Chapter 8
Experience from Parametric Rolling of Ships

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8.1 Introduction

Parametric rolling of merchant ships are rare events but probably less rare than most shipping companies and officers consider them to be. The cases with large amplitude rolling that result in shift of cargo or other critical consequences are of course noted. Many of these incidents have, however, due to lack of detailed records and understanding, been categorized as "normal" heavy weather damage even though they have developed due to parametric excitation. The vast majority of less critical parametric rolling events are probably not even noted and most certainly not documented.

Historically, ship safety standards have developed as reactions on serious casualties. Famous examples are the loss of Titanic which initiated the development of the SOLAS convention, and the loss of Estonia which forced numerous amendments to the convention. In a similar manner, parametric rolling incidents with a container vessel reported in [6] and with a Ro–Ro Pure Car and Truck Carrier (PCTC) reported in [13] have influenced the ongoing process of development of new intact stability standards, e.g., [14, 15].

Many initiatives at IMO nowadays aim at turning from the traditional reactive development of regulations toward a more proactive regime for the future. In order

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to be able to identify potential hazards before they develop into large-scale losses, it is of utmost importance to analyze also incidents and near critical events that are far more common than the recognized accidents.

From the early works by Grim [8] until the present day, a large number of studies on parametric rolling based on analytical and numerical models and model scale experiments have been published. The availability of data from real full-scale events is, however, very scarce. This chapter reviews three recent full-scale events with parametric rolling. The objective is to make the experiences from these events available to the research community and in light of these events discuss on-board operational guidance for assisting crews in avoiding parametric rolling.

8.2 Parametric Rolling of Ships

The primary mechanism in parametric rolling of ships is the time variation of the restoring moment created by the varying relation between the geometry of the ship hull and the wave surface as the ship travels through the waves. The prerequisites for parametric rolling to develop can be summarized as follows:

1. Sufficiently large relative variation of stability is generated when the ship travels through waves. This in turn requires a combination of:
    (a) flared hull form with large beam/draft ratio,
    (b) sufficiently high waves, and
    (c) relatively low average stability ($\overline{\mathrm{GM}}_0$).
2. Resonance, meaning
    (a) encounter period about half of (or equal to) the roll natural period, and
    (b) resonance condition according to 2(a) being kept for a sufficient number of wave encountering cycles (regularity).
3. Sufficiently low roll damping.

Passenger cruise ships and fishing vessels are examples of ship types that might experience stability variations that can be critical regarding parametric roll excitation, e.g., [3, 20]. Also, ships optimized for large volumes of low weight cargo, such as Lo–Lo container vessels and Ro–Ro ships, can experience very large stability variations and therewith related sensitivity to parametric roll excitation, e.g., [6, 13]. At the far end on this scale are modern Ro–Ro PCTCs. The standard ocean going PCTC with a length of about 200 m and panamax breadth has developed from a rather traditional hull form of the 1970s into today's highly stability optimized hull form which is able to carry significantly more cars by increased cargo hold height.

During the last decade, a new class of larger car and truck carriers (LCTC) with 230 m length and a capacity of about 8,000 cars have been introduced. An example of such a vessel is given in Fig. 8.1, typical main particulars are given in Table 8.1, and typical stability variations in regular waves are exemplified in Fig. 8.2.

Fig. 8.1 A modern LCTC

Table 8.1 Main particulars for a typical LCTC

Length over all	227.8	m
Beam, moulded	32.26	m
Height to upper deck	34.7	m
Draft, design/max	9.5/11.3	m
Deadweight at max draft	30,137	t
Number of car decks	13	–

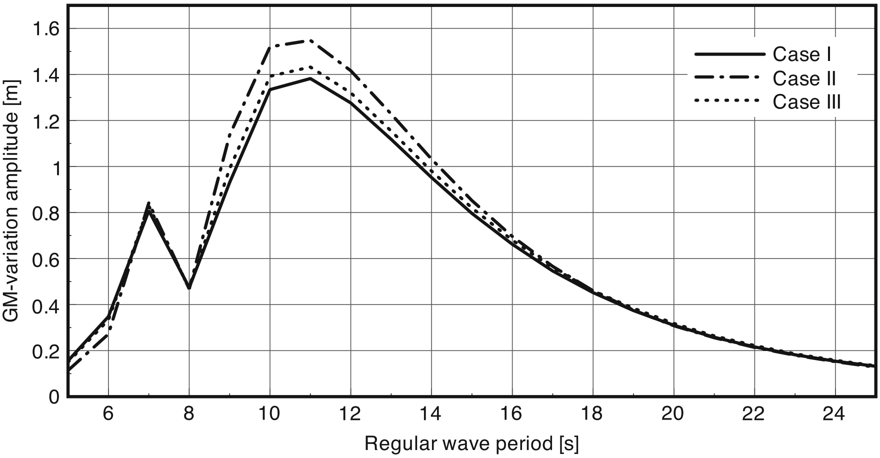

Fig. 8.2 Quasi-static stability variation in regular head/following waves with a wave height of 4 m for the three presented cases

8.3 Service Experience

As a forerunner in the development of modern PCTCs and LCTCs, the Swedish shipping company Wallenius had an early awareness of the potential problems with stability variations in waves for this type of ship. Early in the 1990s, the company supported the research project at the KTH Royal Institute of Technology in Stockholm [11] which eventually resulted in the advanced Seaware EnRoute Live onboard decision support system for seakeeping. Wallenius was then the first shipping company to make the Seaware EnRoute Live system a standard within its fleet. The cooperation with Seaware has extended to include also follow-up analysis of incidents and proactive analysis of dynamic stability properties of new ships at the design stage. In 2004, Wallenius and Seaware prepared a common report of a head sea parametric roll incident that was submitted by Sweden to the IMO SLF subcommittee [13]. The report describes probably the first time ever when full 6-DOF motions have been recorded from an actual parametric rolling event in irregular seas. In 2009, Wallenius, Seaware, and KTH joined a cooperative research program to further develop knowledge and tools in this area.

