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Research and Development Report

Analysis of Actually Encountered Hull Response of Containerships and Use of Load Correction Factor Considering Route and Seasonality

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1. Overview and Purpose

Accurate estimation of the maximum loads actually encountered by ships is important from the perspective of hull structural strength assessment for achieving reasonable hull structural prediction. Except in fatigue strength assessments, hull responses other than low-probability events which occur during rough weather are not critical when considering hull structural strength. On the other hand, in decisions regarding container stowage, the general practice is to calculate the loads acting on container stacks using the ship hull motion obtained considering the sea weather (sea states) corresponding to the respective navigation areas of each voyage. In the case of containerships, efforts to prevent container spill accidents are made by avoiding waters where waves above a certain height are expected, and in some cases, the container stacking height is determined based on sea weather forecasts if the voyage is short.

However, in analyses of measured data on hull motion, which is directly linked to the stacking height of containers, the correlation between the measured data and predicted loads has not been studied, in spite of the existence of numerous actual-ship measurement plans, and the types of ship motions that occur in actual seas are not necessarily clear. Hull motions in designated sea states are frequently evaluated using the Response Amplitude Operator (RAO) per unit wave height and the wave spectrum and sea state information. Nevertheless, many uncertainties regarding the motions that occur in ships in actual seas still remain. For example, it has been pointed out that singular motions such as parametric roll, which are difficult to evaluate by the above-mentioned method, may cause large inclination in containerships (Luthy, 2023). Therefore, in this research, we examined the hull responses that should be considered for safe navigation of containerships by clarifying the hull motions which affect container lashing strength actually encountered by ships by analyzing the ship motion data measured in actual-ship measurement projects in the past.

2. Methodology

2.1 Analysis Target and Method

The analysis target was multiple mega-containerships for which gyro data were collected in past actual-ship measurement projects. Roll motion is the most dominant factor in container lashing problems, but lashing problems are also affected by the pitch angle and pitch angle acceleration. Therefore, these three factors were considered as the analysis target. In handing the measured data, the data were linked to AIS (Automatic Identification System) data, making it possible to analyze the location, time and motion as a set.

Since not only statistical data, but also time-series gyro data were available for the target ships of this analysis, the amplitude of hull motion was found by the zero up-crossing method. Due to the enormous volume of data, the data were classified by voyage, and the analysis was carried out focusing on the maximum values of motion for each voyage. In dividing the data by voyage, cases in which the time at a speed below 4 knots exceeded 5 hours were regarded as a call at a port, and this was defined as the end of the voyage. It may be noted that this standard was decided by a trial-and-error process.

In this analysis, it is possible to obtain the period of motions because time-series data exist. Since the predicted loads for each voyage are used as the target of comparison with the measured data, the metacentric height (GM) of a ship is also necessary in order to calculate the predicted roll angle, as described in section 2.2. Since GM is not included in the AIS data or the measured data for the actual ships, GM is estimated by calculating the natural roll period by Fourier transformation by applying a bandpass filter to the time-series data of the roll angle. Here, the bandpass filter was set based on past experience.

As a result of the division in voyage units described above, data were obtained for 605 voyages with a total time of 3 726 days. Average duration of the voyage is 6.2 days.

2.2 Comparison Target

The maximum values of the hull motion for each voyage obtained as described in 2.1 were compared with the significant wave height and predicted loads. As the predicted loads for assessment of container lashing strength, the general method is to calculate coefficients in advance using the wave scatter diagrams for each sea area obtained from Global Wave Statistics (GWS), and specify those coefficients in rules (e.g., Helge Rathje et al., 2013). In contrast to this, ClassNK prepared more realistic wave scatter diagrams for encountered sea states by developing a voyage pattern model that considers the rough weather avoidance behavior of ships, using a combination of AIS data and wave hindcast data (Fujimoto et al., 2024). As the target of comparison with the above-mentioned measured data, in this research report, we used the measured values of hull motion evaluated based on the encountered wave scatter diagrams for each route and season prepared by the method proposed by Fujimoto et al. described above, which are considered to be closer to the actual encountered motion of containerships.

3. Analysis Results

3.1 Routes and Container Stacking Parameters

The voyage histories of the target ships are shown in Fig. 3.1.1. Although many voyages are on the Asia-Europe route, ships are also assigned to the Asia-North America route and the Atlantic route. By voyage duration, the largest number, 263 voyages, were voyages of 3 days or less, and only 3 voyages exceeded 30 days. Since such long voyages are difficult to imagine, these are thought to be voyages that could not be clearly divided (multiple voyages were combined into one voyage). However, since data division in this voyage unit is for convenience, this is not particularly a problem in the present analysis.

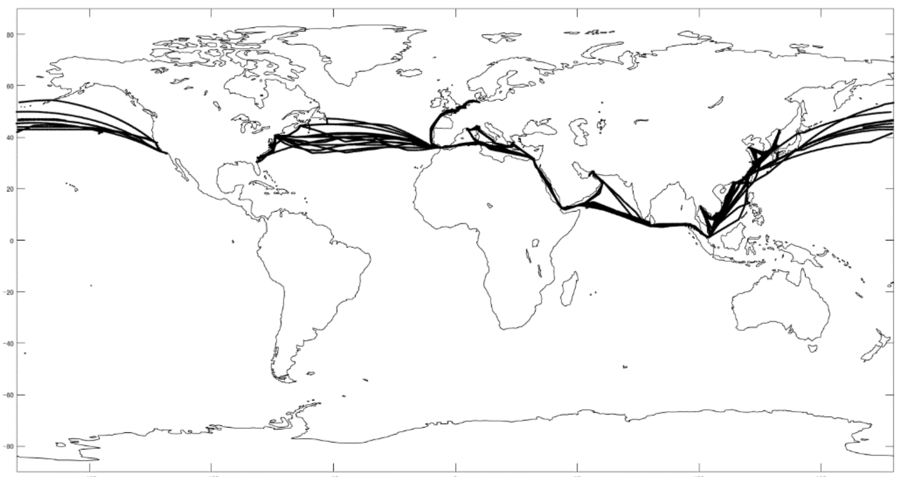


Fig. 3.1.1 Routes of target ships in this analysis

Next, the relationship of the ship draft and voyage duration and the relationship of GM and voyage duration are shown in Fig. 3.1.2 and Fig. 3.1.3, respectively. Here, draft is normalized by the summer season, fully loaded draft, and GM is normalized by the ship breadth. When the voyage duration is long, the ship tends to have a small GM and deep draft. Fig. 3.1.4 shows the relationship between GM and draft, which have a roughly negative correlation. Fig. 3.1.4 includes data in which both the draft and GM are small. If the roll response is small, a clear peak cannot be observed when the natural period is estimated from time-series data. Since this suggests the possibility that GM may not have been estimated properly, it can be noted that these data are not necessarily reliable.

