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Classification of Parametric Rolling for Seagoing Ships and Percentage Distribution for Multiple Sea State Parameters

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ABSTRACT: In this paper, parametric rolling is divided into 5 heavy grades, establishing a classification for parametric rolling. This is achieved by a multi-parameter application in the simulations. For this purpose, parametric rolling, established criteria and the state of the art are considered and the results are summarized. Based on this, parametric rolling is successfully simulated using discrete simulation in MARIN [1]. Five heavy grades are introduced so different classes of parametric rolling can be distinguished. Furthermore, dependencies and probabilities for the occurrence of parametric roles in relation to the see are determined numerically. This will later be used in an assistance system on board ships to compute the prediction of parametric roll using an AI.

1 INTRODUCTION

Parametric rolling divides the maritime world into those that regard it as a rare phenomenon and therefore poses little or no danger to spng, and those that regard parametric rolling as a ubiquitous serious hazard to shipping.

The challenge is to attribute specific marine accidents to parametric rolling. As a result, numerous investigation reports end up stating that heavy rolling caused the marine accident, but not parametric rolling. Nevertheless, few accidents are attributed to parametric rolling. As in 2008 when the CMV CHICAGO EXPRESS [2] experienced severe rolling of up to 44 degrees during a typhoon and one seaman died and another was hospitalized with serious injuries. Despite the presence of parametric roll detection documentation on board, the M/S FINNBIRCH [3] sank between Öland and Gotland in 2006, experiencing roll angles of 30-35 degrees. But even weather forecasts cannot prevent this phenomenon, as experienced by the SVENDBORG MAERSK [4] on February 17, 2014, when she encountered heavy weather on her way from Rotterdam behind the English Channel and experienced rolling angles of up to 41 degrees. 517 containers went overboard and 250 were damaged.

Parametric rolling may affect almost the entire range of ships, not only on the open sea, but also on the coast and even in the North and Baltic Seas. The hull forms most at potential risk tend to be those with flared fore and aft extremities or a flat transom stern paired with wall-sided ship sides near the waterline amidship [5] such as container ships and pure car/truck carriers [6].

In the process of maritime automation, an early warning system for parametric rolling becomes indispensable. To this purpose, the present thesis first explains the phenomenon of parametric rolling in Chapter 2, followed by the state of the art in Chapter 3. Chapter 4 contains a separate approach to risk prediction of the probability of parametric rolling of ships based on ship motions and sea state parameters.

The evaluation follows in Chapter 5, with a discussion in Chapter 6.

2 THE PHENOMEN OF PARAMETRIC ROLLING

In this chapter first the phenomenon of parametric rolling in longitudinal directed waves is described and then the sea and ship parameters supporting parametric rolling.

2.1 *Parametric Rolling*

Parametric rolling bases on the change of ship stability over a short period of time in wave trough (solid line) and wave crest (dashed line) in longitudinal directed waves as shown in figure 1. This concerns larger vessels with flared fore and aft decks for instance pure car/truck carriers and container vessels [6].

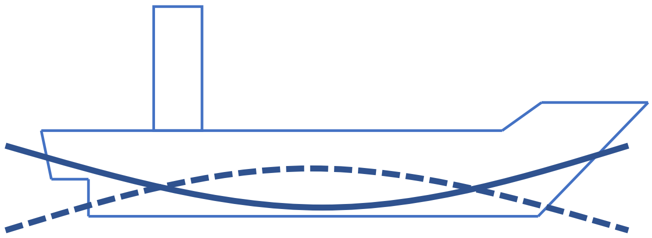

Figure 1. Wave trough and crest.

Figure 1 shows the ship in a wave trough (solid line). Here, the area of the water surface increases because the bow and stern immerse deeper into the water. Consequently, the water surface coefficient c_w increases compared to the calm position, which also increases the longitudinal stability. In the wave crest (dashed line), the behavior is the reverse. The waterplane area decreases due to the fact that the midship lies deeper in the water, but the bow and stern come out of the water. This reduces the longitudinal stability. As a result, the metacentric height GM increases and decreases with longitudinal directed waves and oblique waves.

In the design phase of a vessel the metacentric height GM has been calculated according to the intact stability rules (example: DNV GL, Rules and Guidelines I-1-1-Section 28-B.2 Design Criteria [7] for each ship by the restoring moment and the corresponding lever arm. On the other hand, if the wavelength is about equal to the ship's length and the ship's rolling period is about twice the frequency of the encounter, there will be a righting moment that is not sufficiently damped by the water and thus causes the ship to rapidly oscillate. This oscillation within a short time is called parametric rolling or parametric rolling resonance.

2.2 *Parameters*

This chapter describes the requirements that support parametric rolling.

