing the ship's course or speed to avoid such parametric rolling if necessary. Examples of polar charts are given below. In the charts shown here, 0° is the head sea and 180° is the following sea.

A) Polar charts based on significant wave heights

This kind of polar chart shows the anticipated roll angles for several significant wave heights, which is useful for predicting the maximum roll angles when the ship encounters the significant wave heights at particular encounter angles and a certain ship speed.

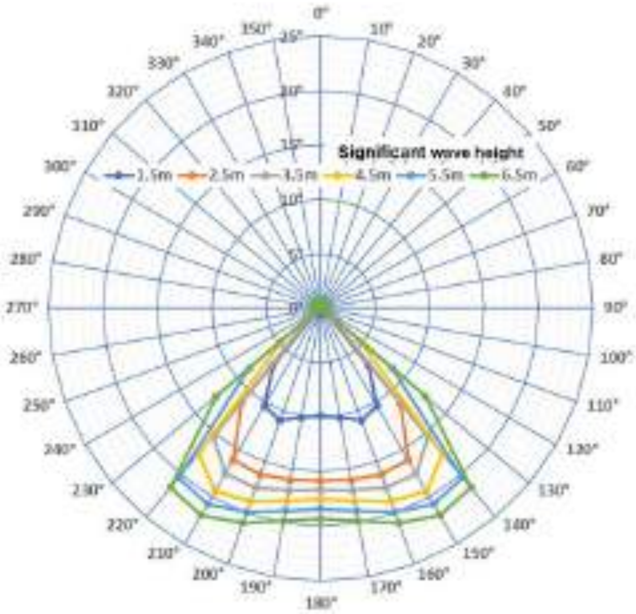


Fig. A6-8 Example of polar charts based on significant wave heights
(as per loading condition [draft and *GM*] and ship speed)

B) Polar charts based on ship's speed

This kind of polar chart shows the anticipated roll angles for different ship speeds, which is useful for predicting the maximum roll angles when the ship takes an intended course with different ship speeds.

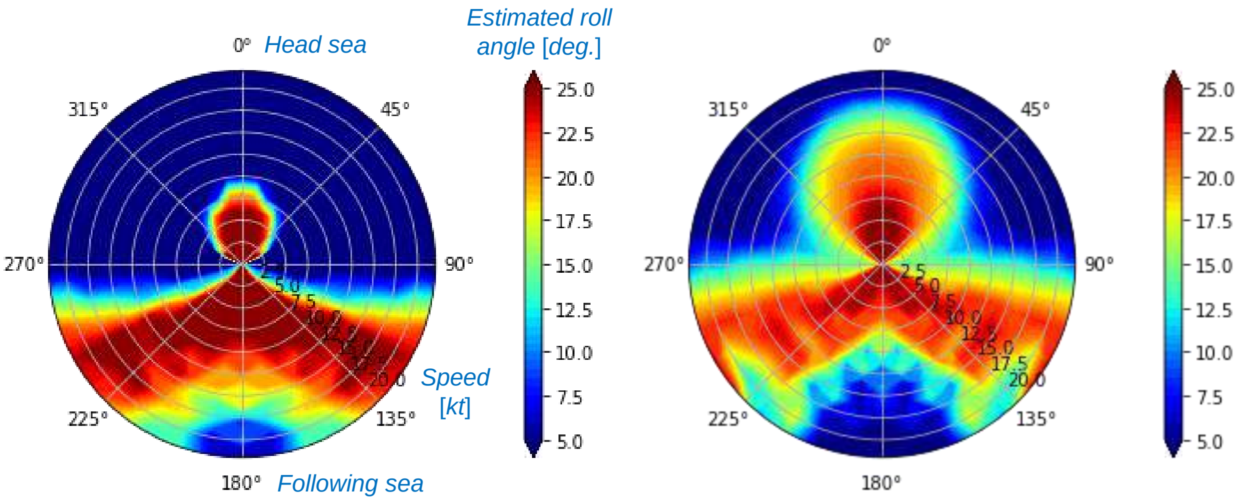


Fig. A6-9 Example of polar charts based on ship speed
(as per loading condition [draft and *GM*] and wave height)