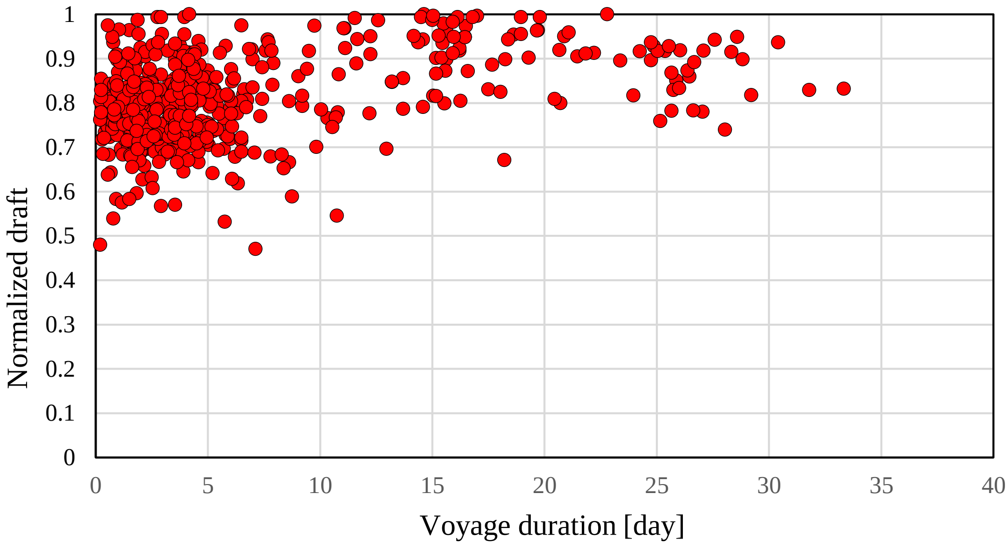


Fig. 3.1.2 Relationship of normalized draft and voyage duration

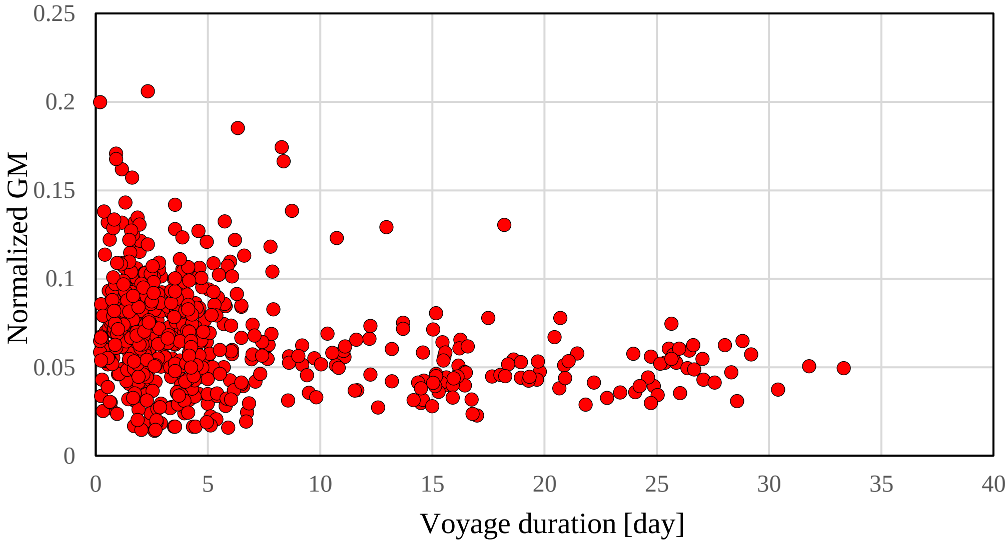


Fig. 3.1.3 Relationship of normalized GM and voyage duration

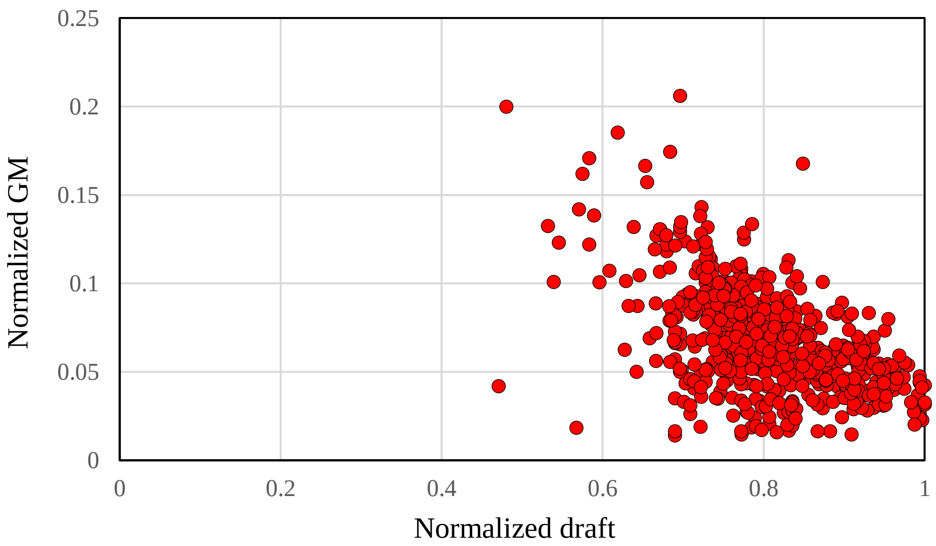


Fig. 3.1.4 Relationship of normalized GM and normalized draft

3.2 Exceedance Probability of Measured Data

Figs. 3.2.1, 3.2.2 and 3.2.3 show the exceedance probability of the measured data for the roll angle, pitch angle and pitch angle acceleration, respectively. Since data are only available for about 10 years, it is difficult to consider these data are adequate. Nevertheless, if the data are extrapolated, it can be thought that the values would be smaller than the maximum value (so-called 10^{-8} equivalent value) for ship motion in the North Atlantic Ocean over the expected lifetime (25 years) of a ship.

