Review of seakeeping criteria for container ship sustainable speed calculation in rough weather

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ABSTRACT: This paper presents overview of existing seakeeping criteria for ship speed calculation in rough weather, applicable for large container ships. Sea states describing rough weather are given for North Atlantic sea environment according to the IACS recommendation Note No.34. Criteria are calculated for different ship responses in short-term sea states based on the response amplitude operators (RAO). 3D panel method is employed for computation of RAOs, while 2-P Pierson–Moskowitz wave spectrum is used for short term spectral analysis. Seakeeping criteria considered in the study are slamming, deck wetness, and vertical acceleration at bow. Sustainable ship speed is determined as combination of selected criteria and it is presented in polar plot diagrams for representative sea states. Practical overview how seamen feel operational criteria and which is sustainable speed in real life is also presented. In the conclusion, critical assessment of criteria is performed and guidelines for future research are provided.

1 INTRODUCTION

Maritime transport has a great role in global transport of goods and products. Ship operations have to be optimized because of accuracy and safety of transportation. Component of safe transport is durability of ship structure which is affected by loads. Large part of total loads on ship structure is caused by sea waves. Ship maneuvering is one of ship operations that has effect on extreme values of wave loads. Wave heading and ship velocity are maneuvering components that can be changed by seamen. Open sea ship maneuvering in non-extreme environment conditions, largely, is a routine. Problems appear when ship is in extreme environment conditions when loads on ship structure are on high level. In those cases maneuvering has to be done such as changing direction of wave heading and/or reducing speed. Knowledge of wave loads and sustainable speeds simplify decisions to seamen. Seamen have to respect operability criteria for voluntary speed reduction and route changing in order to avoid possible damage of ship structure or cargo. Operability criteria considered in this paper are slamming, deck wetness, and vertical acceleration.

Limiting values of operability criteria used in the present paper are given by Kehoe (1973), Ochi and Motter (1974) and Aertssen (1963, 1966, 1968, 1972). Review of limiting values given by mentioned authors is also presented by Lloyd (1998). Influence of criteria limiting values are shown on example of 9200 TEU container ship by operability polar plots and other types of operability diagrams. Diagrams are discussed from the point of view of seafarers and their practical applicability is investigated.

2 OPERABILITY CRITERIA

Limiting values of operability criteria are used in seakeeping studies to validate ship response on different sea states. Exceeding limiting values leads to a reduction of ship operability. Operability limiting values represent border between acceptable and unacceptable phenomena such as number of bottom slamming in one minute or amount of vertical acceleration on fore perpendicular, etc. However, mentioned border is hard to define. Data from service therefore have priceless value. Statistical analysis of service data in comparison with seakeeping calculations gives the best validation of operation limiting values.

2.1 *Slamming*

At certain ship speeds and certain sea states bow of the ship emerges out of the sea. Re-entry leads to impact between flat bottom in the forward part of the ship and the sea surface. Result of impact is the suddenly developed force that produces transient vibrations of the hull, known as whipping. Seafarers can clearly feel slamming because vibrations of the hull complicate normal activity on board such as steerage, navigation, cargo control, etc. Slamming also complicates repose of the crew which is very important for ship safety. Emerging of the bow is result of relative motions between sea surface elevation and ship motion components such as heave and pitch. Slamming will occur if relative motion is larger than draft of the ship and if relative speed is larger than critical speed (Ochi & Motter 1974).

Ochi defined a critical relative speed of the bow as:

$$v_{cr} = 0.093\sqrt{g \cdot L} \tag{1}$$

where v_{cr} is critical relative velocity, g is acceleration of gravity and L is length of the ship.

Limiting value of slamming is usually given in term of probability. Probability of slamming is given as (Journée 1976):

$$P_{slamming} = e^{-\left(\frac{D^2}{2m_{0r}} + \frac{v_{cr}^2}{2m_{0v}}\right)} \tag{2}$$

where D is draft of the ship, m_{0r} is zero spectral moment for relative motion, and m_{0v} is zero spectral moment for relative velocity. Limiting values of probability for slamming are given by many authors for merchant ships (Table 1).

Table 1. Limiting values of probability for slamming by different authors

Author	Ochi and Motter (1974)	SRA Japan (1975)	Aertssen (1963, 1966, 1968, 1972)	Moan et al.(2006)
Limiting value	0.03	0.01	0.03	0.02

2.2 *Deck wetness*

Appearance of deck wetness can happen at any place on the ship where freeboard is not high enough. It usually occurs on fore part of the ship when relative motion of the bow exceeds height of the freeboard on bow. Deck wetness can cause equipment damage and loss of the cargo, especially on container ships.

This type of seakeeping criteria is the most recognizable amongst seafarers because it is visually attractive. Probability of deck wetness is given as (Journée 1976):

$$P_{deck\ wetness} = e^{-\left(\frac{f_x^2}{2m_{0r}}\right)} \tag{3}$$

where f_x is freeboard on section x of the ship, m_{0r} is zero spectral moment of relative motion. Limiting values of probability for deck wetness are given by many authors for merchant ships (Table 2).

Table 2. Limiting values of probability for deck wetness by different authors

Author	Ochi and Motter (1974)	SRA Japan (1975)	Moan et al.(2006)
Limiting value	0.07	0.02	0.05

2.3 *Vertical acceleration at forward perpendicular*

Absolute vertical acceleration on bow can cause damage of the structure or equipment. Furthermore, excessive accelerations could disturb seafarers in their normal activity on ship. Inexperienced or not adapted seafarers feel seasickness that leads to impossibility of normal work and deficit of safety on ship. Vertical accelerations on the bridge are also very important for seafarers but are not taken under considerations when calculating operability. Limiting values (RMS) for vertical acceleration are given for different types of ships (Table 3.).