In addition to making the technical decision support system a standard on board the ships, Wallenius has also at various occasions informed their ship officers about underlying causes of parametric rolling, the specific character of the ships, and recommended actions to avoid critical situations. The shared knowledge and understanding has most likely prevented a number of critical situations but has also made it possible to identify situations where parametric roll actually occurred and enabled collection of important data for further analysis. We will here discuss three such events that represent three principally different modes of parametric rolling:

Case I: Principal parametric resonance where the period of encounter is half of the roll natural period in following seas
Case II: Principal parametric resonance where the period of encounter is half of the roll natural period in head seas
Case III: Fundamental parametric resonance where the period of encounter coincides with the roll natural period in following seas

The events have occurred within the last two years and with the same ship design but with two different ship individuals.

8.3.1 Case I – Principal 2:1 Parametric Resonance in Following Seas

In this case, the ship had been idling for some hours in head sea at about 5 knots outside a port that was closed due to bad weather. Some 20 min after the ship had slowly turned back and increased speed to about 10 knots, a sudden heavy rolling developed. Time series of roll, pitch, speed, and heading are given in Fig. 8.3. As seen the rolling developed very fast, in the first sequence from moderate 2–4° up to 20° in just four roll cycles. In the second sequence, a rolling amplitude of 30° was reached. A clear 2:1 relation between the roll and pitch periods can be observed during the critical sequences. The rolling was stopped by the Master changing over to hand steering and turning the vessel back toward the waves.

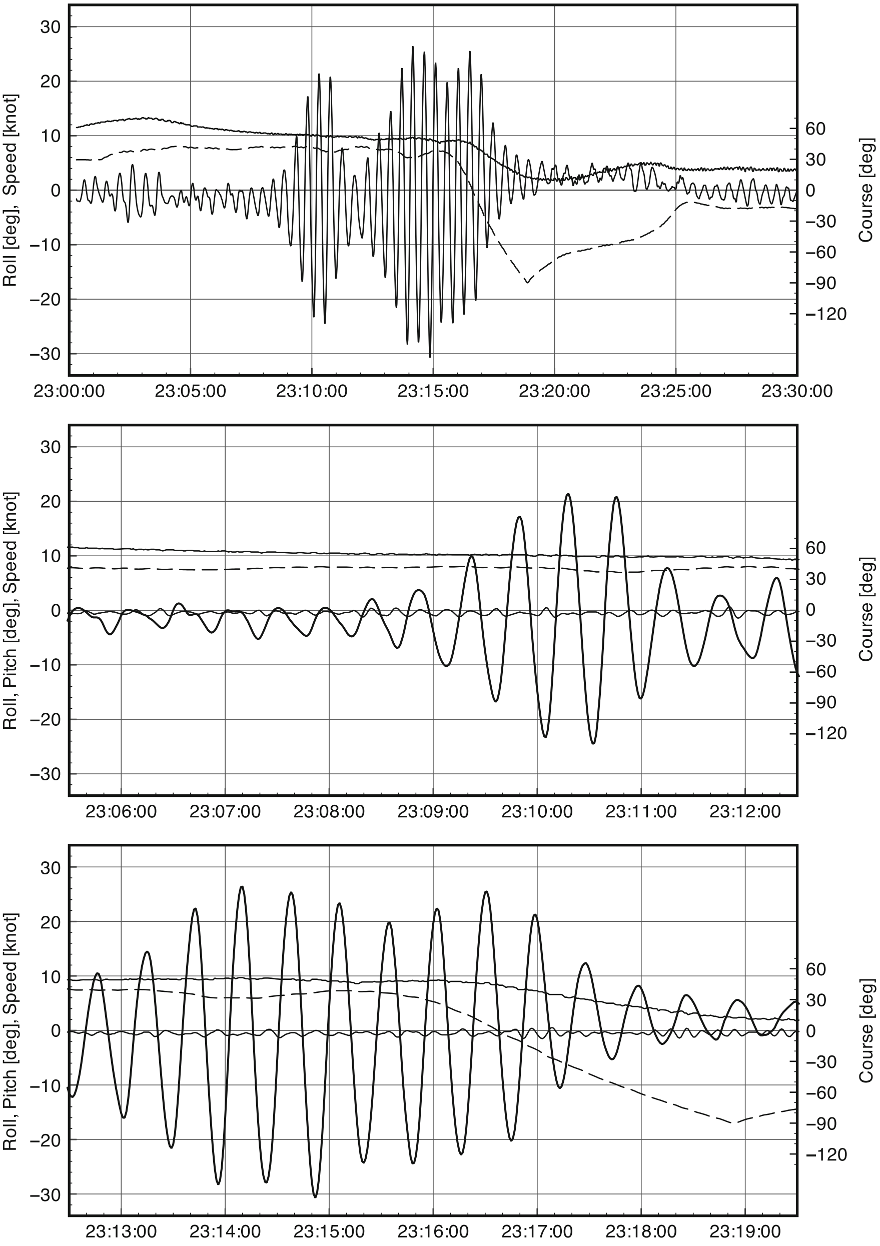

Fig. 8.3 Recorded data for Case I

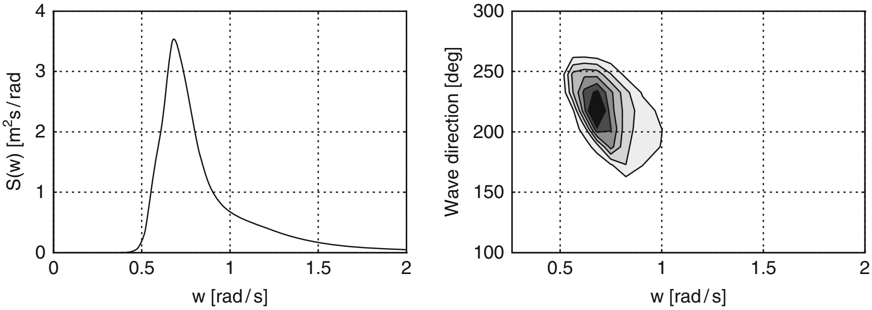

Fig. 8.4 Unidirectional (*left*) and directional (*right*) reanalysis wave spectrum for the area in question 3 h before the incident. (ECMWF Mediterranean Wave Analysis)