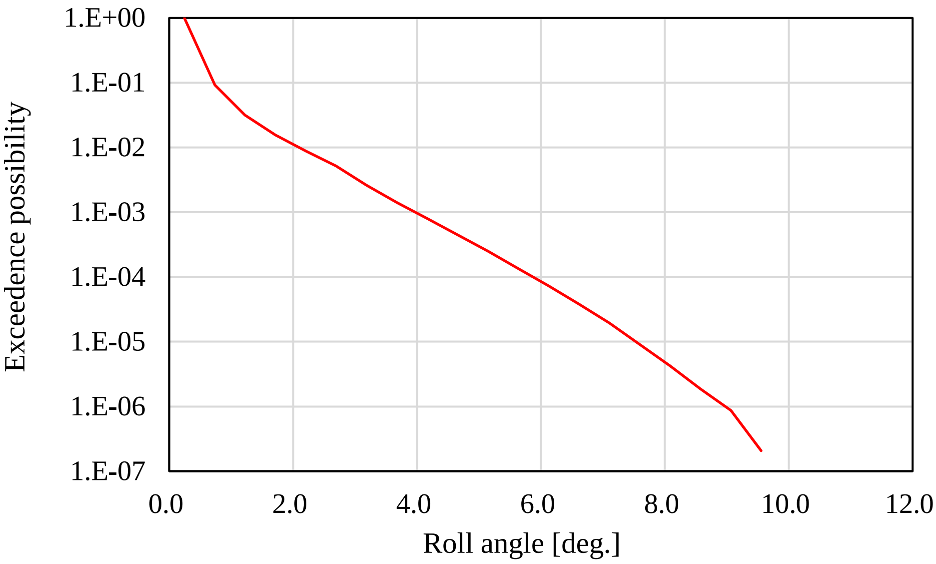


Fig. 3.2.1 Exceedance probability of roll angle

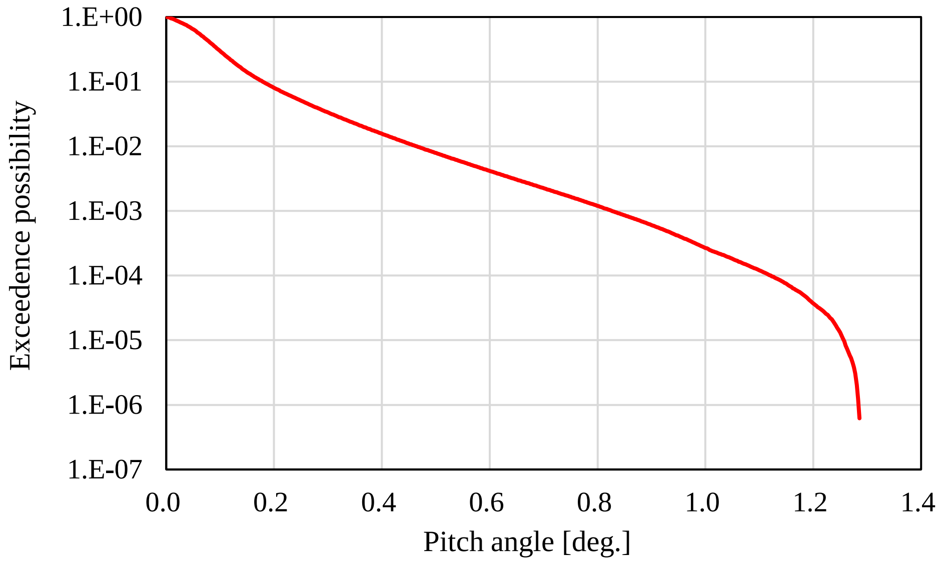


Fig. 3.2.2 Exceedance probability of pitch angle

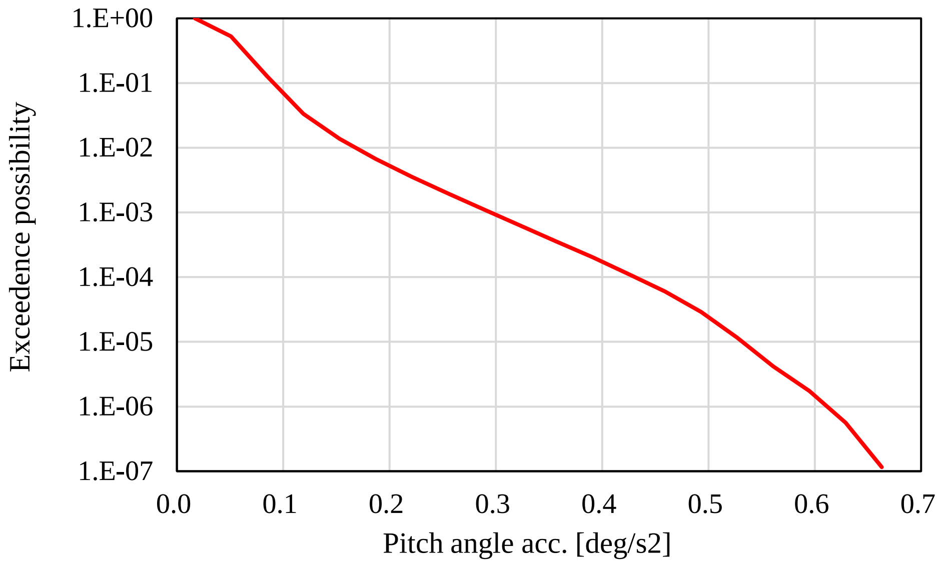


Fig. 3.2.3 Exceedance probability of pitch angle acceleration

3.3 Comparison of Measured Value and Predicted Maximum Value of Hull Motion

3.3.1 Method of Evaluating Predicted Maximum Value of Hull Motion

To determine whether the long-term prediction-based approach gives a conservative (i.e., safe) evaluation of hull motion, the predicted load for each voyage was evaluated by calculating the load correction factors corresponding to the sea area and month of each voyage by the method described in section 2.2, and multiplying the maximum predicted value of hull motion for the case equivalent to unrestricted service by the calculated load correction factor (Eq. 3.3.1). This maximum predicted value of hull motion is generally used as the predicted load in assessments of ship structural strength and cargo lashing strength.

$$X_{LC} = \frac{X_{i,j}}{X_{NA25}} X_{NewC} \qquad 3.3.1$$

Here, X_{LC} is the predicted load after load correction, X_{NA25} is predicted long-term value for 25 years in the North Atlantic considering the ship operational effect coefficient, $X_{i,j}$ is the 25-year long-term predicted value targeted at a certain route and certain month considering avoidance of rough weather and X_{NewC} is the load in unrestricted service (including operational effect, nonlinear effect) specified in ClassNK's Rules for the Survey and Construction of Steel Ships Part C (2023). For the load correction factors found here, the same factors can be found from WACDAS, which was released this year by ClassNK. Furthermore, the motion RAOs necessary in calculating long-term predictions were calculated based on Matsui (2021). Here, however, 0.65 is given as the lower limit of the load correction factor $X_{i,j}/X_{NA25}$, based on the ClassNK Guidelines for Container Stowage and Lashing Arrangements (Edition 3.2). Similarly, GM is also set so as not to be less than the minimum value of GM ($[0.002 - 10^{-5}(B - 40)]B^2$).

3.3.2 Results of Comparison of Measured Hull Response and Predicted Hull Response

The measured hull response for each voyage was compared with the hull response obtained by the assessment method in section 3.3.1. Fig. 3.3.1 shows regarding roll angles. In all cases, the prediction method gave a conservative assessment, as the predicted values were larger than the actual measured values. Although the predicted roll angles shown on the *x*-axis are clustered around 10°, this is due to the use of the minimum correction factor value of 0.65, as mentioned in section 3.3.1. Figs. 3.3.2 and 3.3.3 also show the comparison of the measured values and predicted values for the pitch angle and the pitch angle acceleration, respectively. The measured pitch angle is less than 3° for all voyages and has some margin in comparison with the predicted value. On the other hand, the pitch angle acceleration is relatively close to the predicted value in some cases. This result is attributed to the fact that the pitch angle acceleration has a shorter synchronous period than the pitch angle.

However, as can be seen in Fig. 3.3.1, among the roll angles, roll angles of approximately 10° can be seen in the measured values, and although the measured values are slightly smaller than the predicted values, both are almost in agreement. Since such relatively large roll angles could be seen, the actual-ship measured data for the roll angle were investigated in detail.

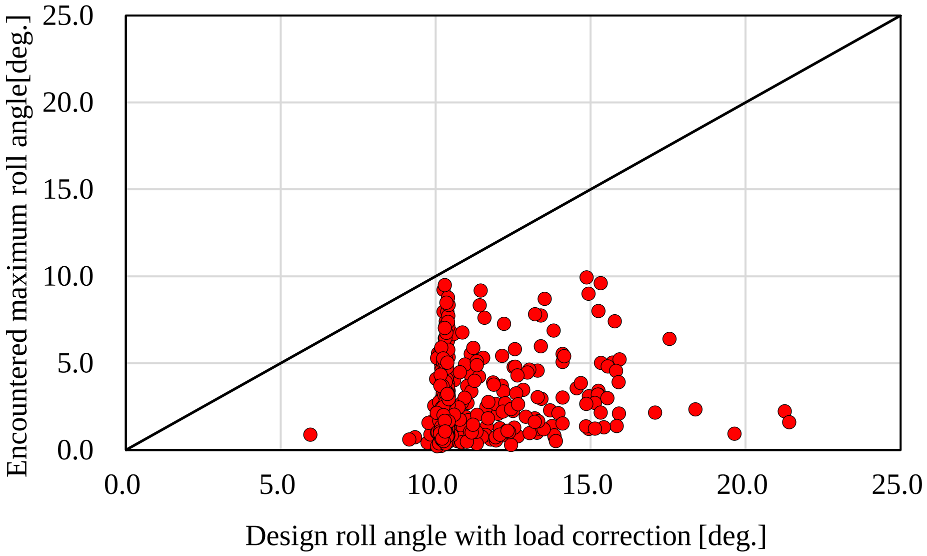


Fig. 3.3.1 Comparison of predicted values and measured values of roll angle

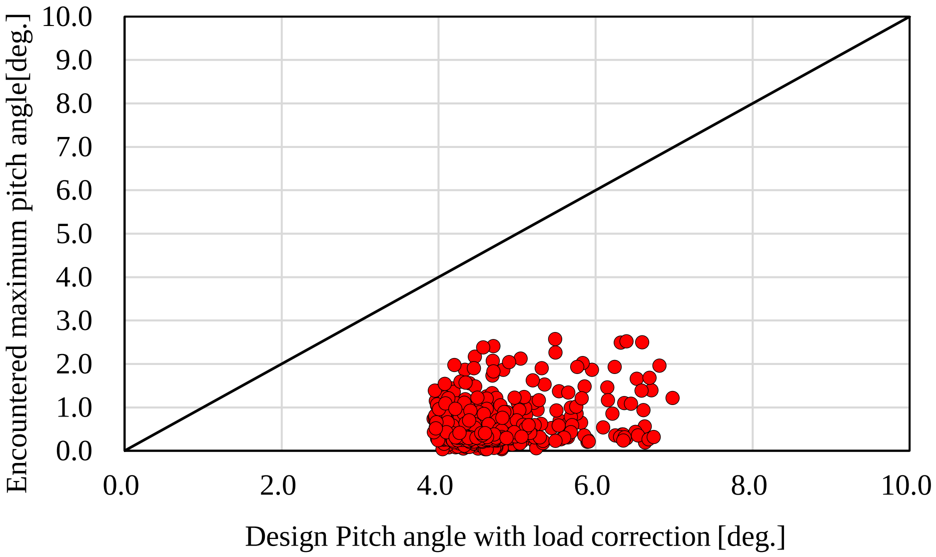


Fig. 3.3.2 Comparison of predicted values and measured values of pitch angle

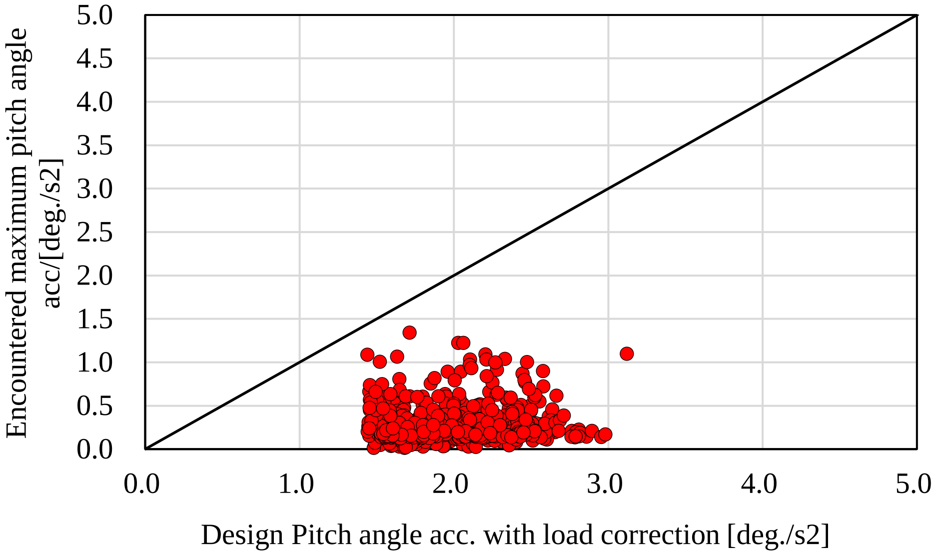


Fig. 3.3.3 Comparison of predicted values and measured values of pitch angle acceleration

