On the influence of sea state idealizations and wave directionality in dynamic stability assessments

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ABSTRACT

Simplified spectral based methods, concluded feasible for on-board analysis of dynamic stability limits in previous studies, are here adjusted for use in short crested seas and applied on a RORO ship using detailed forecast 2D wave spectra and corresponding idealized spectra. The general trend is that the idealized spectra result in over prediction of the probability of exceeding dynamic stability limits with a few exceptions resulting in under prediction. The results highlight the importance of proper representation of the wave environment in dynamic stability assessments. The results are discussed in the context of operational guidance and routing.

KEYWORDS

sea state idealization; wave spectra; wave directionality; parametric rolling; pure loss of stability

INTRODUCTION

As ships are getting larger, more advanced and optimized, the need for in-service assessment of ship safety and performance, and therewith related operational guidance and routing, increases. In-service intact stability assessments can be performed in different ways on different levels of complexity, for example: in terms of look-up tables and charts as in IMO (2007); based on pre-calculations with multi-degree of freedom simulation methods as in Levadou & Gaillarde (2003); based on real-time on-board time-domain simulations as in Krüger et al. (2008); or based on simplified methods for estimation of dynamic stability limits as in Ovegård et al. (2012). Independently of approach, a crucial aspect is the recognition and representation of the wave environment.

In the most simplistic way the wave environment is estimated visually by the crew. The limitations in such approach are obvious, not least for complex mixed seas and also that it is dark half the time. In-situ measurements, such as X-band radar techniques or estimation methods based on ship motion measurements, are limited to real-time and cannot be used for routing purposes. Routing is usually performed based on forecasts. Since the bandwidth in the shore-ship data communication generally is very limited, the forecast sea state information sent to the ship is however normally limited to just a few parameters, such as significant wave height, mean period, and main propagation direction, sometimes separated in one wind wave system and one swell system. From these parameters a simplified sea state representation can then be re-created on-board based on idealized wave spectrum functions. The limitations are here related to the shortcomings of the forecast model and how the idealized spectral models represent complex mixed sea states.

Not many studies are found in the literature on the influence of wave directionality on ship stability and response predictions. One example is Mynett et al. (1988) where model experiment comparison is made between ship responses in uni-directional and directional seas, concluding pronounced differences for seas with wind and swell contributions with different main directions and spreading. Another example is Graham & Juszko (1993) where ship responses in a 2D hindcast spectrum are compared with responses in a corresponding 10-parameter spectrum, and a 2-parameter spectrum with standard spreading function, concluding significant differences for bi-modal seas. Both these studies are limited in ship types, speeds and sea states, neither of them discuss the influence of wave height, nor do they draw conclusions on the quantitative aspects the errors might imply in practice.

The present study is a continuation of Ovegård et al. (2012) and Björnsson (2013). The objective is to highlight the issues of sea state idealization and wave directionality in in-service intact stability assessments and related operational guidance and routing. In Björnsson (2013) the consequence of sea state idealization in the calculation of ship responses and added resistance was studied. In Ovegård et al. (2012) the simplified spectral based methods for analysis of dynamic stability limits presented in Dunwoody (1989a&b) and Bulian (2010), were thoroughly evaluated in head and following long crested seas and concluded to be feasible for use in operational guidance and routing. Here these methods are adjusted for short crested seas and applied on a RORO ship. Comparison is made between stability limits in detailed 2D representations of the wave environment from a global wave model and corresponding idealized representations. The methodologies and significant results are reviewed and discussed in relation to operational guidance and routing.

SIMPLIFIED METHODS FOR DYNAMIC STABILITY ASSESSMENT

The methods presented in Bulian (2010), Dunwoody (1989a&b) and Ovegård et al. (2012) are based on the assumption that the roll restoring variation in irregular waves can be considered to be a linear stationary Gaussian stochastic process. This is here represented by the variation in metacentric height

$$x(t) = GM(t) - GM_{cw} \qquad (1)$$

where $GM(t)$ is the momentary metacentric height and GM_{cw} is the calm water metacentric height. Linear signal theory can hereby be used to calculate the spectral representation of the GM-variation $x(t)$ as