Table 8.2 Wave spectral parameters from re-analysis data for three hours before and after the event

Time [h]	H_s [m]	T_p [s]	T_z [s]
−3	4.3	9.2	6.9
+3	3.8	9.2	7.0

Table 8.3 Conditions summary for Case I

$\overline{GM}_0$ [m]	T_0 [s]	H_s [m]	T_p [s]	λ_p/L [-]	V [kn]	β [deg]	T_{Ep} [s]	T_0/T_{Ep} [-]
1.2	28	4.1	9.2	0.55	10	0	14.3	1.95

With the purpose of establishing as good as possible depiction of the sea state at the time and position of interest, re-analysis wave data in terms of directional wave spectra for a 0.5×0.5 degree grid has been obtained from ECMWF. This data covers from three hours before to three hours after the incident. The wave spectra consisted mainly of wind waves with limited directional spread and a narrow frequency peak. The wind data from the same re-analysis data source was concluded to be in compliance with the on-board wind observations. The directional and the corresponding unidirectional wave spectra assembled from the ECMWF data three hours before the incident are displayed in Fig. 8.4.

The wave spectrum parameters calculated from the available spectra 3 h before and after the incident displayed in Table 8.2 indicates that the sea state was rather stationary. Through interpolation, the significant wave height and the spectrum peak period at the incident are determined to 4.1 m and 9.2 s, respectively.

Table 8.3 presents a summary of characteristic parameters for this case. The ship was loaded close to its design draft and had a $\overline{GM}$ of 1.2 m. The sea state parameters are here based on the reanalysis of the wave spectra discussed above and the assumption that the average period within high amplitude wave groups tends to approach the peak period. The characteristic wave length λ_p and the encounter period T_{Ep} are here hence determined for a harmonic wave whose period equals the

Table 8.4 Conditions summary for Case II

$\overline{\mathrm{GM}}_0$ [m]	T_0 [s]	H_s [m]	T_z [s]	T_p [s]	λ_p/L [-]	V [kn]	β [deg]	T_{Ep} [s]	T_0/T_{Ep} [-]
2.3	21	5–6	8–9	11–13.5	0.9–1.3	9–14	140–190	8–11.5	1.8–2.6

Table 8.5 Conditions summary for Case III

$\overline{\mathrm{GM}}_0$ [m]	T_0 [s]	H_s [m]	T_p [s]	λ_p/L [-]	V [kn]	β [deg]	T_{Ep} [s]	T_0/T_{Ep} [-]
1.3	23	4.1	10.5	0.8	18–20	20–50	16–26	0.7–1.2

spectral peak period of the irregular sea state (the same comes for Tables 8.4 and 8.5). It should be noted that this gives a simplified picture of the irregular seaway and that conclusions should be drawn with this in mind.

To the officers on board at this occasion, the parametric rolling occurred “out of nowhere” in conditions that were far from being perceived as potentially dangerous. The significant wave height was only about 4 m and, as seen in Fig. 8.3, the motions were very small prior to the onset with practically no pitch and only a few degrees rolling. However, the fact that the ship was idling with reduced speed put her into a 2:1 parametric resonance that she would not encounter for regular service speeds in the same sea state. In addition, the relatively low $\overline{\mathrm{GM}}$, although well above regulatory minimum stability, contributed to the sensitivity.

8.3.2 Case II – Principal 2:1 Parametric Resonance in Head Seas

In the second case, the ship was running in head sea with a speed of about 11 knots on route southward close outside the coast of New South Wales in Australia. During a period of about four hours, the ship encountered clear parametric roll excitation a number of times with amplitudes up to about 20°. Time series of roll, pitch, speed, and heading are given in Fig. 8.5. As for Case I, a clear 2:1 relation between the roll and pitch periods can be observed during the critical sequences. The pitch amplitude is here however significantly larger due to the head sea condition.

For this case, wave data are available from the nearby Eden wave buoy, managed and operated by the Manly Hydraulics Laboratory, Sydney. This buoy is a nondirectional Waverider type buoy manufactured by the Dutch company Datawell BV. In Fig. 8.6, the position of the buoy is shown on a map (marked by triangle), along with the sailed track and positions where parametric rolling occurred (marked by dots). The distance between the buoy and the position of the last parametric rolling event, closest to the buoy, is about 9 nautical miles. Measured wave spectra from the Eden wave buoy, and corresponding spectral parameters, are given in Figs. 8.7 and 8.8.

The conditions for this case, in terms of characteristic parameters, are summarized in Table 8.4.