Primary characteristics are:

1. If the rolling period T_R of the ship is twice the encounter T_e period [8].

$$T_R \approx 2 \cdot T_e \tag{1}$$

where $1,8 \le \frac{T_R}{T_e} \le 2,1$ [9]

2. The wavelength λ is about the ship length between the perpendiculars L_{pp} [8].

$$\lambda \approx L_{pp} \tag{2}$$

with $0,7 \le \frac{\lambda}{L_{pp}} \le 1,3$ [9]

3. Longitudinal or quartering sea with the encounter angle β [8].
   For forward sea:

$$315° < \beta < 45° \tag{3a}$$

For aft sea:

$$135° < \beta < 225° \tag{3b}$$

Secondary characteristics are:

4. The variation of the location of the metacentric height GM in figure 2 plays an important role for the stability of the ship, as described in chapter 2.2. The relation of the variation of GM and the parameter (1) can be simplified without damping as follows [10].

$$f(x) = -0,25x + 1 \; for \; 2 < x < 4 \tag{4a}$$

$$f(x) = 0,25x + 1 \; for \; 4 < x < 6 \tag{4b}$$

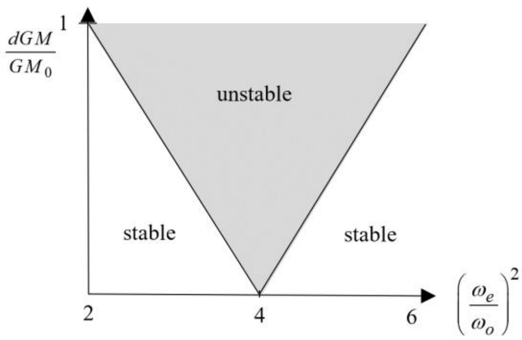

Figure 2. Variation of the metacentric height GM, with the initial metacentric height GM_0

5. After the guide for the assessment of parametric roll resonance in the design of container carriers [8] following inequality must be satisfied that the vessel may be susceptible to parametric rolling, with ω_0 the roll natural frequency of vessel, ω_a the roll natural frequency to magnitude of changing GM, ω_e the frequency of encounter for head and following seas with: $\omega_w +/- 0,0524 * v_s * \omega_w^2, \omega_m$ the roll natural frequency to mean value of GM, ω_w the frequency of wave and μ the roll damping.

$$0,25 - 0,5 \cdot q - 0,125 \cdot q^2 + 0,03125 \cdot q^3 - \frac{q^4}{384} \le p \le 0,25 + 0,5 \cdot q \tag{5}$$

where:

$$q = \frac{\omega_0^{\,2}}{\omega_e^{\,2}} \quad and \quad p = \frac{\omega_m^{\,2} - (\mu \cdot \omega_0)^2}{\omega_e^{\,2}},$$

$$\mu = 0,03 \quad and \quad \omega_0 = \frac{7,854 \cdot \sqrt{GM_0}}{B}$$

$$\omega_m = \frac{7,85 \cdot \sqrt{GM_m}}{B}$$

where

$$GM_m = 0,5(GM_{max} + GM_{min})$$

$$\omega_a = \frac{7,85 \cdot \sqrt{GM_a}}{B}$$

where

$$GM_a = 0,5(GM_{max} - GM_{min})$$

$$\omega_e = \omega_w + 0,0524 \cdot v_s \cdot \omega_w^{\,2} \qquad \textit{for head seas and}$$

$$\omega_e = \omega_w - 0,0524 \cdot v_s \cdot \omega_w^{\,2} \qquad \textit{for following seas.}$$

6. And when the inequality (5) is met, following must be checked [8]:

$$\mu \frac{\omega_0}{\omega_e} < q * k_1 * k_2 * \sqrt{1 - k_3^{\,2}} \tag{6}$$

where

$$k_1 = 1 - 0,1875 q^2$$

$$k_2 = 1,002 p + 0,16 q + 0,759$$

$$k_1 = \frac{q^2 - 16}{16q} + \frac{\sqrt{q^4 + 352 q^2 + 1024 p}}{16q}$$

From different existing works these 6 parameters and their limits (1-6) have been identified for this paper, which will find their meaning in chapter 4. First follows chapter 3 with the existing works and their application of the specified parameters.

3 RELATED WORK

Due to the controversial nature of the topic, various methods and approaches have already been developed to avoid or mitigate parametric rolling. In this chapter, the various methods are divided into three categories. First, there are the methods that provide a preventive guide (3.1) and thus can be applied before starting to sail. Next are the monitoring methods (3.2), which focus on warnings during an ongoing voyage. And finally, the methods that serve to predict (3.3) the parametric rolling.

3.1 *Guiding methods*

The IMO developed a guidance document in MSC.1/Cir. 1228 to avoid dangerous situations such as parametric rolling. Based on the parameter (1), (3a) and (3b) the following polar plot was generated [11]. This plot (figure 3) shows a dangerous zone where the risk of parametric roll is high if the above three parameters are met in a certain combination. Using this ship-specific diagram, the navigator is capable of avoiding exactly these combinations by changing the speed or the course.