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Some Remarks on Simplified Operational Guidance for Parametric Rolling

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Key Words: *Second generation intact stability criteria, Grim's effective wave, ship course*

1. INTRODUCTION

For preventing stability failure modes which are not covered by the existing intact stability code1), International Maritime Organization (IMO) approved the second generation intact stability criteria in 20202). It includes not only design criteria but also operational guidance, so a ship failing to comply with the design criteria could be operated with the operational guidance. This scheme is based on the current safety level of many ships realized with good seamanship for properly selecting ship's speed and course depending on the encounter sea states. The operational guidance can be prepared in the three ways: probabilistic, deterministic, and simplified ones. The probabilistic operational guidance requires the upper boundary of the 95% confidence interval of the stability failure rate estimated by the direct counting of the Monte Carlo simulation using the experimentally validated numerical model is smaller than the 10^{-6} (s^{-1}). The deterministic one requests that the three-hour maximum roll angle estimated by the Monte Carlo numerical simulation is smaller than half the critical roll angle such as 20 degrees. Since the operational guidance should cover all possible speed and course ranges together with environmental and loading conditions, the computational cost for preparing these types of guidance could be not always feasible for practical purposes. Therefore, the use of the simplified operational guidance is highly expected. For this guidance, the explanatory notes approved by the IMO3) clearly states that "any simple conservative estimations for the sailing conditions that should be avoided in each relevant sea state, can be used if they are shown to provide a superior safety level compared to the design assessment requirements. In particular, Level 1 or Level 2 vulnerability criteria of the Guidelines for vulnerability assessment in chapter 2 can be used." Since the methodology of the vulnerability criteria is based on the single degrees of freedom model in regular waves, the preparation of the guidance could be feasible for most of practical users.

Among the five failure modes that the second generation intact stability criteria deal with, parametric rolling failure mode attracts attentions of the naval architects because of frequent accidents of container losses. For parametric rolling, the IMO3) also provide an example of preparation procedures which is based on the Level 2 vulnerability criteria. Unfortunately, it could specify dangerous speed but not for the dangerous course relative to the wave direction so that the simplified operational guidance could be too simple for the ship operators. Therefore, the proposal of methodology for developing simplified operational guidance for ship forward speed and course is urgent. Since the IMO requests us to prove the proposed guidance more conservative the safety level estimated by the probabilistic simulation used for design criteria. Thus, it is preferable that the new proposed criteria have some probabilistic framework.

2. METHDOLOGY USED IN DESIGNED CRITERIA

The level 2 vulnerability criteria consist of two checks: the first check is for occurrence of parametric rolling and the second one deals with the magnitude of parametric rolling. This paper focuses the second check because the container damage occurs only with larger roll amplitude.2)

In this scheme3), irregular ocean waves describing the ITTC spectrum are replaced with a longitudinal regular wave. Its wavelength is equal to the ship length and its crest is situated at the midship. The effective wave spectrum is determined by the least square method within the ship length. Assuming that the spectrum is narrow, the 1/3 largest wave height is calculated so that it changes in time. This concept is known as Grim's effective wave4). Since the relationship between the wave and restoring variation is non-linear but non-memory, this concept is used in place of the linear superposition principle. Once the effective wave height is determined, the restoring moment in waves can be obtained using the non-memory relationship.

Then, an uncoupled roll equation is used with this time-varying restoring moment and non-linear roll damping moment. The roll damping moment is estimated with Ikeda's simplified method5), which is empirical formulae from the results of Ikeda's prediction method for damping components6). Here the ship is assumed to run with the service forward speed and the various heading angles. Here the representative wave frequency is assumed to be equal to the frequency of the incident wave, the length of which is equal to the ship length, based on the water dispassion relation of linear water wave. As a result, the wave encounter frequency depends on the heading angle. The restoring moment, however, is assumed to be the same as that in longitudinal waves because it can be regarded as a conservative approximation. The direct wave excitation is ignored. Based on the numerical calculation, the number of heading angles is set to be 123).