$$S_x(\omega,\mu,U) = |\mathrm{Y}_x(\omega,\mu,U)|^2 S_w(\omega,\mu) \qquad (2)$$

where ω is the angular frequency, μ is the direction, U is the ship speed, $S_w(\omega,\mu)$ is the wave spectrum, and $\mathrm{Y}_x(\omega,\mu,U)$ is the GM-variation transfer function which here is calculated according to Palmquist (1994). Since it is the wave length and not the wave frequency that is governing the stability variations, the GM-variation spectrum should be calculated in the global frequency domain. The encounter frequencies however have to be considered when analyzing the resonance condition in case of parametric rolling and the persistence time below a critical GM-level in case of pure loss of stability as described in the following.

According to Bulian (2010) a pure loss of stability failure can be assumed to occur when the persistence time τ of the GM-variation $x(t)$ below a critical level

$$x_L = GM_{crit} - GM_{cw} \leq 0 \qquad (3)$$

is longer than a critical threshold, τ_{crit}. In Bulian (2010) a Pure Loss Failure Index (PLFI) is formulated as the probability that at least one pure loss of stability failure occurs within a certain exposure time T_{exp}. The index is formulated as

$$PLFI = 1 - e^{-\lambda_F T_{exp}} \qquad (4)$$

where the failure intensity λ_F, under the assumption that the process is narrow banded, can be expressed as

$$\lambda_F = \begin{cases} \dfrac{\omega_z}{2\pi} e^{-\frac{x_L^2}{2m_{0,e}}\left(1+\tan^2\left(\frac{\omega_z \tau_{crit}}{2}\right)\right)} \ \forall\ \omega_z < \dfrac{\pi}{\tau_{crit}} \\ 0 \ \forall\ \omega_z \geq \dfrac{\pi}{\tau_{crit}} \end{cases} \qquad (5)$$

For a certain speed U and relative heading μ_{rel}:

$$m_{n,e} = \int_{\mu_1}^{\mu_2} \int_0^{\infty} {\omega_e}^n S_x(\omega, \mu, U) d\omega d\mu \quad (6)$$

$$\omega_e = \left| \omega - \frac{\omega^2}{\Omega} \right| \quad (7)$$

$$\Omega = \frac{g}{U cos\mu_{rel}} \quad (8)$$

$$\omega_z = \sqrt{m_{2,e}/m_{0,e}} \quad (9)$$

where $\mu_1 \leq \mu \leq \mu_2$ only includes following wave components.

According to Dunwoody (1989b) a GM-variation in waves produces an effect analogous to a reduction in the roll damping. A 2:1 parametric roll failure can be assumed to occur if the GM-variation related roll damping reduction at an encounter frequency equal to twice the roll natural frequency is larger than the ship roll damping. A Parametric Roll Failure Index (PRFI) could hereby be formulated as

$$PRFI = E[\zeta^*]/\zeta \quad (10)$$

where ζ is the linear roll damping expressed as a fraction of the critical damping and ζ^* is the GM-variation related roll damping reduction. $E[\zeta^*]$ is the expected value of the roll damping reduction, which according to Dunwoody (1989b) can be calculated as

$$E[\zeta^*] = \frac{\pi g^2 S_{x,e}(\omega_e = 2\omega_n, U)}{4\omega_n \omega_d^2 r^4} \quad (11)$$

where g is the gravitational constant, r is the roll radius of gyration, ω_n and ω_d are the un-damped and damped roll natural frequencies, and $S_{x,e}$ is the GM-variation encounter spectrum.

Usually in linear response calculations there is a way around determining the encounter spectrum by only considering results that can be expressed in terms of spectral moments, which as in (6) can be determined based on the non-transformed spectrum. Here, however, transformation of the GM-variation spectrum to the encounter frequency domain is inevitable for the determination of $S_{x,e}(\omega_e = 2\omega_n, U)$. For following seas the singular frequency $\omega = 0.5\Omega$ and the multi-valued nature of the encounter spectrum around this frequency have to be carefully considered. The encounter spectrum is here determined as

$$S_{x,e}(\omega_e, U) = \int_0^{2\pi} S_{x,e}(\omega_e, \mu, U)\, d\mu \quad (12)$$