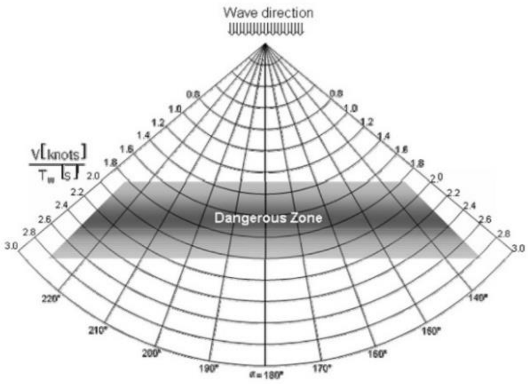

Figure 3. Dangerous zones of synchronous and parametric rolling motions, v is the vessel speed in knots, T_w, the wave period in seconds, α is the encounter angle, whereby 180° are following seas.

The OCTOPUS Software [12] is a ship motion analysis software for sea-keeping analysis of ships and offshore floating structures. It can therefore also be used to represent parametric and synchronous rolling in polar diagrams. In addition to parameters (1), (2) and (3a/b), a critical wave height and low roll damping are supplemented in this case, resulting in a polar diagram for rolling motion. This illustrates different areas for surfing, parametric and synchronous rolling in relation to the ship's speed and the angle of encounter with the waves. This plot (figure 4) serves as an orientation for the navigator, under which loading conditions the ship could get into dangerous situations. So, the navigator can also avoid these areas by adjusting the speed or course.

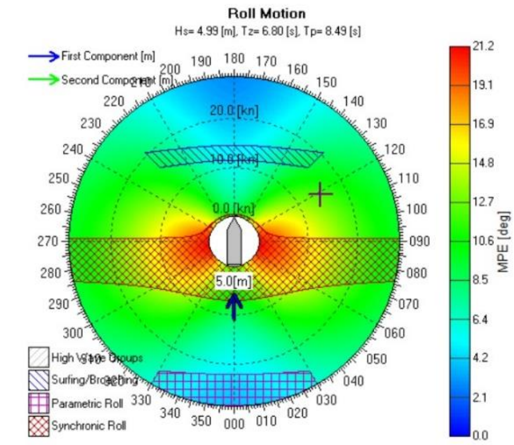

Figure 4. Polar diagram generated by Octopus Software for the sea state H_s=4,99m (significant wave height), T_z=6,80s (zero crossing period) and T_p=8,49s (modal period). The radius shows the ship speed, the colors show the dangerous zones, the headings from 0° to 360° are outlines around, MPE = most probalbe extreme in degree.

S. Ribeiro and C.G. Soares [5] present a prediction method based on time domain non-linear strip theory model with six degrees of freedom. Whereby the roll damping is determined directly from experimental data and by applying Frank's Close fit method, the hydrodynamic effects are based on a potential flow stripe theory. The validation is carried out by comparing the numerical predictions with the experimental results for a container ship based on the parameter (3) and (4). In the polar plot (figure 5) the risk zones of the parametric rolling are highlighted. Speeds from 0 to 16kn were recorded and simulated in heading sea. Also, in this case, the polar plots serve as an operational guidance for the navigator to avoid parametric rolling by avoiding the red areas.

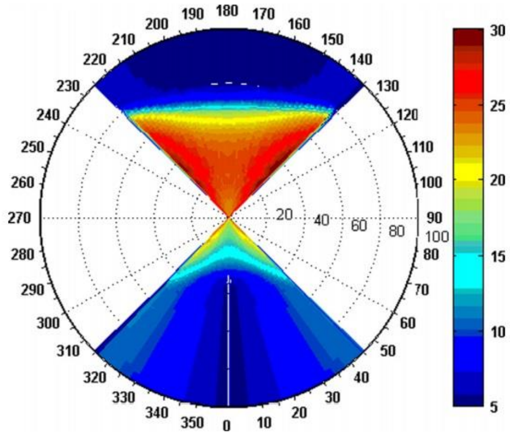

Figure 5. Polar diagram of predicted roll motion, for headings from 0-45 degrees and 135-180 degrees. The warm colors show the areas which exceed 20 degrees of rolling angle. Under the limits, the colors are cold. Vessel speed is from 0-16 knots, the wave height is given with 6 meters and the ratio between ship lengths and wavelength is 1.4. The simulations took each 1200 seconds.

3.2 *Monitoring Methods*

PAROLL [13] is a real-time detection system for merchant vessels and is patented as condition-monitoring system. It is based on low-cost motion sensors, whereby an algorithm extrapolate information's about the frequency, the roll and pitch motion. First the algorithm examines parameter (1), whether the rolling period is approximately twice the period of the wave encounter by using the pitch oscillation as equivalent. Secondly, the algorithm analyses whether the rolling and pitching movements are phase synchronous. Also the parameter 2, 3a and 3b in addition to the wave height has to be fulfilled. So that an alarm is emitted. In the full-scale validation, predictions were made in approximative 70% of cases. This refers to rolling movements above 10°. PAROLL is able to issue a warning 40 roll cycles in advance, giving the crew 1.5 to 12 minutes to act. The systems work without any ship parameters so that it is easy to install on any ship.