3.3.3 Relationship of Hull Response and Sea State and Stacking Parameters

Since the hull response to waves generally shows a correlation with the wave height and the roll angle tends to increase as GM becomes larger, the roll angle was compared with the significant wave height and GM, as shown in Figs. 3.3.4 and 3.3.5, respectively. For comparison, the values of the pitch angle and pitch angle acceleration with respect to the significant wave height are also shown in Figs. 3.3.6 and 3.3.7, respectively. Regarding the relationship between the roll angle and the significant wave height H_S, Fig. 3.3.8 shows the relationship between the roll angle and H_S for each GM. According to Figs. 3.3.4, 3.3.6 and 3.3.7, there is clearly a positive correlation between the significant wave height and the roll angle, pitch angle and pitch angle acceleration. In particular, a good positive correlation can be seen between the pitch angle and the significant wave height. On the other hand, although the largest roll angle (voyage No. 104) is seen at a significant wave height of about 6 m, comparatively large roll angles of more than 8° are measured even at significant wave heights of 2 to 3 m. Furthermore, even under a condition where the natural period is long (approximately 26 s to 28 s), namely, when GM is around 0.04 *B*, a roll angle of around 8° can be observed in Fig. 3.3.8, and at the largest roll angle, GM = 0.056 *B* and the natural period is long (approximately 23 s), as expected. At such long natural periods, it is known that waves synchronized with the actual sea state are infrequent. For example, in the wave scatter diagrams in IACS Rec. 34 rev. 1, the upper limit of the mean wave period is 19.5 s.

In explaining why the correlation of the roll angle with the significant wave height is weaker than that of the pitch angle, because the synchronous period of rolling motion is long, and almost no ship motion occurs when a ship encounters short waves, even when the wave height is large.