where

$$S_{x,e}(\omega_e, \mu, U) = \sum_{j=1}^{3} \frac{S_{x,j}(\omega_j, \mu, U)}{\left|1 - \frac{2\omega_j}{\Omega}\right|} \quad (13)$$

$$0 \leq \omega_1 < 0.5\Omega \quad (14)$$

$$0.5\Omega < \omega_2 < \Omega \quad (15)$$

$$\omega_3 \geq \Omega \quad (16)$$

Based on a convergence study the singular frequency $\omega = 0.5\Omega$ is resolved with two frequencies $\omega = 0.5\Omega \pm 10^{-9}$ and with $\Delta\omega = 10^{-5}$ in an interval around $\omega = 0.5\Omega$.

Theoretically the parametric roll stability limit is defined by PRFI=1, which corresponds to a stability variation related roll damping reduction equal to the ship roll damping. In Ovegård et al (2012) this was considered to be too conservative for the PCTC in that study and RPFI=4 is instead used as the critical level. What to be used as critical level in the assessment of PLFI depends on the desired safety level. In Ovegård et al (2012) PLFI=0.1% is used and it is concluded that the critical levels should be tuned for each ship.

SEA STATE REPRESENTATIONS

Weather centra such as ECMWF (the European Centre for Medium-range Weather Forecasts) generate detailed 2D wave spectra as part of their weather forecasts. Fig. 1 gives an example of an ECMWF forecast spectrum and the corresponding parameters.

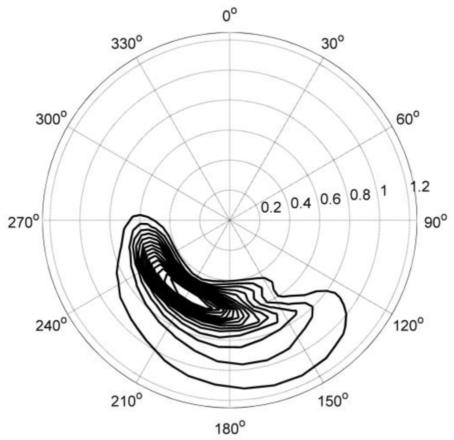

Fig. 1: Example of a two-dimensional ECMWF forecast wave spectrum for the location N34E-31 at 00:00. Angular directions in a global coordinate system, north up. Radial frequencies in rad/s. For this sea state ECMWF provides the following parameters: Total wave height Htotal=6.3 m. Wind waves: Hs=5.5 m (significant wave height); Tm=8.8 s (mean period); μ=185 deg (main direction). Swell: Hs=3.2 m; Tm=11 s; μ=243 deg.

As mentioned in the introduction, the bandwidth in shore-ship data communication is usually too limited to permit complete forecast spectra to be sent to the ship. Hence, the forecast information available aboard is generally limited to just a few parameters. For on-board guidance and routing purposes simplified sea state representations therefore have to be re-constructed based on the available parameters and idealized wave spectrum functions. For the purpose of evaluating the influence of such simplifications on the accuracy of on-board stability assessments, simplified sea state representations are in the present study generated based on significant wave height, mean period, and main wave direction for one wind wave system and one swell system, as provided by the ECMWF-model, using an ISSC spectrum with a standard cosine-squared spreading function to represent wind-waves and a one-dimensional 3-parameter Ochi-Hubble spectrum to represent swell.

RESULTS

The RORO ship Finnbirch, with data according to Table 1, is here used as an applicatory example. This ship capsized and sank due to reduced stability in quartering seas (Hellner & Bexell 2008). An example of the GM-transfer function at 20 knots is given in Fig. 2. As seen the maximum stability variations 0.55 m/m occur for waves with frequencies $\omega \approx 0.7$ rad/s, which corresponds to wave lengths equal to the ship length. This in combination with the natural roll period 0.42 rad/s (Table 1) and the frequent occurrence of waves with mean frequencies around 0.6 to 0.8 rad/s, make it obvious that the ship also is in the risk zone for parametric rolling. This has also been shown in previous studies (e.g. Ovegård et al. 2012, Krüger et al. 2008).

Table 1: Data for Finnbirch. When calculating PLFI the following are used: T_{exp}=3600s; GM_{crit}=0.15m; τ_{crit}=7.5s (as in Ovegård et al. 2012).