The ship was in light loaded condition and had a $\overline{\mathrm{GM}}$ of about 2.3 m. Sea state and operational parameters are here given in terms of intervals to reflect the fact that

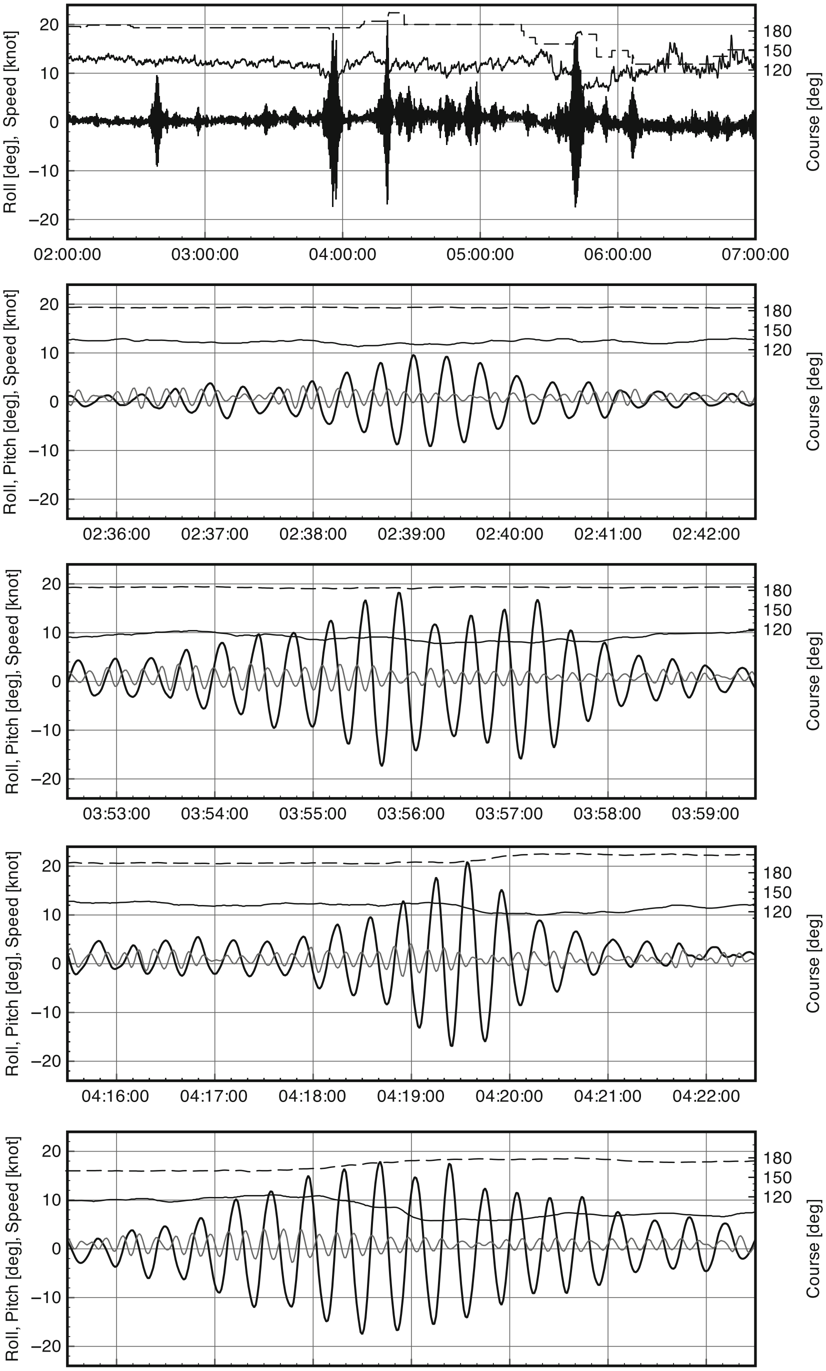

Fig. 8.5 Recorded data for Case II

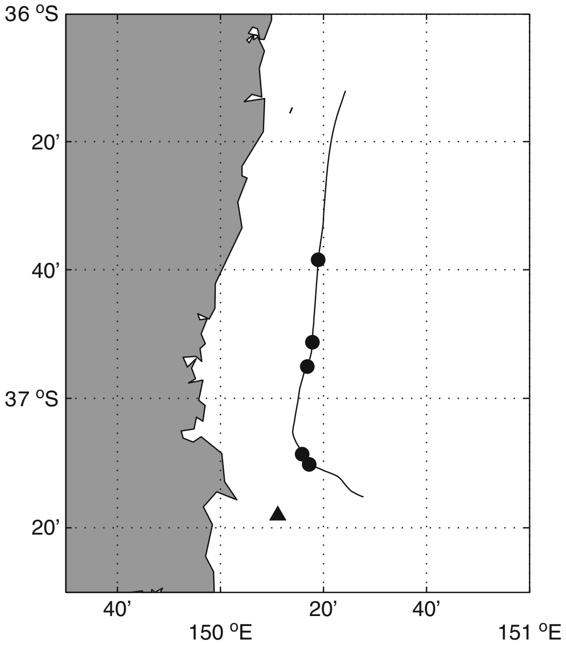

Fig. 8.6 Map image of the New South Wales coast in Australia showing the sailed track of the ship heading south. The dots indicates positions where parametric rolling occurred. The triangle shows the position of the Eden wave buoy

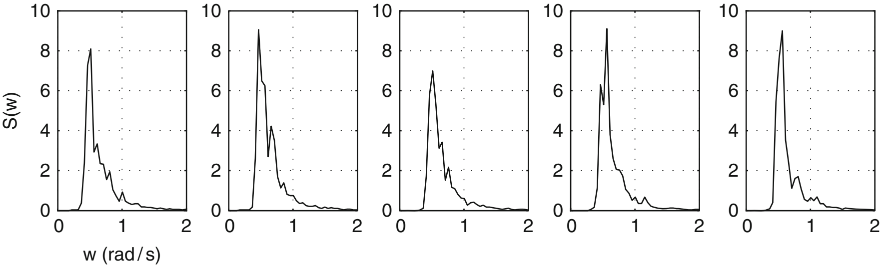

Fig. 8.7 Measured wave spectra from Eden wave buoy between 02:00 (*leftmost*) and 06:00 (*rightmost*) local time, with one hour increment

parametric rolling sequences occurred over a period of about four hours, over which neither the sea state nor the operational condition may be considered stationary. The forecast available on board at the time showed a rapidly increasing wave height away east of the coast but underestimated the wave height close to the coast. This was due to the relatively low spatial resolution in the forecast which was based on the global ECMWF wave model.