The obtained equation was numerically solved with the initial condition such as the roll angle of 5 degrees and the roll angular velocity of 0. Ignoring the transient roll behaviour, the steady roll amplitude should be determined. Because of nonlinearity, the outcome is not necessarily a typical parametric rolling,

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which is subharmonic and has period almost equal to the natural roll period and known as “principal parametric rolling". In some cases, even chaos can be found so that it requires an expert knowledge to understand the obtained time series. The initial stage of the criteria development at the IMO used an averaging method, which outputs all possible principal parametric rolling without the initial state dependence. However, at the later stage it was replaced with the time domain simulation because the averaging method sounds complicated. Whichever method is used, nonlinearity of the system provides us some difficulty.

The design criteria use the wave scatter diagram for the North Atlantic, which represents the joint probability density of the significant wave height and zero-crossing mean wave period. For each sea state, the effective wave height should be calculated and then the relevant roll amplitude can be determined by the above-mentioned procedure. If the roll amplitude exceeds 25 degrees, the sea states should be regarded as dangerous. Then the occurrence probability of the dangerous sea states should be calculated by integrating the joint probability within the dangerous sea states in the wave scatter diagram. If the obtained probability exceeds 0.025, the ship under the assumed loading condition should be regarded as vulnerable to parametric rolling. The acceptable value of 0.025 was determined to exclude the accident of the C11 class post-Panamax containership in the North Pacific[7)].

3. SIMPLIFIED OPERATIONAL GUIDANCE AS AN EXAMPLE PROVIDED BY THE IMO

In the explanatory notes to the second generation intact stability criteria[3)], an example of the simplified operational criteria as follows. If the sea state is regarded as dangerous under the particular ship speed by using the method described in chapter 1, such ship speed should be avoided regardless the heading angle. This is simple to be prepared but it does not help the operator to select the ship course relative to the wave direction.

The authors compare the application of this simplified operational guidance and the existing model experiments in irregular waves. The comparisons for the C11 class containership in head waves are shown in Figs. 1-2. The simulation results to be used in the simplified operational guidance somewhat overestimate the experimental results in irregular waves[8)].

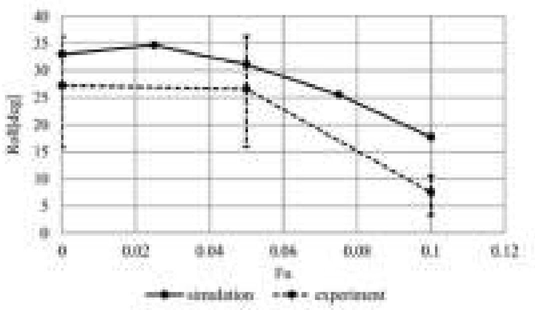

Fig. 1 Comparison in the roll amplitude between the simulation to be used for simplified guidance and the model experiment in irregular waves for the C11 class containership in head seas with the significant wave height of 7.82 m and the mean wave period of 9.99 s for different Froude numbers.

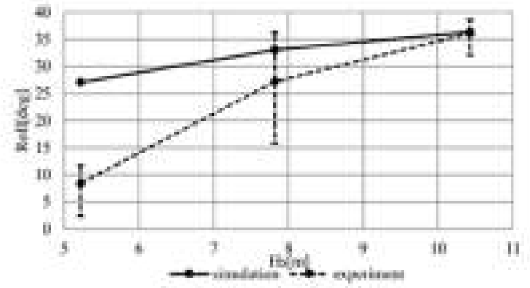

Fig. 2 Comparison in the roll amplitude between the simulation to be used for simplified guidance and the model experiment in irregular waves for the C11 class containership in head seas with the mean wave period of 9.99 s and the Froude number of 0.0 for different significant wave heights.

The comparison for the 150m-long containership in following waves is shown in Fig.3. Here the roll angle of 80 degrees indicates capsizing. The reason for the frequent occurrence of capsizing due to parametric rolling is small metacentric height, which is critical to the 2008 IS Code and severest sea state in the oceans. In this case, also the simulation results to be used in the simplified operational guidance somewhat overestimate the experimental results in irregular waves[9)].