3.3 *Prediction Methods*

MARIN [14] presents a prediction based on linear calculations of ship movements, which estimate the hydrostatic stability variations as the cause of parametric roll (parameter 4). With a reduction in roll damping according to Dunwoody, the safe operating limits of the vessel are obtained (see Figure 6).

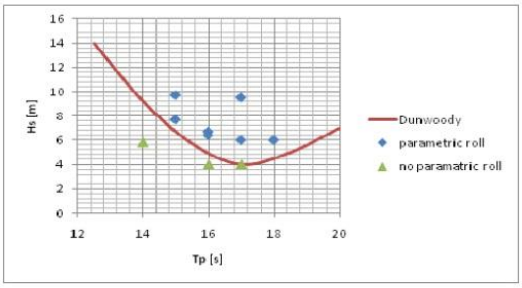

Figure 6. Comparison of test results, line is the calculated result, the markers are experimental, *Hs* is the significant wave height and *Tp* the wave peak period, for a container vessel of 250 meters lengths.

WaveSignal SigmaS6 basing on WaMoS II from OeanWavesS GmbH [15] is a real-time system to warn of waves in a specific time window. The forecast covers the following 180 seconds and identifies abnormal waves by using x-band radar and predictive analytics. A non-adaptive algorithm was used at the beginning, which assimilated all raw radar data over the entire sampling range at rates of more than 2.1 Msps. This simplified the testing phase, so adaptive algorithmic methods were added at a later stage. First, the sea surface is measured over a spatio-temporal range, hereinafter referred to as the observation range. This is followed by the application of pre-processing methods and the calculation of the magnitude and phase of wave vector coefficients. Finally, the phase shift of the wave vector coefficients is used for propagation, therefore for the prediction of the sea surface profile at space-time offsets.

This results in the prediction (see Figure 7) of a wave field derived from statistical sea state parameters as well as 3-dimensional sea surface height maps from nautical X-band radars. The method is based on the spectral analysis of radar data using a 3-dimensional (fast) Fourier transform.

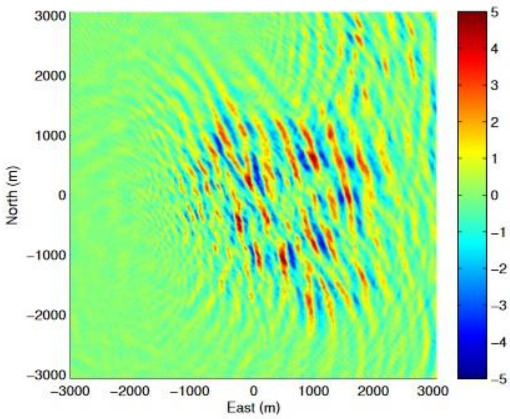

Figure 7. Prediction of T+180s of the wave field, the colors indicate the wave elevation in meters, with a wave direction towards north-east over 3 kilometers.

3.4 *Recapitulation of Existing Works*

The previous methods are based on the isolated parameter as they are described in Chapter 2, so the methods do not combine all the evaluated parameter (1-5) and uses them for prediction or probability calculation. The difficulty in predicting parametric rolling lies in the conditions that vary every passing second, the same as the sea. The parametric rolling should be predicted in a time frame in which the ship's command can react, but no false alarms should occur. In addition, the previous methods do not reflect the severity of the parametric rolling (classification) or the probability. The own approach is to increase the accuracy of the detection by using multiple parameters so that no early warnings are generated.

4 CLASSIFICATION OF PARAMETRIC ROLLING USING MULTI PARAMETER IN THE SIMULATION

To begin the question of understanding what parametric rolling means numerically must be clarified. For this purpose, accident reports and simulation are used as the basis of identification. Numerical limits are set which describe parametric rolling. Once it has been established what parametric rolling is numerically, parametric rolling can be simulated. For this process the multiple parameters from chapter 2.2 are used for. Their dependencies are represented in an event tree. The five severity classes of parametric rolling will result from the simulations. They are then described in detail. An algorithm, which perpetuates the numerical conditions for parametric rolling from IV.A, recognizes and counts the events which occur, allowing the probability of occurrence under certain conditions for parametric rolling to be calculated.

4.1 *Identification of Parametric Rolling*

To define numerical values, we return to the definition of parametric rolling from the relevant literature. Parametric rolling is defined as a significant increase in rolling motion that becomes dangerous for the crew, the cargo and the ship [8]. Neither the time nor the roll angle is specified.