In this case, the officers on board became aware that they were in conditions with potential parametric resonance, but had during the first hours limited options to choose a more favorable heading or speed. Eventually, they made a course deviation of about 50° which led into somewhat more severe seas but enabled the ship to get out of resonant conditions.

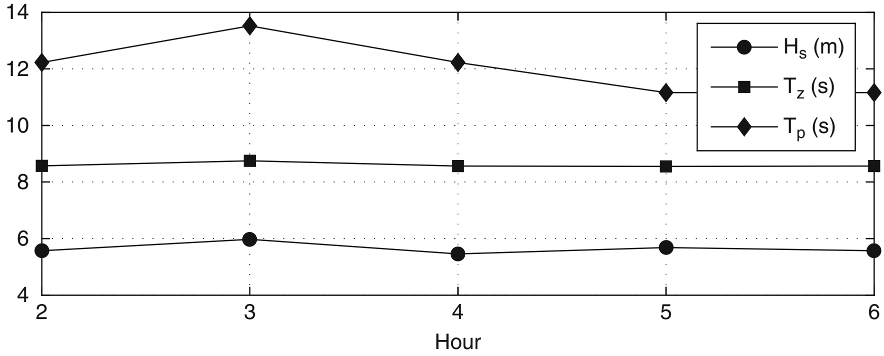

Fig. 8.8 Spectral parameters derived from the wave spectra in Fig. 8.7

8.3.3 Case III – Fundamental 1:1 Parametric Resonance in Following Seas

In the third case, the ship was running at full service speed in quartering seas with a relative heading of 20–40°. The master notified the office about a strange rolling behavior characterized as "neither synchronous nor parametric, perhaps more like loss of stability." On a number of occasions during a couple of hours, the officers turned to manual steering in order to interrupt increasing roll with amplitudes up to 10–15°, but the situation was not considered critical enough to make any general changes in course and speed.

Time series of roll, pitch, speed, and heading are given in Fig. 8.9. During the critical sequences a clear asymmetric development of the roll motion can be seen, which indicates a one-to-one relation between stability variation and rolling periods. The time sequences also clearly show the active steering on board to interrupt the resonance.

In this case with quartering sea, the rolling becomes a complex mixture of direct wave induced synchronous excitation, wind heeling and asymmetric parametric excitation, and less experienced and educated officers would most likely not even have noted the special behavior under these conditions.

For this case, sea state data was obtained from the high-resolution wave model run on the 25th of September 2010, 00 UTC. This means that the wave spectrum presented here represents the $+12$ h forecast (12 UTC). In relation to using reanalysis data, the present data source is considered by meteorologists to provide a better estimate of the sea state due to the higher spatial resolution in the operational high-resolution wave model, in relation to reanalysis data that is run using lower spatial resolution. Figure 8.10 shows the forecast wave spectrum for a position close to the ship. The significant wave height of this spectrum is 4.1 m, the peak period is 10.5 s and the directional spreading is relatively low.