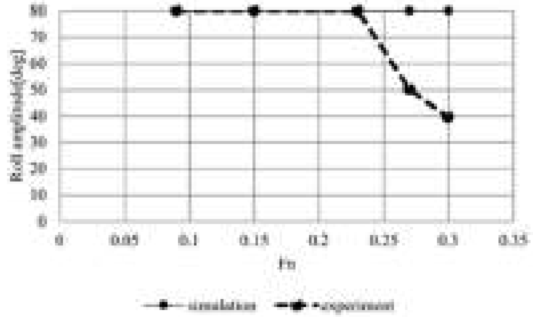

Fig. 3 Comparison in the roll amplitude between the simulation to be used for simplified guidance and the model experiment in irregular waves for the 150m-long containership having the metacentric height of 0.15m in following seas with the significant wave height of 13.26 m and the mean wave period of 10.92 s for different Froude numbers.

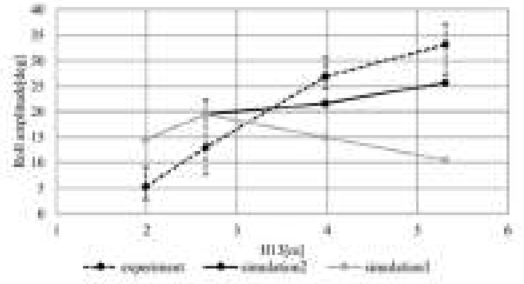

Fig. 4 Comparison in the roll amplitude between the simulation to be used for simplified guidance and the model experiment in irregular waves for the 192m-long PCTC in head seas with the mean wave period of 9.76 s and the Froude number of 0.0 for different significant wave heights.

The comparison for the 192m-long PCTC in head waves is shown in Fig.4. In this case, the simulation results to be used in the simplified operational guidance, which is labelled as "simulation 1" do not always overestimate the experimental results in irregular waves10). This is because the roll amplitude in regular waves does not always increase with the increasing the wave height, which is due to the increase of the mean of GM with the wave height. Roughly speaking, the amplitude of the GM variation is proportional to the wave height, while the mean of GM variation is proportional to the square of the proportional to the wave height. Thus, sometimes the condition for the parametric roll can be violated at a certain wave height or above. On the other hand, the roll amplitude in irregular waves normally increases with the increasing the wave height because of the spectrum of incident waves. To confirm this mechanism, the simulation ignoring the mean of GM variation is also shown as "simulation 2". As a result, the roll amplitude ignoring the mean of GM variation increases with the increasing wave height. This is a drawback of the simplified approach using the effective regular waves. Thus, the second check of the level 2 criterion requires to keep the maximum roll amplitude if the roll amplitude decreases with the increasing wave height as mentioned in the explanatory notes. Therefore, the same procedure should be applied to the simplified operational guidance3).

In conclusion, the calculation based on the second check of the level 2 criterion normally overestimates the model experiment. Since the numerical model used for the full operational guidance is required to be validated with model experiments, this simplified operational guidance for parametric rolling is expected to provide conservative estimates for the danger of parametric rolling in actual longitudinal seas. The remaining issue is the absence of the requirement for heading in this simplified guidance. However, the magnitude of parametric rolling in oblique waves can be reduced if the heading angle leaves from the longitudinal waves. Therefore, the safety level realised with this simplified operational guidance for parametric rolling is logically higher than that with full operational guidance.

This description would be included as a part of the explanatory notes to be published as an IMO MSC circular soon3).

4. IMPROVING DIRECTION OF SIMPLIFIED OPERATIONAL GUIDANCE

4. 1 Short-crestedness of incident waves

For actual application of operational guidance onboard, it is necessary to take account for short-crestedness of incident waves. Nevertheless, the methodology for vulnerability criteria to be used for ship design is for long-crested irregular waves because it is more conservative. In fact, Grim's effective wave concept was extended to short-crested irregular waves by one of the authors11). The spectrum of the effective wave, $S_{\eta_{eff}}$, can be calculated as follows:

$$S\eta_{eff}\left(\omega, L_{pp}, \alpha\right) = \left[\frac{\frac{\omega^2}{g} L_{pp} \boldsymbol{\cos}(\chi)\, \boldsymbol{\sin}\left(\frac{\omega^2}{2g} L_{pp} \boldsymbol{\cos}(\chi)\right)}{\pi^2 - \left(\frac{\omega^2}{2g} L_{pp} \boldsymbol{\cos}(\chi)\right)^2}\right]^2 S(\omega, \alpha) \qquad (1)$$