In effort to localize parametric roll from the simulations, it is necessary to have limit values at which a roll movement is considered as parametric roll. For this context, values found in accident reports as well as in the previous studies are compared (see tab.1).

Table 1. Roll angel, time range and encounter angle for parametric rolling from related works and accident reports

No.	Vessel type	Reference	roll angel [deg]	time range [s]	encounter angle [deg]
1	RoPax	[16]	25	50	35
2	Research	[16]	35	20	315
3	Panmax	[17]	>15	/	/
4	Container	[12]	20	25	/
5	Container	[2]	44	/	100-130
6	Container	[13]	18	100	/
7	Container	[9]	20	/	335-25
8	Container	[18]	20	100	120-240
9	Container	[19]	30	30	155-180
10	Container	[3]	30-35	3 moves	2
11	Container	[4]	38-41	/	/
12	Container	[20]	30-40	/	155-205
13	Container	[21]	25-30	5 moves	180
14	Container	[22]	30	100	335-25
15	Container	[23]	18	10	/
16	Container	[24]	20	2 moves	/
17	Container	[25]	15-20	/	30
18	Container	[5]	20	/	335-25 155-205

From table 1, the definition of parametric rolling can now be defined in more detail:

1. Ship type/model
   As can be seen from table I, these are container ships, most of which suffer from parametric rolling or are used for investigations. To ensure the comparability with other methods and due to the vulnerability of specific ship designs with flared fore and aft extremities or a flat transom stern paired with wall-sided ship sides near the waterline amidship [5] to parametric rolling, a container ship is used for the simulations. The acquired ship model for the MARIN software [1], has a length overall of 400m, between perpendiculars 382m, a beam of 56m, a draught of 15.5m and a dry mass of 214,000t.
2. Roll angel
   In the table 1 the existing works present roll angles of 20 degrees and above. Nevertheless, when considering the accident reports, higher roll angles of 25 degrees and even closer to 30 degrees are found. Less than one third of the accidents are caused by roll angles around 20 degrees. Therefore, for further considerations and the identification of the parametric rolling, roll angles over 25 degrees are examined.
3. Time range t
   Conversely, the time ranges for the theoretical work are set very high with up to 100 seconds and the time ranges of the accident reports are very short from only two rolling movements to approx. 30 to 100 seconds. It follows that, for safety reasons, short time ranges must be recorded in which the ships build up to high rolling angles. In this work, time windows of less than 60 seconds are thus considered.
4. Encounter angle
   According to the accident and investigation reports in table 1, these are longitudinal or quartering sea which induces parametric rolling.

For this paper the following threshold values can be derived from these observations and characteristics and subsequently used for simulation of parametric rolling.

RESULT: Concrete definition of parametric rolling. It can be concluded from this that parametric rolling is identified in the simulations for a containership, for forward sea with an encounter angle of $\beta = 0°$, when the roll angle increases from a small roll angle (<5°) to more than 25° within a period of 60 seconds and no damping takes place within the roll-up (see description of parametric rolling in chapter 2.2).

4.2 *Generating of parametric Rolling*

For the simulation of the parametric rolling, the software of MARIN is used. Also, a container ship model with a length of 400 m, a width of 56 m and a draught of 15.5 m is used [1].

To be able to identify parametric rolling, the ship model must be simulated under different parameters. For this purpose, all wave periods, lengths, heights, and ship speeds could be compared step by step. Due to the presence of these multiple parameters in multiple combinations, this would lead to an immense number of simulations. To simplify this, the parameters are narrowed down by including the requirements mentioned in chapter 2.3. By specifically limiting the parameters and simulating them in combinations, a parameterization is therefore carried out by means of a discrete simulation.

1. Encounter period T_e
   In the first step the wave period T_{e1} is set to 1.8 times.
2. Wavelength λ
   The wavelength λ is calculated the minimum, mean and maximum of the range as in chapter 2.2 for 0.7, 1 and 1.3 times.
3. Angle of encounter β
   The encounter angle is first set to β = 0°.
4. The variation of GM is not considered in the first step.
5. Ship's speed v_s
   Corresponding from the formula (5) the ship's speed is applied v_s single, double, triple and quadruple.
6. Wave height ζ
   The wave heights are needed for the simulation. For an initial parameterization, the wave heights are used in a step size of 1m from 1-20m, as no information is available on the areas in which parametric rolling occurs more strongly.