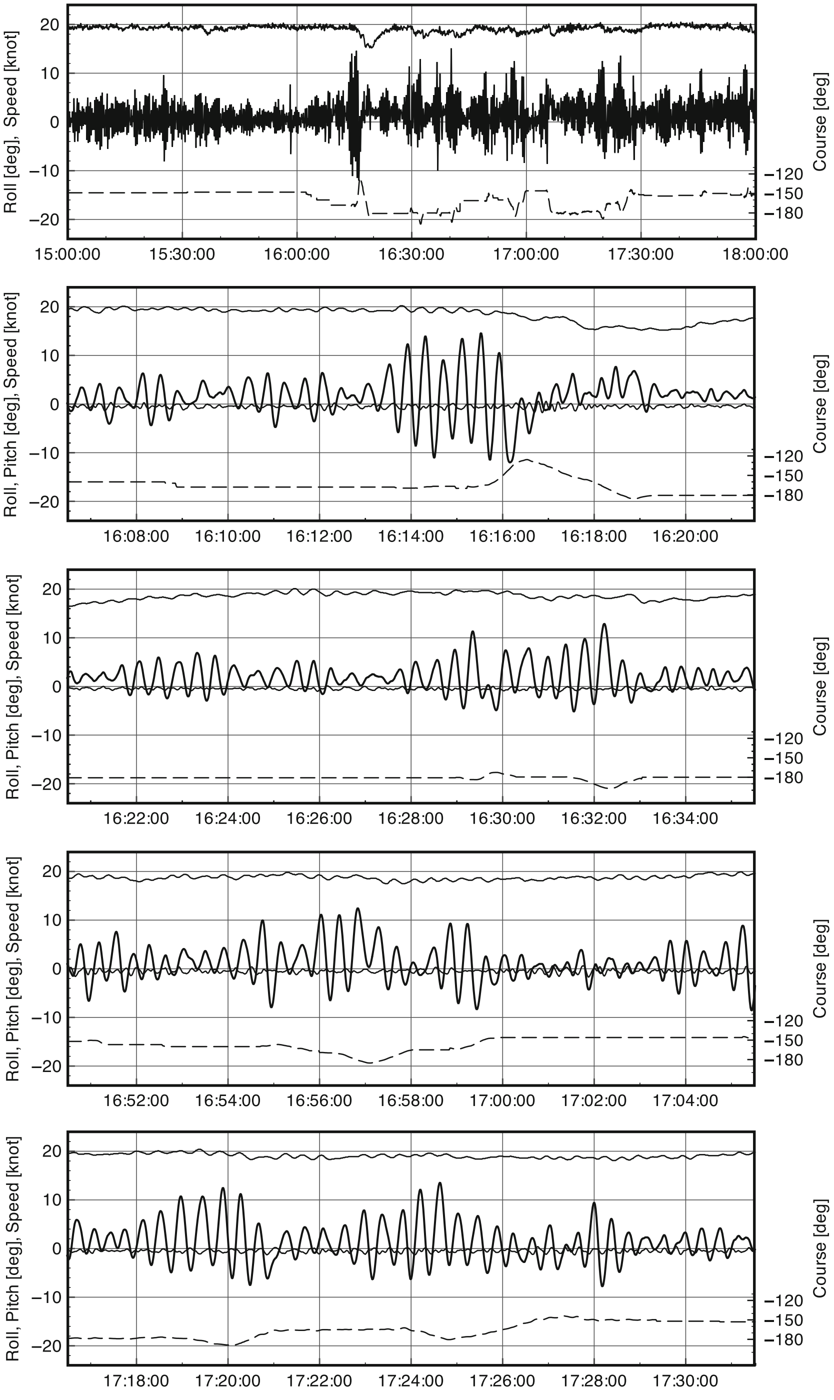

Fig. 8.9 Recorded data for Case III

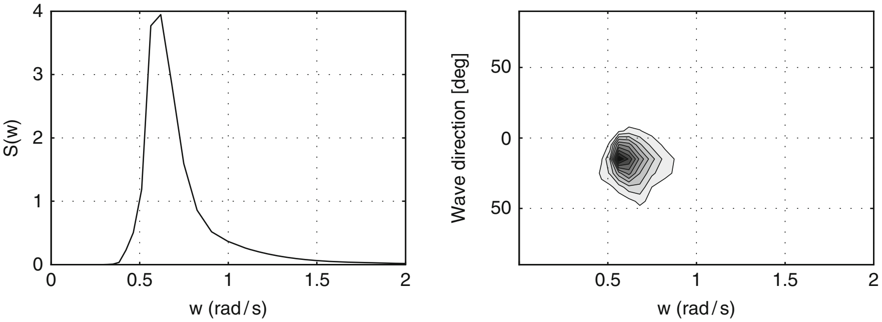

Fig. 8.10 Unidirectional (*left*) and directional (*right*) forecast wave spectrum for 12:00 UTC at a position close to the ship position

The ship was medium loaded and had a $\overline{\mathrm{GM}}$ of about 1.3 m. As for the previously presented cases, a summary of characteristic parameters is given in Table 8.5, showing T_0/T_{Ep} ratios in the 1:1 region.

8.4 Operational Guidance

The concept of operational guidance is about providing information on how a specific ship, in a specific loading condition, is expected to behave in a certain environmental condition as a function of ship speed and heading, thus providing assistance to the master on how to operate a vessel with respect to ship dynamics. This can be applied both strategically as part of weather forecast-based route planning procedures, in order to avoid potentially critical situations in the first place, but also and equally important, tactically in terms of real-time guidance based on actual conditions. For nonlinear and rare events such as parametric rolling, the importance of operational guidance is specifically highlighted since it is very hard, even for an experienced seaman, to sense the criticality in advance, as demonstrated particularly in Cases I and II earlier.

There are many different approaches to supplying operational guidance on board ships, ranging from the [14] circulars, through more advanced precalculated polar plot documentation, to on-board computer systems for real-time or forecast-based evaluation of all possible risks related to ship dynamics. The concept based on precalculated polar plots allows for using very sophisticated dynamic models, e.g., nonlinear multi-degree-of-freedom models, but faces problems in terms of recognizing real conditions, e.g., wind waves and swell from different directions and varying wave spectral shapes and bandwidths. The other approach using real-time calculations, will generally have to use more simplified models for CPU efficiency, but can more easily handle the complexity of real wave conditions. The fact that there are such a large number of crucial parameters involved, depending on loading and operating conditions as well as on environmental conditions in terms of wave spectra, speaks in favor for computer-based systems capable of measuring and computing real-time risk indicators that can trig alerts.

Implementation of operational guidance for parametric roll prevention constitutes an integration of many different topics, some frequently addressed within the research community, and some that are of more practical nature. One topic is the mechanical modeling of the dynamic problem. Another is the definition of the input to the dynamic model, which in this case is constituted by the stochastic seaway. Further, the dynamic model include parameters related to the ship, the loading condition and the operating condition, which in practice are not always as easy to define as one might anticipate.

8.4.1 Dynamic Modeling

A simple dynamic model of parametric rolling in heading or following seas can be formulated in terms of a linear single DOF equation of motion:

$$\ddot{\phi} + 2\delta\dot{\phi} + \omega_0^2 \frac{\overline{\mathrm{GM}}(t)}{\overline{\mathrm{GM}}_0}\phi = 0, \tag{8.1}$$

where δ is the roll damping, ω_0 is the undamped natural frequency, and $\overline{\mathrm{GM}}_0$ is the metacentric height in calm water. $\overline{\mathrm{GM}}(t)$ is the time variation of the metacentric height which in regular waves with an encounter frequency of ω_{e} can be expressed as:

$$\overline{\mathrm{GM}}(t) = \overline{\mathrm{GM}}_m + \overline{\mathrm{GM}}_a \cos(\omega_{\mathrm{e}} t), \tag{8.2}$$

where $\overline{\mathrm{GM}}_{\mathrm{m}}$ and $\overline{\mathrm{GM}}_{\mathrm{a}}$ are the mean and amplitude of the $\overline{\mathrm{GM}}$-variation in the regular wave in question, e.g., [21]. Figure 8.11 shows solutions to (8.1) and (8.2) as critical (shaded) areas where combinations of relative stability variations and relative periods result in growing parametric rolling (more than 10° degrees roll amplitude growth in less than ten cycles). The roll damping used has been determined from model tests and is considered representative for the presented cases. For illustration purposes the relative stability variations and relative periods for the cases have been indicated in Fig. 8.11 based on the data in Fig. 8.2 and Tables 8.3–8.5 taking the irregular sea state parameters T_{p} (peak period) and H_{s} (significant wave height) as representatives of the regular wave period and wave height. One could consider operational guidance based on a similar approach, e.g., as suggested in [23]. However, depending on rather drastic simplifications of the stochastic properties of the seaway such an approach is less feasible for quantification of actual amplitudes or risk levels.