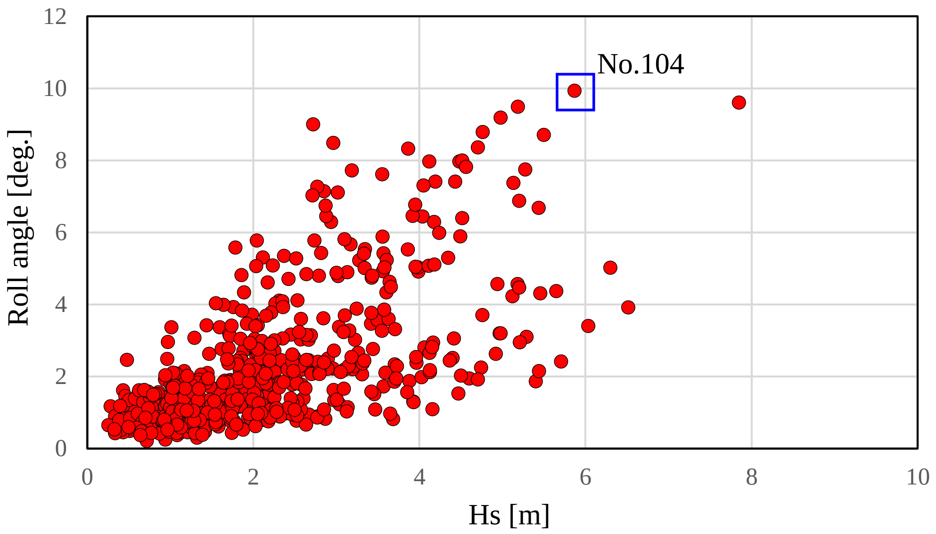


Fig. 3.3.4 Relationship of roll angle and significant wave height H_S

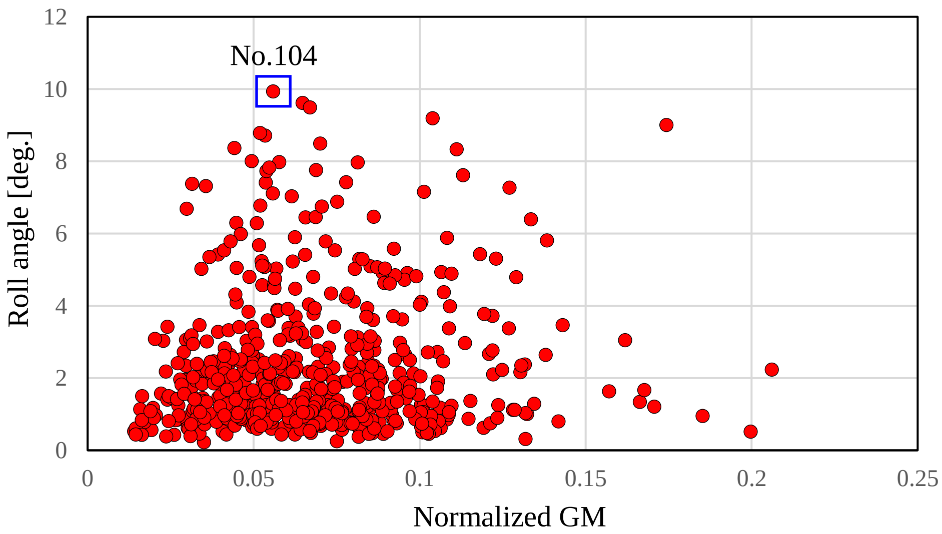


Fig. 3.3.5 Relationship of roll angle and normalized GM

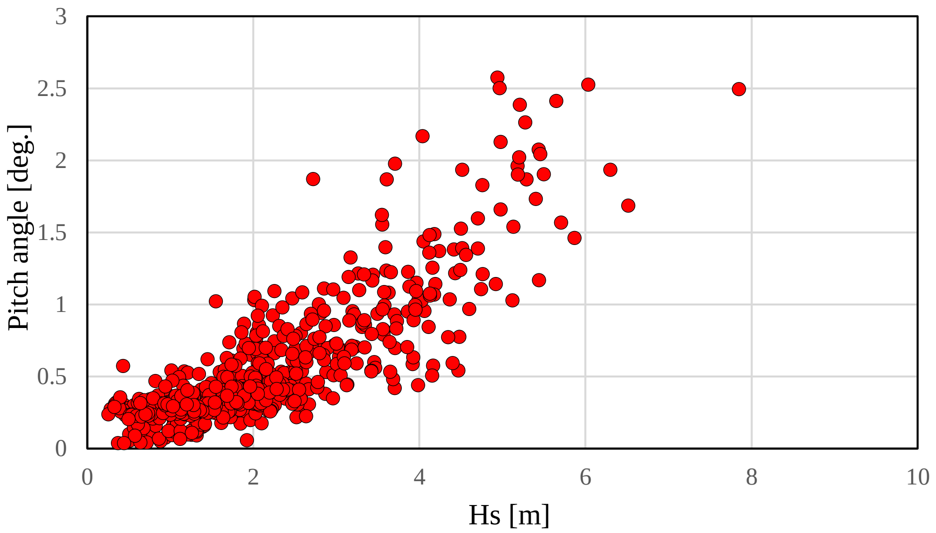


Fig. 3.3.6 Relationship of pitch angle and significant wave height H_S

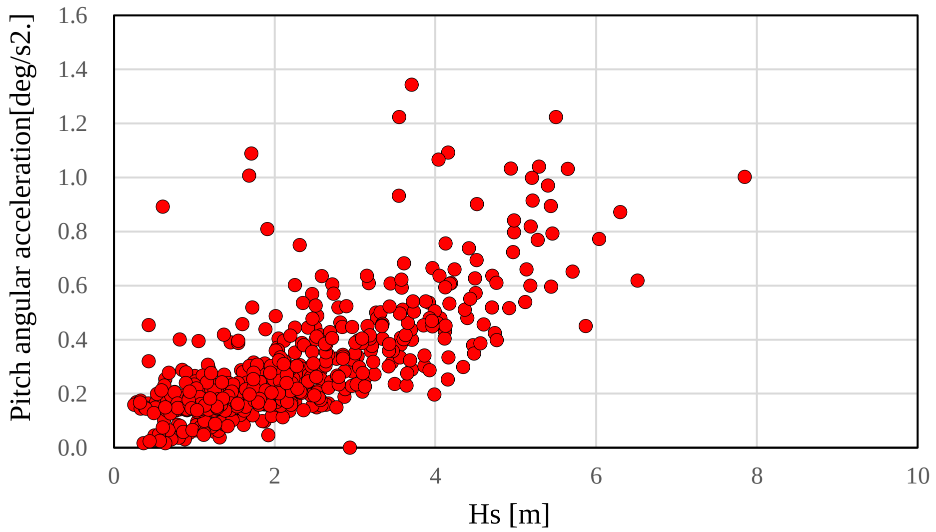
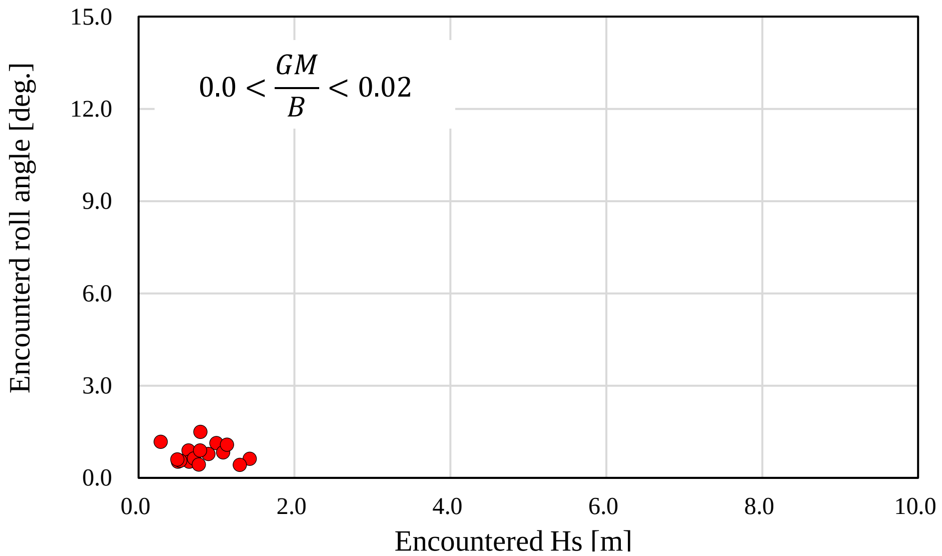
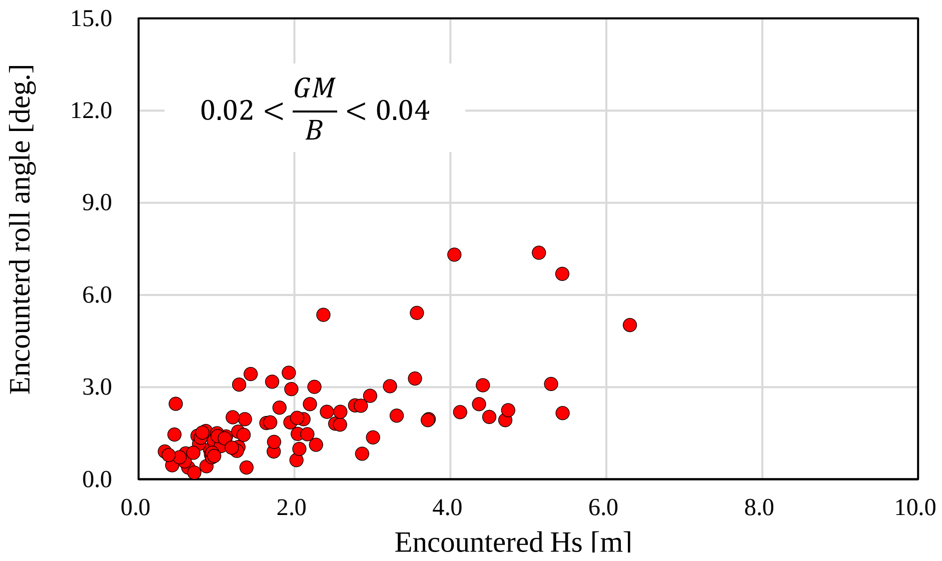
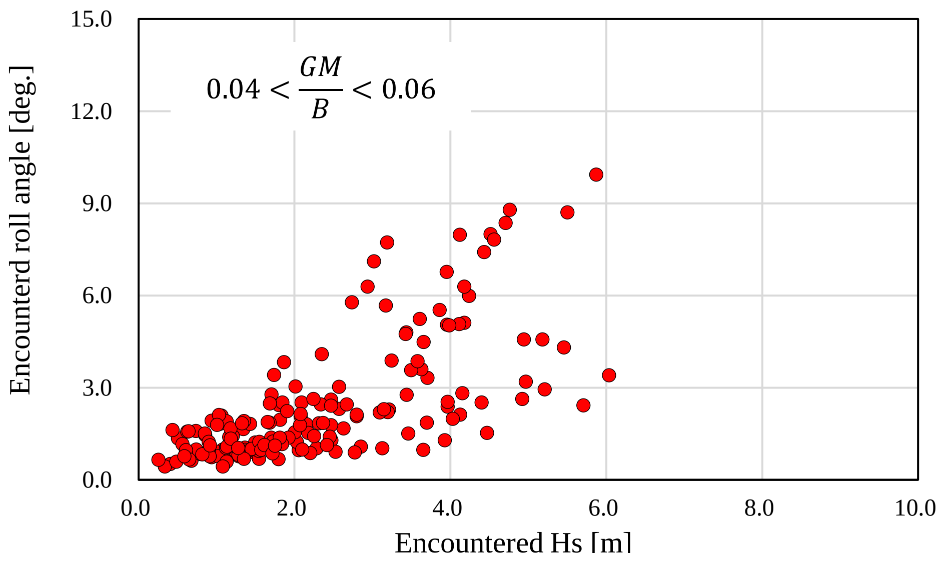


Fig. 3.3.7 Relationship of pitch angle acceleration and significant wave height H_S

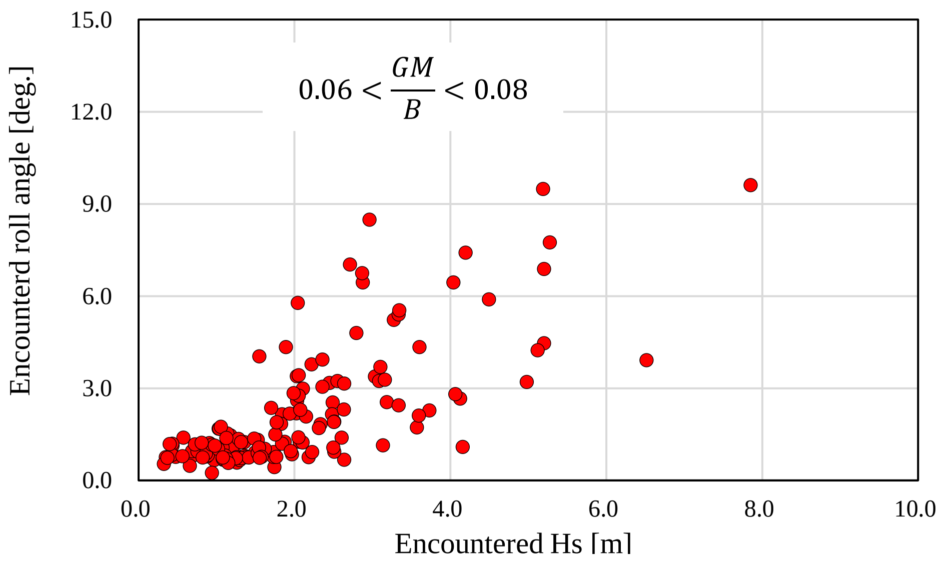




$0.02 < \frac{GM}{B} < 0.04$
Encounterd roll angle [deg.]
Encountered Hs [m]
0.0
3.0
6.0
9.0
12.0
15.0
0.0
2.0
4.0
6.0
8.0
10.0



$0.04 < \frac{GM}{B} < 0.06$
Encounterd roll angle [deg.]
Encountered Hs [m]
0.0
3.0
6.0
9.0
12.0
15.0
0.0
2.0
4.0
6.0
8.0
10.0



$0.06 < \frac{GM}{B} < 0.08$
Encounterd roll angle [deg.]
Encountered Hs [m]
0.0
3.0
6.0
9.0
12.0
15.0
0.0
2.0
4.0
6.0
8.0
10.0