This leads to an event tree for the discrete simulation:

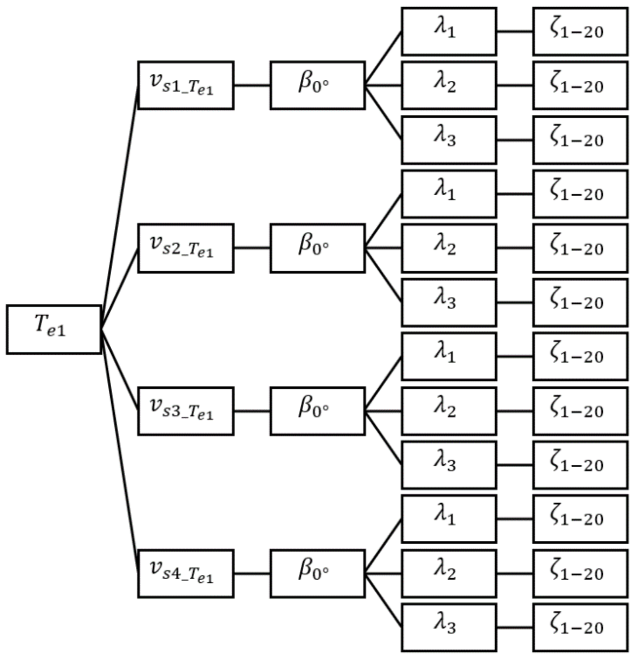

Figure 8. Event tree for T_{e1}=T_R/1,8

The figure 8 shows that the wave period T_{w2} is divided into 4 different possible ship's speed $v_{si\_T_{w2}} = v_s \cdot i$ with i = 1…4. From here, only the encounter angles *β=0°* are initially parameterized, further into three calculated wavelengths λ each for $\lambda_1 = \lambda \cdot 0,7$, $\lambda_2 = \lambda \cdot 1$ *and* $\lambda_3 = \lambda \cdot 1,3$. Here the parameterization continues with twenty different wave heights $\zeta_{(1\text{-}20)}$. The simulation is carried out using the MARIN software based on this event tree in order to next identify the dependencies of the multiple parameters (parametrization).

4.3 *Discrete Simulation*

For parameterization, the individual simulations are performed according to the specifications of the event tree. For this purpose, the simulations are performed over a duration of 7200 seconds and with an increment of 1s.

All simulations have been summarized in tabular form. Table 2 is an exemplary listing of some simulations that showed parametric rolling.

Table 2. Examples for simulations with parametric rolling

Sim No	V_s [kn]	T_w [rad/s]	λ [m]	ζ [m]	β [°]	start time [s]	roll angle max[°]	roll movement
21	7,464	17,87	496,6	11,92	0	6770	25,94	x
139	3,732	17,87	382	11,92	0	477	43,05	x
140	3,732	17,87	382	13,11	0	3013	30,89	4
144	3,732	17,87	382	17,88	0	840	29	3
145	3,732	17,87	382	19,07	0	678	43,03	3
145	3,732	17,87	382	19,07	0	896	27,43	3
145	3,732	17,87	382	19,07	0	1951	39,81	3
149	3,732	17,87	382	23,84	0	1335	31,26	2
175	3,732	17,87	267,4	11,92	0	477	43,05	x

The evaluation of the individual simulations showed large differences between the types of parametric rolling. Strong and less strong, as well as faster and slower reactions of the ship were shown. Another feature was the frequency of occurrence within a simulation, which was reduced to a single or multiple events. These differences provide evidence for the characteristics of serial parametric rolling and the classification into 4 severity classes.

4.4 *Classification of Parametric Rolling*

Most Different degrees of severity of parametric rolling can now be derived from the previous simulations of parametric rolling. Here, the accident reports coincide with the simulations generated.

4.4.1 *Serial parametric rolling*

Describes the repeated occurrence of parametric rolling within the same simulation. The ship experiences several continuous parametric rolling (see figure 9 and table 2) within 7200 seconds. In the simulation 145 the parametric rolling appeared 3 times.

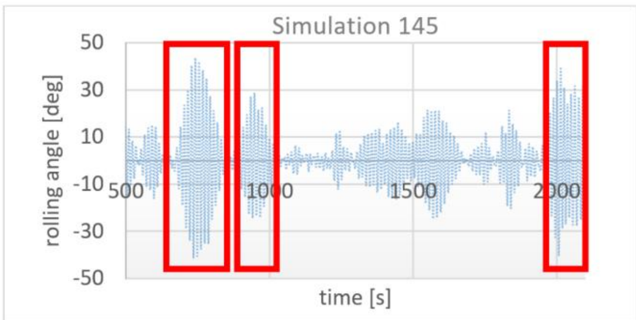

Figure 9. Serial parametric rolling with v_s= 7,25kn, *β* = 0°, T_w=17,87s, *λ*= 382m, *H*=19,07m

4.4.2 *Class1: Very extreme parametric rolling*

After two rolling movements of the vessel (see figure 10 and table 2). The simulation 149 shows that the vessel moves two times and is rolling up to 31,26°.