The stability variations for the three cases in Fig. 8.2 and Fig. 8.11 have been determined by quasi-static balancing in heave and pitch. More advanced

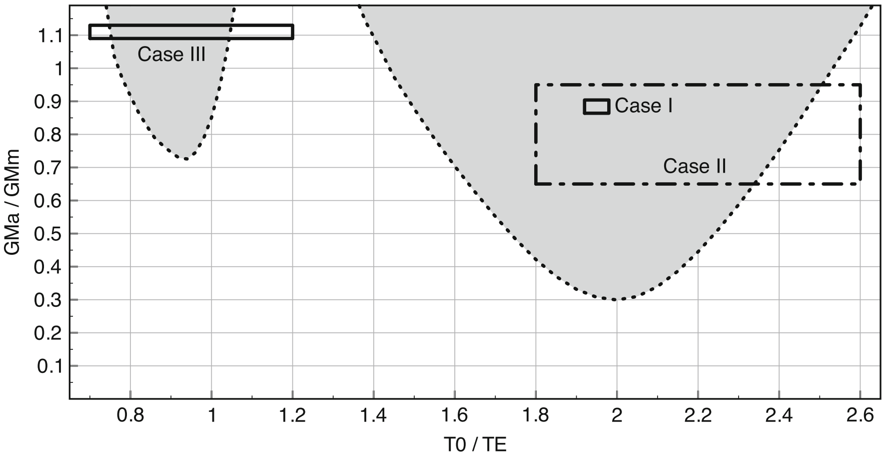

Fig. 8.11 Simplified interpretations of the conditions for the three presented cases in relation to the solutions of (8.1) and (8.2) in terms of critical (shaded) areas where combinations of relative stability variations and relative periods result in growing parametric rolling

single-degree-of-freedom modeling could for example include quasi-dynamic balancing in heave and pitch, nonlinear damping, nonlinear $\overline{\mathrm{GZ}}$ variation, and irregular waves, e.g., [7].

The next level of complexity is multidegree-of-freedom models. The state of the art in multidegree-of-freedom parametric-roll modeling has recently been evaluated in a large benchmark study where different simulation methods were compared to model test data [22]. The overall efficiency of the benchmarked methods was concluded to be low, but this was attributed to the wide spread of individual methods both regarding modeling approaches and performances. A group of leading simulation methods was, however, detected, for which the mean probability to successfully detect the parametric roll resonance in relation to the model experiments was estimated to be around 80%.

All three real cases presented here have been realized numerically using such a multidegree-of-freedom simulation model. The used model is based on work of [9] and participated in the above-mentioned benchmark study. For Cases I and III, both in following sea with focused encountering wave spectra, the simulations were able to give consistent and stable results similar to what was measured. However, for Case II which was in head sea, most realizations did not develop parametric roll at all. Figure 8.12 shows an example from one of the rare sequences where similar rolling developed as was measured on board. The simulations for this case were also very sensitive to small variations in conditions and sea state and would not have been conclusive as basis for guidance on board.

Operational guidance based on multidegree-of-freedom modeling of the ship dynamics is being considered as part of the new generation intact stability criteria, which should comprise the design phase as well as the operational phase [15]. The principle for such approach could, for example, be as discussed in [18] where

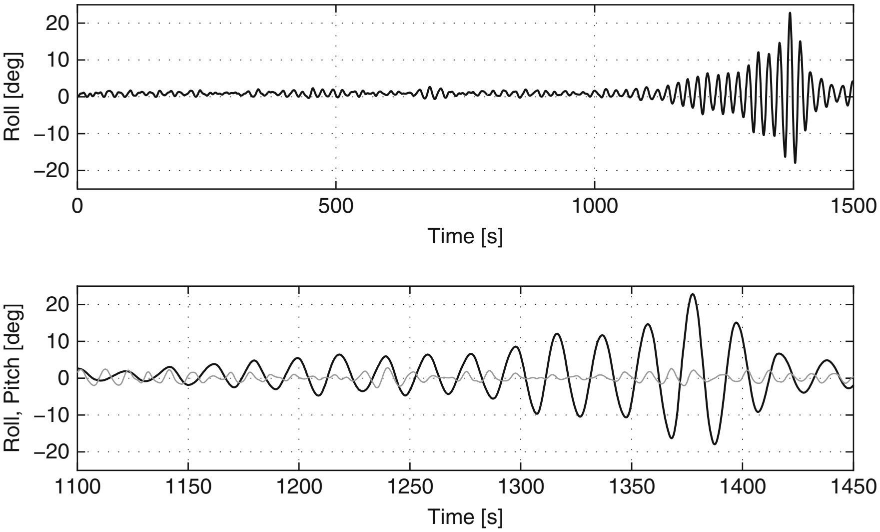

Fig. 8.12 Example of simulated parametric rolling for Case II using a multidegree-of-freedom model

multidegree-of-freedom simulations are used to generate polar plots displaying dangerous combinations of speed and relative heading regarding parametric rolling for a large number of different ship conditions and sea states. With appropriate presentation the precalculated polar plots could then be used for on-board guidance.