Length between perpendiculars [m]	137
Roll damping (assumed) [% of critical]	10
Roll radius of inertia (assumed) [% of ship beam]	35
Metacentric height [m]	1.36
Natural roll period [s]	15
Natural roll frequency [rad/s]	0.42
Speed [kn]	18
Relative heading [deg]	20

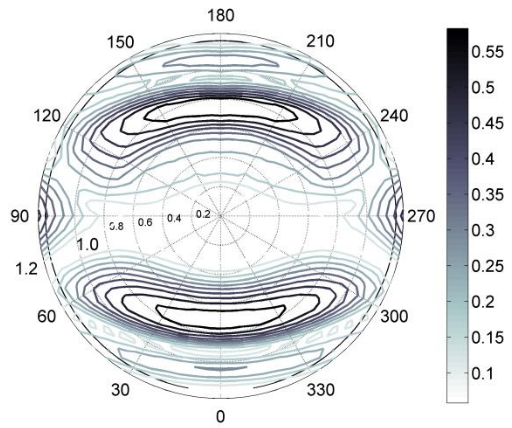

Fig. 2: GM-variation transfer function [m/m] for Finnbirch at 20 knots. Angular directions in degrees in a ship-fixed coordinate system (180 deg head seas). Radial frequencies in rad/s.

Fig. 3 and 4 give examples of the PRFI calculated for the forecast wave spectrum in Fig. 1 and the corresponding idealized spectrum. As seen the agreement is here rather good. At zero speed the PRFI is between 1 and 1.5 when the ship is heading north or south, and between 0.5 and 1 at eastern or western headings. These results can easily be understood by observing the wave spectrum in Fig. 1. As seen a northern and southern ship course corresponds to head and following seas for the wind-wave system (185 degrees) which has an average frequency slightly lower than twice the ship's natural roll period. When the speed is increased to 4 knots the PRFI increase for head seas and decreases in the other relative directions. Also this is what one could expect from Fig. 1 and 2, in that the wave lengths that give the largest stability variations are being encountered at frequencies closer to 2:1 parametric excitation.

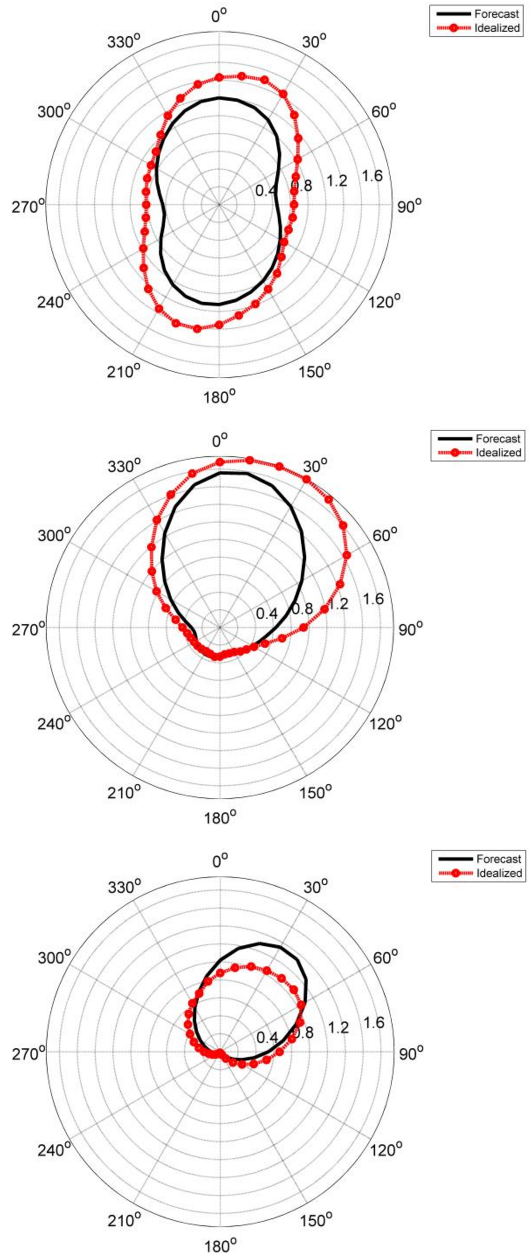

Fig. 3: PRFI (radially) for different ship courses (global coordinate system) at 0, 4 and 12 knots (upper to lower diagram) for the forecasted wave spectrum N32E-30 00:00 and the corresponding idealized spectrum.