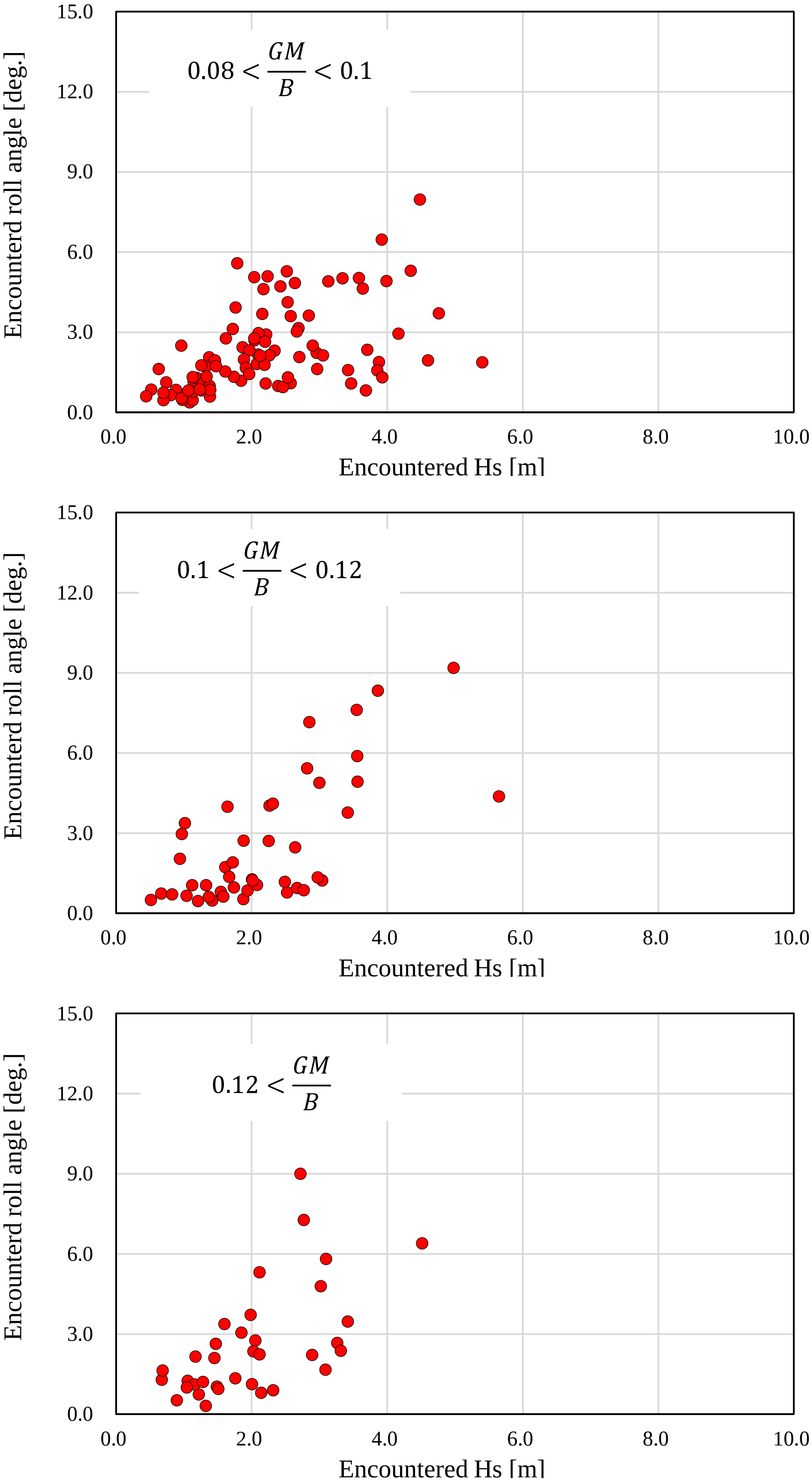


Fig. 3.3.8 Relationship of roll angle and encountered significant wave height H_S for various GM

Therefore, a study was carried out focusing on cases where the roll angle was comparatively large, while the significant wave height was small or GM was small. Table 3.3.1 shows the information on the voyages that were the target of this investigation. Parametric roll is a conceivable cause of the relatively large rolling that occurs under these conditions, i.e., a small significant wave height (small external force) or small GM (long natural period). It is known that the ratio of the roll period and the pitch period ratio when parametric roll occurs is 2 : 1. Therefore, the roll period and pitch period were obtained by the zero up-crossing method from the time-series data for the 300 s period from initiation of rolling until the occurrence of the maximum roll angle. As an example, Fig 3.3.9 shows the time-series data of the pitch and roll angles acquired on Voyage No. 120. Fig. 3.3.10 shows the result of averaging the roll period and pitch period for each voyage. For Voyage No. 396, the ratio of the average roll period and average pitch period is 1 : 1, and the relative heading (wave direction) at this time was 28°. Although the conditions are not completely identical, according to the results of past tank tests and the calculated roll angle RAO, a certain amount of rolling can be seen even at a relative heading of about 30°. Therefore, the estimated cause of rolling in No. 396 is synchronous rolling. It is conjectured that synchronous rolling also occurred on Voyage No. 386, even in a near beam sea, due to combination conditions which are conducive to a long encountered wave period, namely, an oblique following sea and a high ship speed in excess of 17 knots. On the other hand, the cause of rolling in the case of Voyage No. 492 is not necessarily clear, as the heading was 13°, and it can be inferred that the roll angle RAO was small.

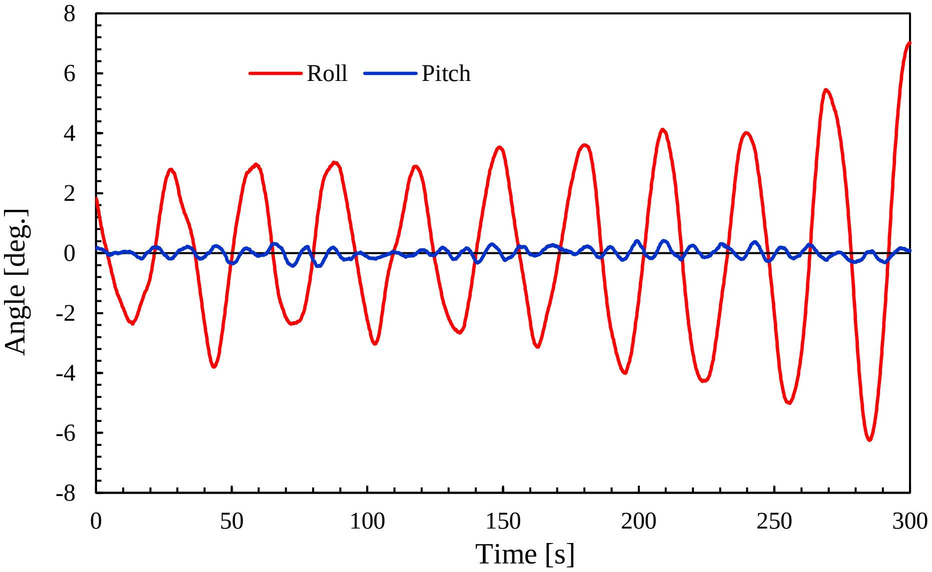


Fig. 3.3.9 Time-series data of roll and pitch

Table 3.3.1 Data of voyages with large roll angles in spite of small GM

Voyage No.	Roll angle [deg.]	H_s [m]	Normalized GM	Heading* [deg.]	Ratio of period
104	9.93	5.87	0.056	-8.55	1.68
120	6.68	5.44	0.030	-48.75	2.71
179	7.31	4.05	0.036	49.93	1.52
386	8.71	5.50	0.053	75.10	1.23
396	8.36	4.71	0.044	27.86	1.07
474	7.37	5.13	0.031	6.12	1.66
492	8.78	4.76	0.052	-13.00	1.20
554	7.82	4.56	0.055	-48.30	1.41

*Heading 0°: following sea

Therefore, in order to examine the possibility that parametric rolling occurred, polar charts[1] were prepared based on Grim's effective wave theory, targeting for containerships with similar sizes, for the case of a significant wave height of 4 m, natural roll period of 28 s and a following sea (wave direction: 0°). The ship speed was set at 0 knots. The results are shown in Fig. 3.3.11, where the ratio of the peak natural roll period Tp to the synchronous period is shown on the abscissa and the roll angle on the polar chart is shown on the ordinate. The value of 2.0 on the abscissa can be regarded as an approximate representation of the ratio of 2 : 1 of the roll period and pitch period. As a result, based on the fact that the initial roll angle is set at 5°, these results confirm that a roll response caused by parametric roll occurred over a comparatively wide range of period ratios. According to Fig. 3.3.11, it is thought that cases No. 104 and No. 474 can also be regarded as parametric rolling, and the possibility that parametric rolling also occurred under the other conditions cannot be denied. However, since these are only the results of a simple estimation, a study that also considers the wave direction is essentially needed.