8.4.2 Definition of Ship Characteristics and Operational Conditions

Regardless of using single or multidegree-of-freedom dynamic modeling, proper consideration the present sea state and ship condition is of outmost importance in assisting the crew with operational guidance to avoid dangerous situations regarding parametric rolling. In principle, both $\overline{\mathrm{GM}}$ and the moment of inertia that together are decisive for the natural roll period T_0, should be determinable based on the data in the loading computer or trim and stability booklet for well-defined loading conditions. However, experience shows that there can be significant uncertainties involved already at this stage, e.g., [17]. A further uncertainty is the effect of free surfaces in liquid tanks. For static stability, this can be equalized with a reduced $\overline{\mathrm{GM}}$. In dynamic rolling situations, the effect might, however, be different due to internal flow resistance in the tanks. Internal liquid movements might also have other effects on the roll motions, especially for ships with active or passive roll stabilizing tanks. The most precise method for determining T_0 is probably to measure the roll period in calm water after a sharp turn or in mild beam seas. Under well-controlled conditions possibly also the damping could be evaluated from forced roll tests, but it is hardly feasible for every ship to exercise this under normal service. Due to differences between $\overline{GM}$ in calm water and the average $\overline{GM}$ in waves, one could also expect a difference between the roll natural period in calm water and in waves. For the here presented ship type and cases, this difference is, however, calculated to be rather small and can hardly be noted in the time series for roll. For other ship types and conditions, this effect might, however, be more pronounced.

8.4.3 Definition of Sea State Parameters

Different approaches are used by crews to make visual estimates of the sea state. In the Revised guidelines to the master for avoiding dangerous situations in adverse weather and sea conditions [14] it is, for example, suggested that the wave period should be measured by means of a stop watch as the time span between the generation of a foam patch by a breaking wave and its reappearance after passing the wave trough. However, besides the simple fact that it is dark half of the time, the precision in such manual estimates is all too low to serve as input in high quality operational guidance. Another source of sea state estimation is weather forecast data in terms of wave parameters or complete 2-D wave spectra. Here, the accuracy will depend heavily on the forecast model and its resolution in relation to the ship position. Case II may here serve as an example. The ship was fairly close to the shore while the forecast was a normal resolution forecast from a global wave model incapable of catching the local effects, and the forecast available on board underestimated the wave heights significantly. Using high resolution data from a local wave model would probably have provided a much better sea state estimate. The next step in sea state estimation is ship based in-situ estimation. One such approach is to estimate the sea state from the ship motions. This approach is adopted in the Seaware EnRoute Live system, using a further refined version of a variational method originally described in [10]. A comparison of a ship motion estimation of the wave spectra to the spectra measured by the Eden wave buoy in Case II is shown in Fig. 8.13. Another kind of in-situ estimation based on image processing techniques on raw X-band radar video signals, may provide reliable frequency and directional spectral information.

8.4.4 The Stochastic Problem

One of the main challenges in quantitative prediction of parametric rolling lies in the fact that it is a highly nonlinear dynamic problem subjected to complex stochastic excitation. This means that parametric rolling in ocean waves generally are rare events, thus requiring attention in terms of methodologies that enable CPU-efficient computation of probability quantities or stability boundaries. The

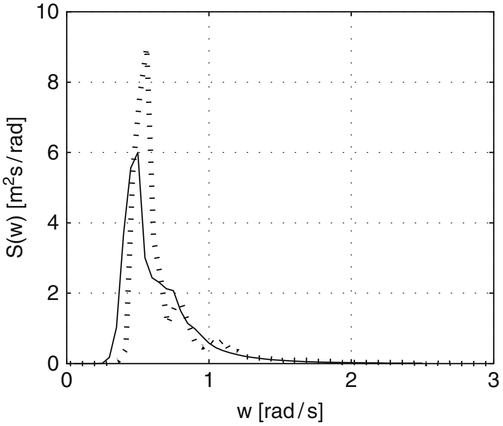

Fig. 8.13 Comparison of wave spectra for Case II. The solid spectrum is estimated in real-time based on ship motions. The dotted spectrum was measured by the Eden wave buoy, approximately 10 nautical miles west of the ship position

most straightforward approach is to perform massive Monte Carlo simulations in terms of a sufficiently large number of realizations of sufficiently long periods of real time. At present, this is hardly a feasible approach for operational guidance due to the CPU power required. It is therefore necessary to investigate other possibilities. Since in practice, parametric rolling in irregular waves will only occur during encountered wave sequences that are "fairly high and regular," one such possibility is to confine the time-consuming nonlinear simulation to such critical wave sequences. Here, wave group theory, split time methods, and first order reliability based methods play important roles, e.g., [1, 16, 19]. If the objective is to find stability boundaries rather than probabilistic quantities for roll amplitudes, there are a few conceptually different possible approaches by which the stochastic problem can be considered. Bulian [2], for example, describes a method to calculate stochastic stability boundaries based on a simplified analytical approach. Another such approach is presented in [4,5] which is based on the concept of $\overline{\mathrm{GM}}$ spectra by considering $\overline{\mathrm{GM}}(t)$ as a linear stochastic process in irregular waves.

8.5 Discussions

The ongoing work under the IMO SLF subcommittee developing vulnerability criteria for ships regarding parametric roll and other critical events in waves is welcomed. Eventually, this will make it possible to settle a refined common standard of minimum stability robustness to be used in design of new ships. In addition to this, we believe further developed operational guidance applicable to both existing and new sensitive ship types will be a natural complement to assure safe service under all conditions. Both design criteria and operational guidance limit values should also preferably relate to relevant ship and operation specific design loads or limits, e.g., for cargo lashings, hence putting the criteria and operational guidance into a more risk-based context.

There are many challenges still to be faced in this development. The risk models should account for both the probability of parametric excitation and the severity of the resulting motions and be based on the specific ship characteristics, operational condition and sea state including inherent uncertainties. We believe full scale service data and analysis from incidents and early warnings are essential in this development as they expose complexities and considerations that are normally not included in well-defined model tests or numerical simulations.

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