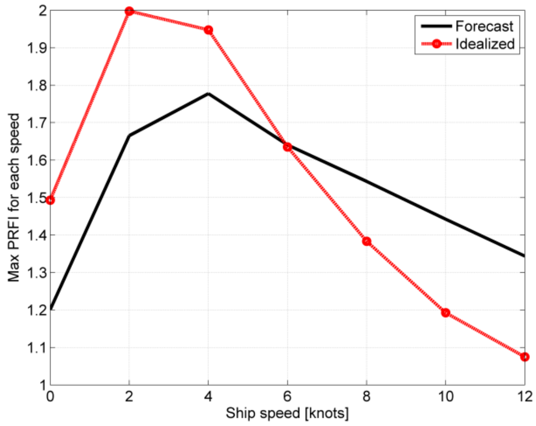

Fig. 4: Maximum PRFI for each speed for the forecast wave spectrum N32E-30 00:00 and the corresponding idealized spectrum.

Fig. 5 gives examples of GM encounter spectra in the ship-fixed coordinate system (where 180 deg corresponds to head seas) for a speed of 4 knots and a course 30 degrees, calculated with the forecast spectrum in Fig. 1 (upper diagram) and the corresponding idealized spectrum (lower diagram). The wind-waves parts of the spectra are rather similar while the one-dimensional swell spectrum in the idealized case (which here has been spread over a directional interval of 10 deg) differs significantly from the forecast spectrum. Considering the good agreement of the PRFI results, the idealized sea state however seems to give a rather good representation of the dynamic stability situation. Fig. 6 gives examples of the PLFI calculated for the forecasted spectrum in Fig. 1 and the corresponding idealized spectrum. As for the PRFI the agreement is rather good, and the results indicate high probability for pure loss failure for headings coinciding with the swell direction. The influence of the one-dimensionality of the idealized swell is however seen as a slight shift of the PLFI maximum.

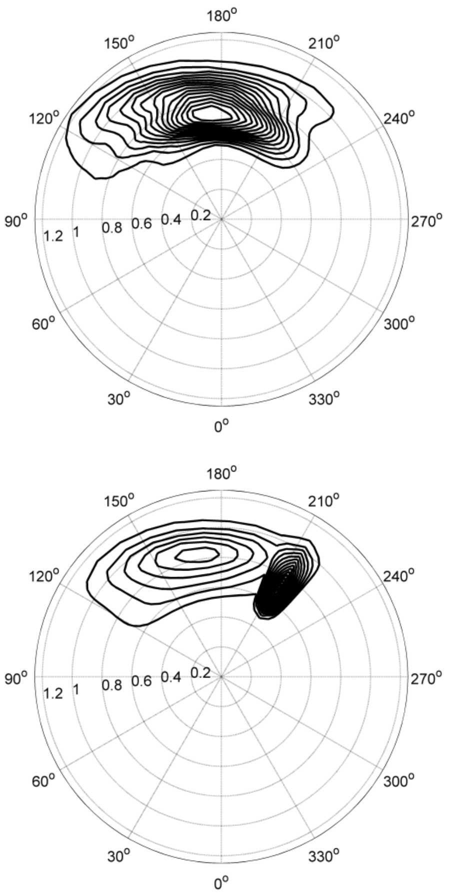

Fig. 5: GM encounter spectra at 4 knots and a ship course 30 deg for the ECMWF forecast wave spectrum N32E-30 00:00 (upper) and the corresponding idealized spectrum (lower). Angular directions in a ship fixed coordinate system (180 deg head seas). Radial frequencies in rad/s.