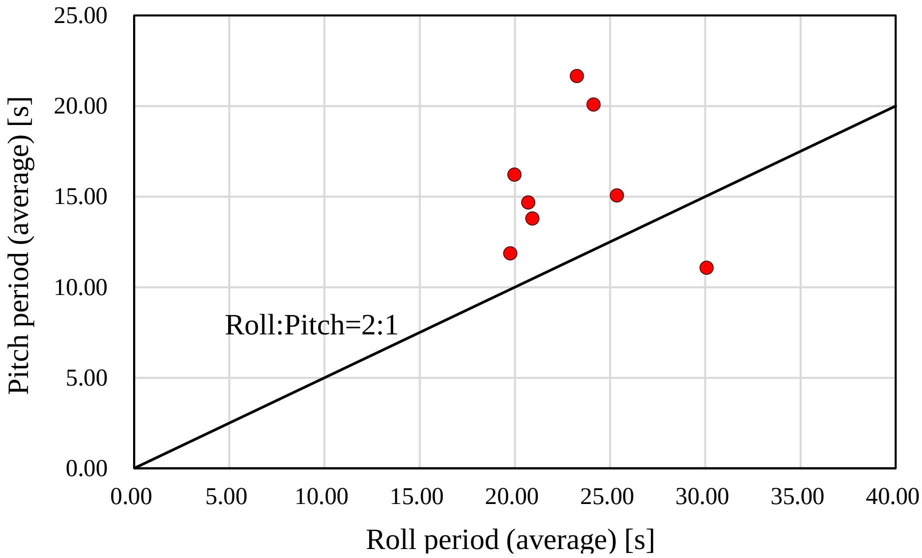


Fig. 3.3.10 Comparison of pitch period and roll period

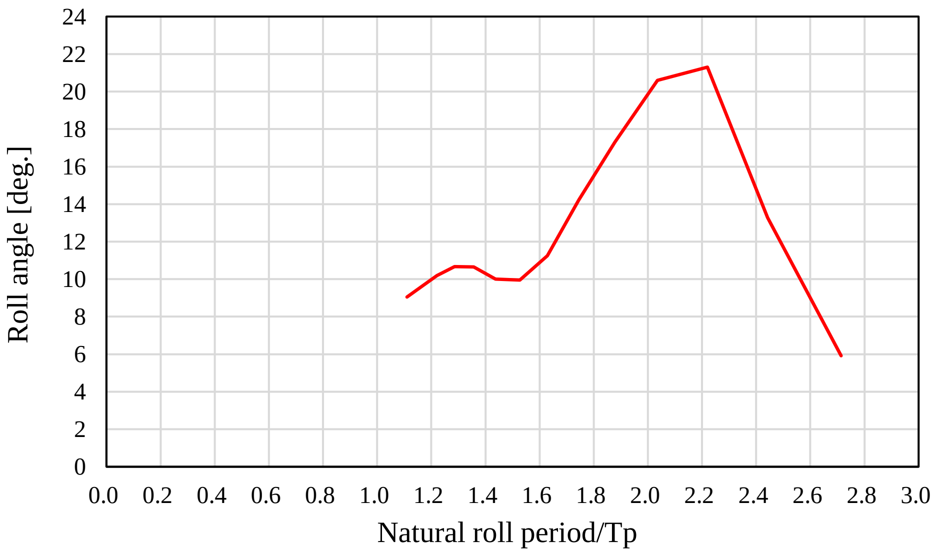


Fig. 3.3.11 Roll angle in polar chart

[1] "Polar chart" indicates a diagram in which the roll angle caused by parametric roll is plotted in the circumferential direction. For the detailed method of preparing polar charts, see Takeda et al. (2024).

3.4 Setting of the Lower Limit Value of Predictions

As mentioned above, the lower limit value of the load correction factor, 0.65, was applied in the comparison of the predicted values and measured values in section 3.3.2. As shown in Fig 3.4.1, if a lower limit value is not provided, there are cases where the predicted value is underestimated in comparison with the encountered values in regions where the roll angle is small. As the estimated cause of this problem, the predicted hull response which is equivalent to the 25-year maximum value in the North Atlantic Ocean assuming unrestricted service includes the effects of avoidance of rough weather and nonlinear effects (which are particularly conspicuous in rolling). In the first place, in waters where sea states with high wave heights do not occur, avoidance of rough weather should not be considered in long-term predicted values using wave scatter diagrams. In addition, although it is known that the nonlinearity of rolling depends on the wave height, it is difficult to assess nonlinear effects in actual waters and actual ships, and it is also difficult to determine those effects accurately by tank tests or numerical calculations. Moreover, as seen in section 3.3, hull motion with a possibility of light parametric rolling was observed several times during the measurement period alone. Considering these facts, setting a load correction factor of 0.65 as the minimum roll angle appears to be a meaningful way of dealing with these uncertainties.

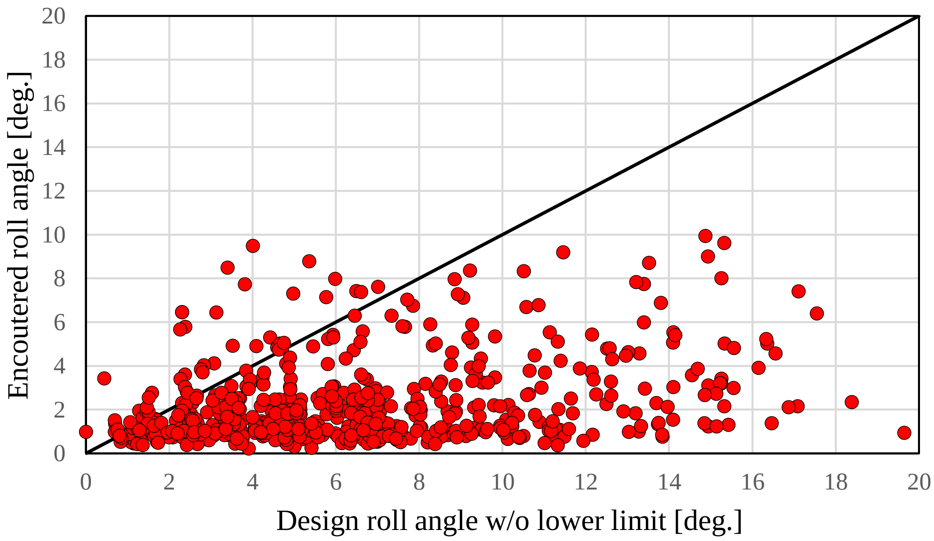


Fig. 3.4.1 Comparison of encountered roll angle and predicted roll angle without lower limit value

4. Comparison with Other Ships

The data analyzed in Chapter 3 are invaluable in that they are time-series data, in other words, data that make it possible to estimate the natural period of rolling. However, the timeframe of the data is limited, only covering a total of about 10 years. Therefore, we examined the possibility of obtaining suggestions of some kind by analyzing the sea states encountered by other ships from wave hindcast data and AIS data, even though these are not motion data. As the target ships, we selected 24 containerships of similar sizes, which are expected to display roughly similar motion in specified sea states, and obtained the encountered significant wave heights of these vessels. (Although the target ships include some for which motion data exist, there are also some periods when the motion data were not recorded.) The target period of the analysis was 30 940 days, representing approximately 85 years. Fig. 4.1 shows a comparison of the encountered significant wave heights H_S. While the vessels with motion data displayed a tendency to navigate in relatively calm sea states, it may be said that the maximum encountered significant wave heights were similar.