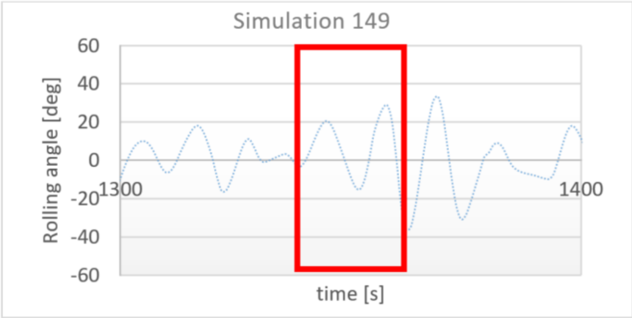

Figure 10. Very extreme parametric rolling with v_s= 7,25kn, β = 0°, T_w=17,87s, λ= 382m, H=23,84m

4.4.3 *Class2: Extreme parametric rolling*

After three rolling movements of the vessel (see figure 11 and table 2). The simulation 144 shows the exceeding of 25° roll angle after the third movement with even 29°.

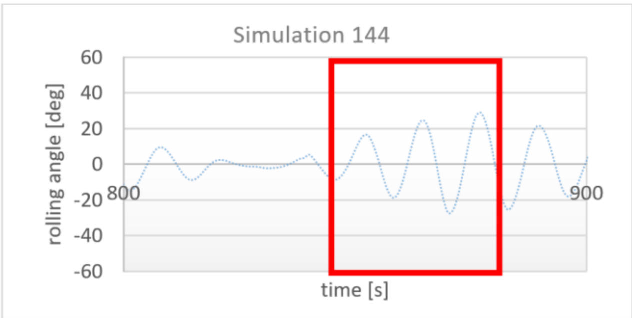

Figure 11. Extreme parametric rolling with v_s= 7,25kn, β = 0°, T_w=17,87s, λ= 382m, H=17,88m

4.4.4 *Class3: Strong parametric rolling*

After fore rolling movements of the vessel (see figure 12 and table 2). In the simulation 140 the ship was rolling fore times to exceed 25° and reached even an angle of rolling of 30,89°.

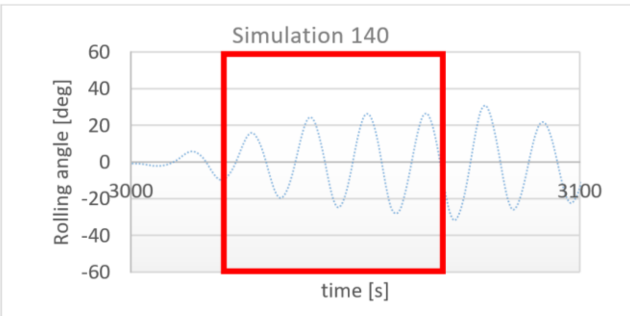

Figure 12. Strong parametric rolling with v_s= 7,25kn, β = 0°, T_w=17,87s, λ= 382m, H=17,88m

4.4.5 *Class4: Simple parametric rolling*

After more than fore rolling movements of the vessel parametric rolling is identified (see figure 13). See as example in the table 2 the simulation 175, where several moves of the vessel results in 43,05° of rolling.

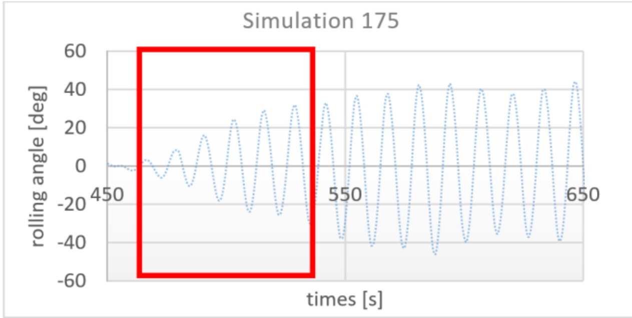

Figure 13. Simple parametric rolling with v_s= 7,25kn, β= 0°, T_w=17,87s, λ= 267,4m, H=11,92m

For the encounter period T_{e1}=T_R/1,8, parametric rolling was detected in the discrete simulation in 35.71%. Within the simulations, serial parametric rolling occurred in 67.5% at a ship speed of 7.25kn. The highest roll angles of up to 44.82° occurred at the ship speed of 7.25kn. Class1 was achieved 15% of the time, Class2 47.5%, Class3 also 15% and Class4 22.5%.

The simulations indicate the dependencies of the multiple parameters on each other so that the parametrization and conditional probability follows.

4.5 *Parametrization and conditional probability*

These dependencies for the multiple parameters of the discrete simulation are shown in figure 14 and are used to calculate the conditional probability of parametric rolling for T_{e2}=T_R/1,8. The highest probability for parametric rolling is for wave heights over 11m (ζ_{10-20}) independently from the wavelength λ and the vessel speed v.