Fig. 7 and 8 give examples of the PRFI calculated for another sea state (N32E-30 09:00). In contrast to the previous case, the agreement between the results based on the forecast and idealized spectra is here very poor, where the idealized spectrum results in significant over predictions of the PRFI. In the previous case (Fig. 1&3-6) the sea state could from the ECMWF parameters be interpreted as blended, with a wind related significant wave height of 5.5 m and a swell related significant wave height of 3.2 m. In this case (Fig. 7-9) the sea state is however in the parameter extraction interpreted as completely swell dominated with a swell related significant wave height of 5.1 m and practically no wind waves. The consequence of this is clearly seen in Fig. 9 where there is a very large difference between the GM-spectrum calculated using the forecast spectrum, which obviously is rather spread, and that calculated using the idealized one-dimensional swell spectrum. The erroneous energy concentration in the idealized spectrum causes the over prediction of the PRFI and similarly also for the PLFI.

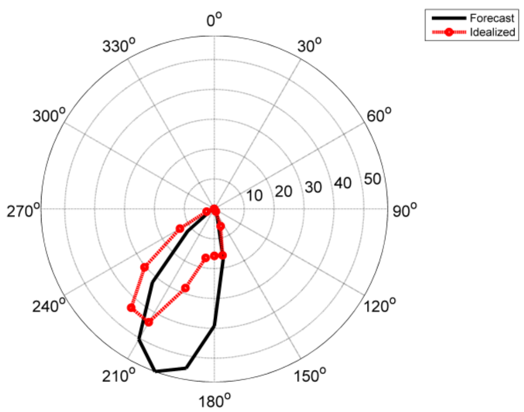

Fig. 6: PLFI (radially in %) for different ship courses (global coordinate system) at 20 knots for the forecast wave spectrum N32E-30 00:00 and the corresponding idealized spectrum.

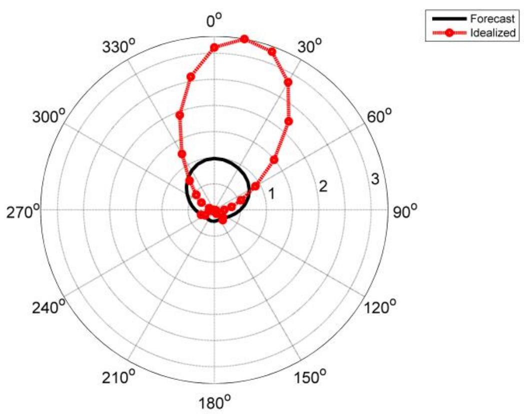

Fig. 7: PRFI (radially) for different ship courses (global coordinate system) at 4 knots for the forecast wave spectrum N32E-30 09:00 and the corresponding idealized spectrum.

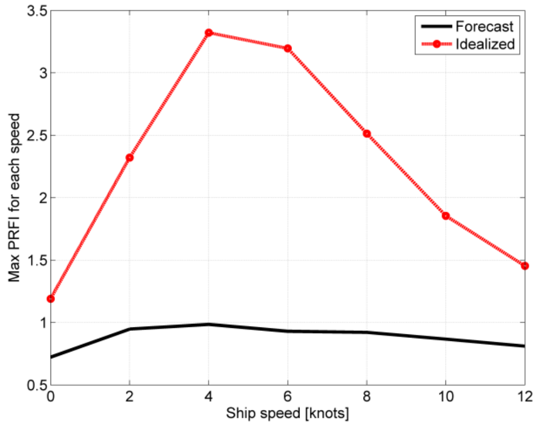

Fig. 8: Maximum PRFI for each speed for the forecast wave spectrum N32E-30 09:00 and the corresponding idealized spectrum.