where $\chi = \overline{\chi} - \alpha$. Here S is the wave spectrum as the function of wave frequency, ω, and wave direction, α: L_{pp} and $\overline{\chi}$ are the ship length between perpendiculars and the ship heading angle from the main wave direction, respectively. Using this formula, the 1/3 largest effective wave height, H_i, and the effective encounter frequency, $\overline{\omega}_e$, can be straightforwardly obtained as follows.

$$H_i = 4.0043 \sqrt{\int_{\alpha=-\pi/2}^{\alpha=\pi/2} \int_{\omega=0}^{\omega=\infty} S_{\eta_{eff}}\left(\omega, L_{pp}, \chi\right) d\omega d\alpha} \qquad (2)$$

$$\overline{\omega}_e = \sqrt{\frac{\int_{\alpha=-\pi/2}^{\alpha=\pi/2} \int_{\omega=0}^{\omega=\infty} \left(\omega - \frac{\omega^2}{g} U\cos\chi\right)^2 S\eta_{eff}(\omega, L_{pp}, \chi) d\omega d\alpha}{\int_{\alpha=-\pi/2}^{\alpha=\pi/2} \int_{\omega=0}^{\omega=\infty} S\eta_{eff}(\omega, L_{pp}, \chi) d\omega d\alpha}} \qquad (3)$$

where U indicates the ship forward speed. It is noteworthy here that the above calculation of the encounter frequency does not assume the wave dispassion relation of the effective wave. This point is different from the current vulnerability criteria but Sakai et al.12) numerically confirmed that effect of this difference is negligibly small because the effective wave is sufficiently narrow.

4. 2 Wave heading effect

For explicitly evaluating the effect of arbitrary wave heading angle, it is necessary to take account for both the reduction of restoring moment and the existence of transverse wave exciting moment. The former can be included in the calculation of Grim's effective wave mentioned above. If the wave heading angle increases from the following waves, the effective wave height decreases so that the restoring moment also decreases11). The latter can be evaluated by an averaging method as proposed by Sakai et al.13). However, in the cases that parametric rolling is important, the parametric excitation effect is dominant than the direct excitation effect. Thus, the direct excitation effect can be ignored.

4. 3 Stochastic effect

The 1/3 largest effective wave height can be calculated as described in Section 4.1. However, the theoretical background for using the 1/3 largest effective wave height is not so solid. As a result, the final safety level cannot be exactly evaluated in theory alone. To overcome this drawback, it is preferable for obtaining the probability density of the roll amplitude starting from the spectrum of the effective wave and the non-memory relationships between the restoring moment and the longitudinal wave height. Recently some successful outcomes were published by using a stochastic averaging method with empirical tuning14). If we integrate the probability density of the roll amplitude exceeding the critical roll angle, the probability of parametric roll exceeding the acceptable roll angle can be quantified for the specified sea states under the assumed ship speed, ship course and the loading condition.

5. CONCUSIONS

Simplified operational guidance for the ship operators selecting the ship forward speed and the heading angle to waves are highly desirable within the scheme of the second generation intact stability criteria, particularly for parametric rolling. Based on the methodology used for the second check of the Level 2 vulnerability criteria, it seems to be possible with the following enhancement.

- Grim's effective wave should be applied to short-crested irregular waves in place of long-crested irregular waves. It allows us to consider the reduction of restoring moment due to the wave heading.

- The wave frequency can be directly estimated from the spectrum of the effective wave without assuming the wave dispersion relation.
- The effect of direct excitation due to the wave heading can be evaluated by an averaging method but can be ignored for a practical purpose.
- The probability of parametric roll exceeding the acceptable roll angle can be evaluated by a stochastic averaging method and Grim's effective wave. It allows us to estimate the safety level guaranteed by such simplified operational guidance.

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CHARTING THE FUTURE

Guidelines on Preventive Measures
against Parametric Rolling (Edition 1.0)
[English]

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