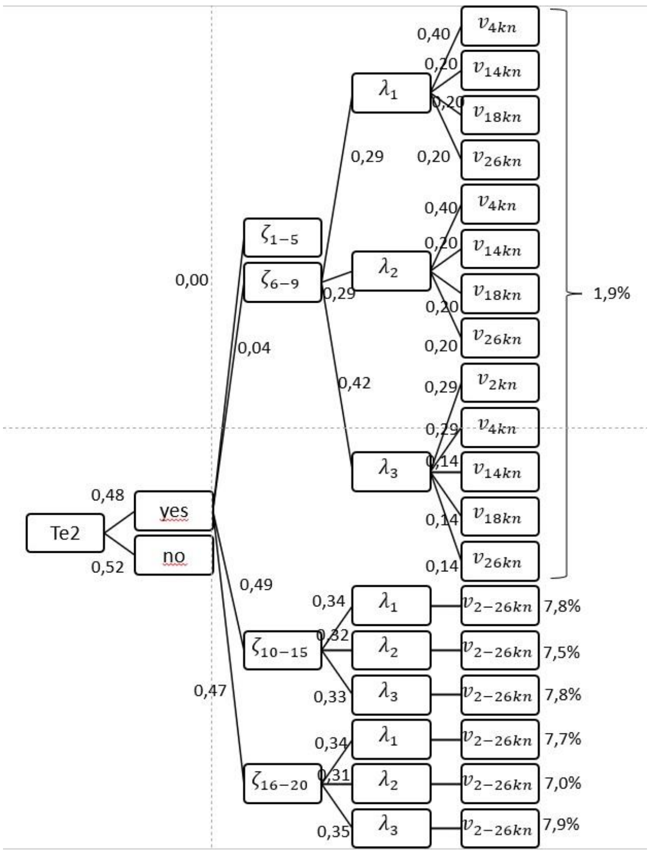

Figure 14. Conditional probability of parametric rolling

5 EVALUATION

In the evaluation, the accuracy of the multiple parameter application is compared to the related works (see table 3).

Table 3. Comparability with related works

	Parameter	Identification of p.R.
IMO [11]	1,3a,3b	100,00%
OCTOPUS [12]	1,2,3a,3b, wave height	100,00%
Silva and Soares [5]	3,4	x
PAROLL (R. Galeazzi, 2014)	1,2, wave height	100,00%
MARIN [14]	4	x
WaveSignal [15]	Radar	x
Multiple Parameter	1,2,3a,3b,5, wave height	48,00%

Table 3 shows that IMO [11], OCTOPUS [12] and PAROLL [13] would have deflected 100% across all simulations. Silva and Soares [5], as well as MARIN [14] and WaveSignal [15], cannot yet be portrayed because they use the variation of GM and a radar image. The own approach of multiple parameters reacted 35.71% of the time or identified parametric rolling in 35.71% of the simulations. By using multiple parameters in combination, it seems that a higher accuracy was achieved compared to the IMO [11], OCTOPUS [12] and PAROLL[13]. Whereas with the three methods listed, each simulation would have been identified as a parametric roll and thus an alarm would have been raised, by using the multiple parameters in combination, a smaller amount of simulation was identified. The limitations that parametric roll must occur from a roll angle of 25°, within 60 seconds, as well as that no damping may occur in the meantime, seem to have increased the accuracy. There is still no comparability with the work of Silva and Soares [5], MARIN [14] and WaveSignal [15], as the metacentric height was not yet considered in this work.

Additionally, as a novelty, the severity of parametric rolling is distinguished in four classes and serial parametric rolling was identified.

6 CONCLUSION/DISCUSSION

During multi-parameter discrete simulation for one wave period, a classification with 4 classes and 1 characteristic were introduced to describe parametric rolling in more detail like the serial parametric rolling, which was already outlined in several accident reports. This opens a more detailed view of the phenomenon. Similarly, the severity of parametric rolling was not differentiated in the past, although differences in the accident reports can be seen here as well. This subdivision into very extreme (class1), extreme (class2), strong (class3) and simple (class4) parametric rolling leads to a much more detailed view than before. It is now possible to distinguish whether a ship enters parametric rolling within 2, 3, 4 or more rolling motions and can thus bring about different countermeasures.

This work therefore allows considering parametric rolling not as a unique phenomenon, but in its diversity of occurrence with the risk of repetition (serial parametric rolling).

As further research, the simplification from chapter 4 would have to be removed and the simulations carried out. This will allow an even more accurate view of this phenomenon. Furthermore, other ship models in MARIN [1], such as a cruise ship or a RoRo (roll-on/roll-off) ship, would also be conceivable for further signings. The vulnerability of the different hulls would be a main point of investigation. Additionally, a further simulation software would have to be used for an evaluation and reliability of the results. Similarly, parameter 4 (variation of GM) needs to be investigated to establish comparability with MARIN [14] and Silva and Soares [5]. Comparability with WaveSignal [15] would only be possible by running both applications simultaneously over a simulation and labelling the deflections.

The next step would be to implement an artificial intelligence, which will serve real-time prediction in the current sea state for assistance systems.

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