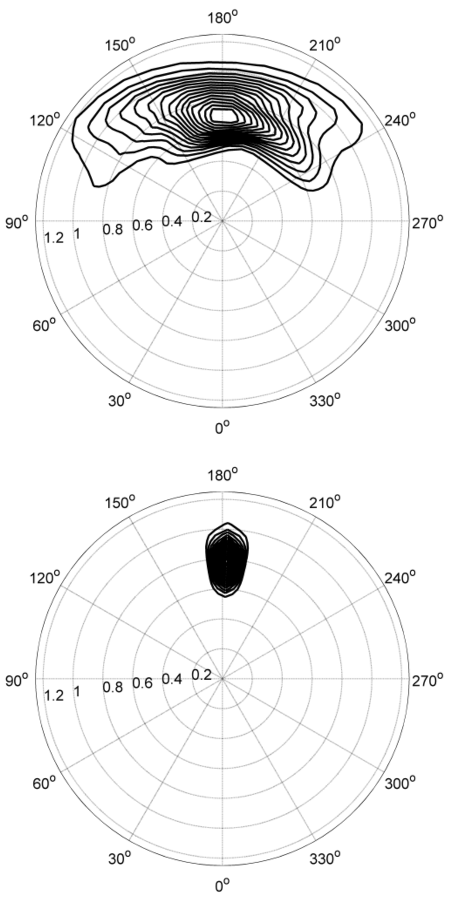

Fig. 9: GM encounter spectra at 4 knots and a ship course 10 deg for the ECMWF forecast wave spectrum N32E-30 09:00 (upper) and the corresponding idealized spectrum (lower). Angular directions in a ship-fixed coordinate system (180 deg head seas). Radial frequencies in rad/s. For this sea state ECMWF provides the following parameters: Total wave height Htotal=5.1 m. Wind waves: Hs=0.47 m (significant wave height); Tm=3.1 s (mean period); μ=205 deg (main direction). Swell: Hs=5.1 m; Tm=9.6 s; μ=192 deg.

To get a more general picture a large number of sea states are analyzed. These are taken from 1530 locations with 1 degree separation between N59E-11 and N23E-52 at every third hour during the 25th of September 2012, in total 12240 sea states (see Björnsson 2013). From these all sea states with a significant wave height larger than 3 meters are chosen giving a total of 2789. For each of these PRFI and PLFI are calculated for ship speeds from 0 to 20 knots and course angles from 0 to 360 degrees.

Table 2 shows the number of sea states, in % of the studied 2789, where the PRFI exceed 1 for any course at speeds 0-12 knots. As seen, using the idealized spectra implies an over prediction of the number of critical sea states in speeds 0-6 knots and a slight under prediction for the higher speeds, compared to using the forecast spectra.

Table 2: Number of sea states, in % of the studied 2789, where PRFI exceeds the critical limit 1.

Speed [kn]	Forecast N > lim [%]	Idealized N > lim [%]
0	10	18
2	37	45
4	36	55
6	23	34
8	14	11
10	8.0	3.0
12	5.0	1.0

Table 3 shows the number of sea states, in % of the studied 2789, for which the PLFI exceeds 0.1% for any course at speeds 16-20 knots. As seen, using the idealized spectra result in over prediction of the failure probability, where twice as many sea states are identified as critical compared to if using the forecast spectra. In general it is observed that the PLFI reaches critical levels for a narrow course interval corresponding to following seas and only for speeds larger than or equal to 16 knots.

Table 3: Number of sea states, in % of the studied 2789, where PLFI exceeds the critical limit 0.1 %.

Speed [kn]	Forecast N > lim [%]	Idealized N > lim [%]
16	3.0	1.0
18	18	35
20	44	74

CONCLUSIONS & DISCUSSION

The simplified spectral based methods for analysis of dynamic stability limits related to parametric rolling and pure loss of stability, presented and evaluated in Dunwoody (1989a&b), Bulian (2010) and Ovegård et al (2012), have here been adjusted for short crested seas and are concluded to give consistent results. Further effort should be put on evaluation based on experiments and multi-degree-of-freedom simulations in short crested seas.

The methods have been applied on a RORO ship in detailed forecast 2D wave spectra and corresponding idealized wave conditions modeled as a combination of wind waves and swell spectra. The general trend is that the idealized spectra result in over prediction of the probability of exceeding dynamic stability limits. A few cases of under prediction are however also found. The results highlight the importance of proper representation of the wave environment in the evaluation of dynamic stability related risks. Over prediction of the risk might for example result in unnecessary and costly detours if the stability assessment is part of a routing procedure. Under prediction might misguide the crew if the stability assessment is part of real-time operational guidance.

The way forward could be to develop improved methods for sea state parameter extraction and spectrum idealization. Another option is to move the operationally related stability assessments ashore to enable making use of the complete forecast information. Establishment of methods for in-situ wave measurements would also be beneficial. These issues should be further considered, for example in stability assessments based on a safety level approach, and in the consideration of operational guidance as part of the framework of the second generation intact stability criteria.

ACKNOWLEDGEMENTS

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