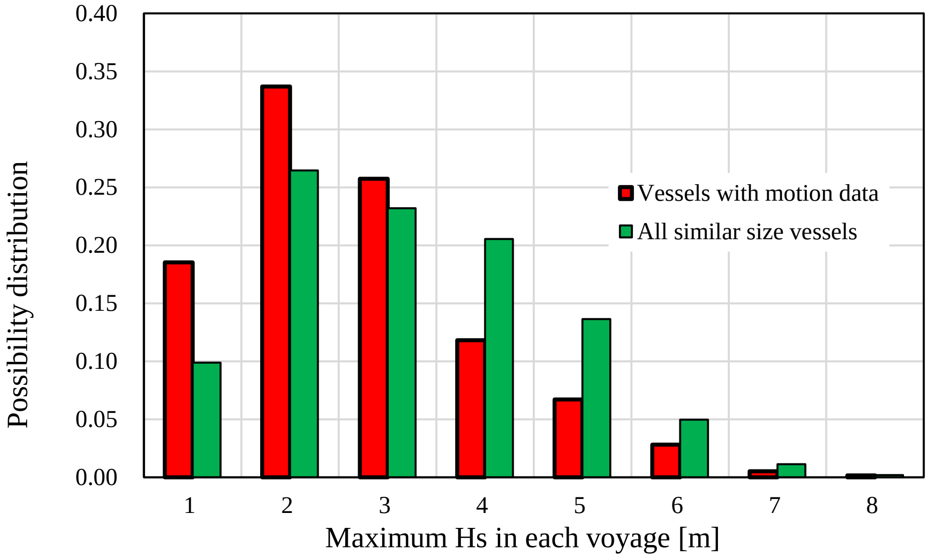


Fig 4.1 Comparison of encountered significant wave heights H_s

On the other hand, the predicted roll angles considering the route and month were found for the vessels without motion data by using the method described in Chapter 2. The results are shown in Fig. 4.2. Since it was not possible to estimate GM, the minimum GM values in the Class NK Guidelines for Container Stowage and Lashing Arrangements (Edition 3.2) are applied in all conditions, and for other unknown parameters, the same values as those of ships with motion data are used. However, when a ship's draft is shallow, it is assumed that the GM will be larger than the smallest GM. Therefore, a normalized draft of 0.7 or larger is used, referring to Fig. 3.1.4. In all cases, the predicted load (roll angle) is 10° or more, and it can be understood that this exceeds the maximum encountered roll angle estimated from the actual ship measurement data and the encountered significant wave height.

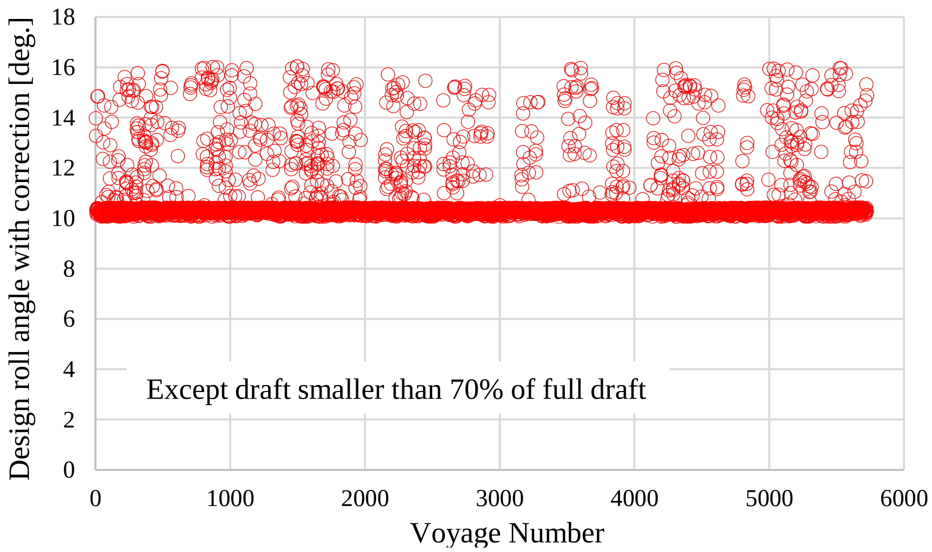


Fig. 4.2 Predicted maximum value of hull motion (roll angle) for each voyage of vessels without motion data

5. Conclusion

Among the actual-ship measured data for multiple mega containerships, the types of motion that occur in large-scale containerships were analyzed, focusing on the roll angle, pitch angle and pitch angle acceleration, which are related to the container lashing problem. The target ships mainly sailed on the Pacific Ocean route and the Asia-Europe route, and the average voyage duration was approximately 6 days. The information and discussion obtained through this analysis are summarized below.

• When the exceedance probability of the measured motions was calculated, the extrapolated 10^{-8} equivalent value was estimated to be smaller than the North Atlantic Ocean 25-year maximum value in all cases.

• In all cases, the measured data for the roll angle, pitch angle and pitch angle acceleration did not exceed the predicted maximum values of hull motion (i.e., predicted loads) considering the wave scatter diagrams of actually-encountered waves corresponding to the route and month. All measured values showed a rough positive correlation with the significant wave height, but the coefficient of correlation was smallest for the roll angle and largest for the pitch angle.

• Focusing on the roll motion, which is directly connected to the container lashing problem, cases in which comparatively large roll angles (7° to 10°) occurred even when GM was small were analyzed. When the zero up-crossing period of the roll and pitch motions was evaluated for the 300 seconds immediately before the largest roll angle occurred, multiple cases that were suspected to involve parametric roll were found.

• Although there are large uncertainties regarding parametric roll and GM, particularly in the case of roll motion, it can be thought that setting an appropriate lower limit value will give a conservative (safe) predicted load.

• Figs. 5.1 and 5.2 show the probability distribution and the cumulative probability distribution, respectively, of the ratio of the predicted value of the encountered roll angle and the maximum actual encountered roll angle. Regardless of whether a load correction factor is applied or not, basically, there are many cases where the encountered roll angle is extremely small in comparison with the predicted roll angle; in other words, there is a margin in the strength capacity of the container stacks. If it is deemed necessary to use this capacity to increasing the stacking height of container stacks, effective utilization of capacity can be increased by using the load correction factor.

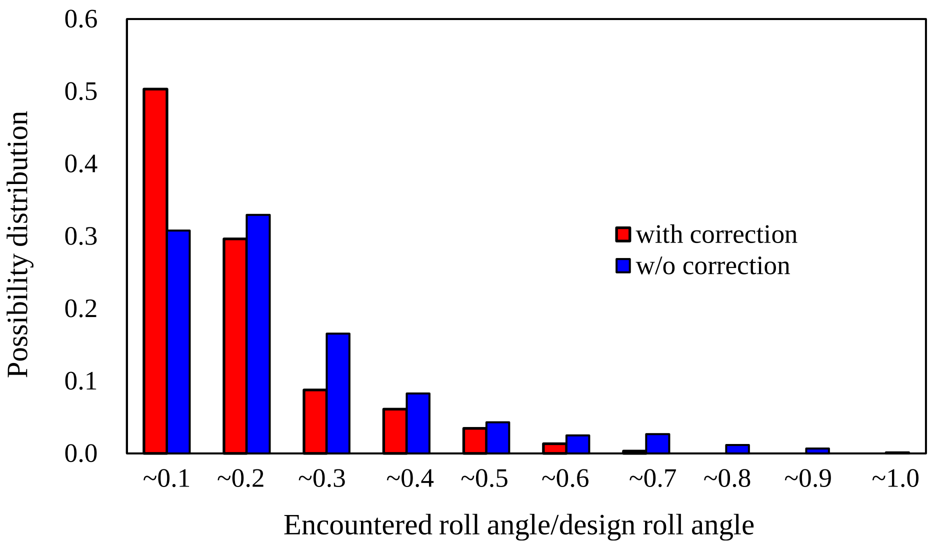


Fig. 5.1 Probability distribution of actual encountered roll angle and predicted maximum encountered roll angle with/without application of a load correction factor

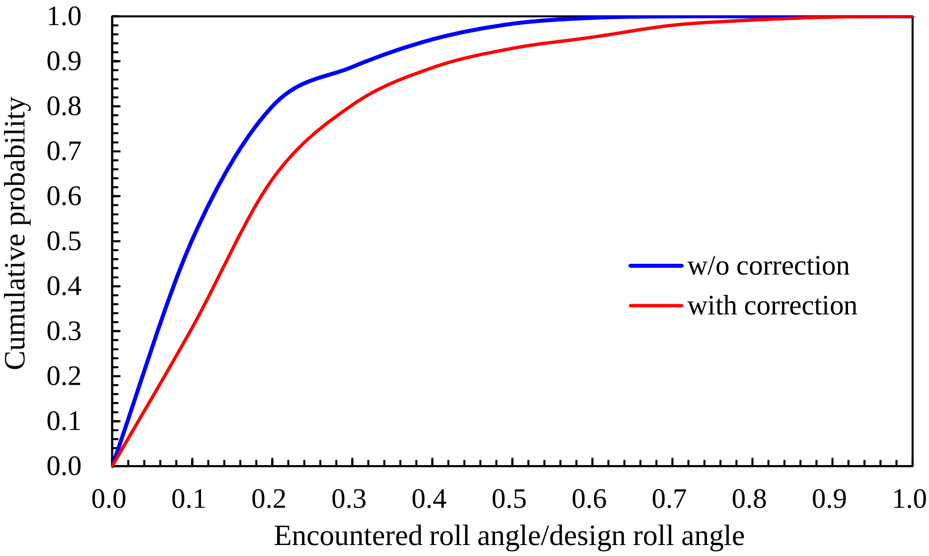


Fig. 5.2 Cumulative probability distribution of actual encountered roll angle and predicted roll angle with/without application of a load correction factor

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