Table 3. Root mean square (RMS) of vertical accelerations at FP (Moan et al. 2006):

Merchant ships	0.275g (L_{pp}<100m) 0.050g (100m<L_{pp}<330m)
VLCC	0.06g
Product tanker	0.19g
Bulk carrier	0.09g
Containership	0.108g

3 PRACTICAL APPLICATION OF OPERABILITY CRITERIA

Application of operability criteria is performed for 9200TEU container ship.

Table 4. Characteristics of 9200 TEU container ship

Lpp	335m
B	42.8m
T	13.17m
v	25kn
Capacity	9200 TEU

Seakeeping features are calculated for different ship responses in short-term sea states based on the response amplitude operators (RAO). 3D panel method is employed for computation of RAOs, while 2-P Pierson–Moskowitz wave spectrum is used for short term spectral analysis. Sea states describing rough weather are given for North Atlantic sea environment according to the IACS recommendation Note No.34 (Table 5).

		Tz - zero period							
		5,5	**6,5**	**7,5**	**8,5**	**9,5**	**10,5**	**11,5**	**12,5**
Hs - significant wave height	**0,5**	865,6	1186,0	634,2	186,3	36,9	5,6	0,7	0,1
	1,5	986	4976,0	7738,0	5569,7	2375,7	703,5	160,7	30,5
	2,5	197,5	2158,8	6230,0	7449,5	4860,4	2066,0	644,5	160,2
	3,5	34,9	696,5	3226,5	5675,0	5099,1	2838,0	114,1	337,7
	4,5	6	196,1	1354,3	3288,5	3857,5	2685,5	1275,2	455,1
	5,5	1	51,0	498,4	1602,9	2372,7	2008,3	1126,0	463,6
	6,5	0,2	12,6	167,0	690,3	1257,9	1268,6	825,9	386,8
	7,5	0	3,0	52,1	270,1	594,4	703,2	524,9	276,7
	8,5	0	0,7	15,4	97,9	255,9	350,6	296,9	174,6
	9,5	0	0,2	4,3	33,2	101,9	159,9	152,2	99,2

Table 5. Interesting sea states from wave scatter diagram - IACS recommendation Note No.34

RAOs are calculated using state-of-the-art seakeeping software Hydrostar (Bureau Veritas 2010) while results are post processed using program Starspec (Bureau Veritas 2010). Calculations are based on 3D panel method and linear potential theory.

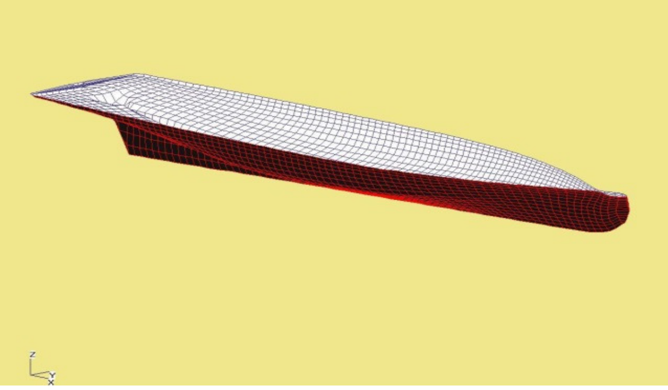

Figure 1. 9200 TEU hydrodynamic model in Hydrostar

3.1 *Calculation of response amplitude operators*

Response amplitude operators (RAOs) are calculated at forward part of the ships for:

- relative vertical motion (Fig.2),
- relative vertical velocity (Fig.3),
- absolute acceleration (Fig.4).

All three RAOs are calculated for four speeds:

$$\frac{1}{4}v = 3.125m/s$$

$$\frac{1}{2}v = 6.430m/s$$

$$\frac{3}{4}v = 9.645m/s$$

$$v = 12.460m/s$$

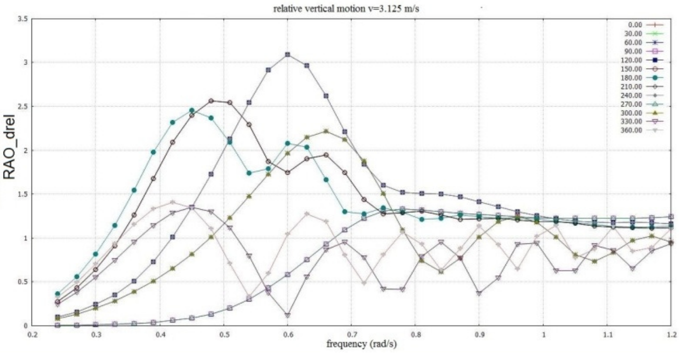

Figure 2. RAO for relative vertical motion, v=3.215m/s

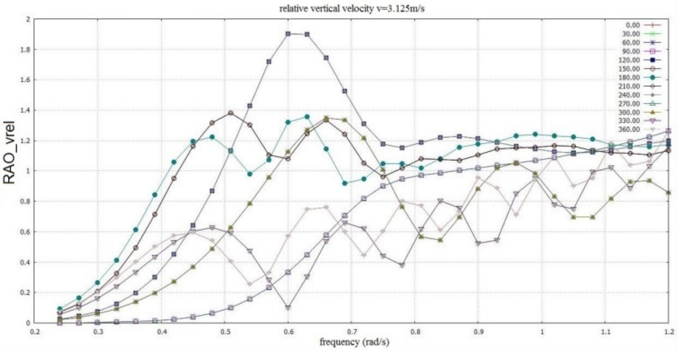

Figure 3. RAO for relative vertical velocity, v=3.125m/s

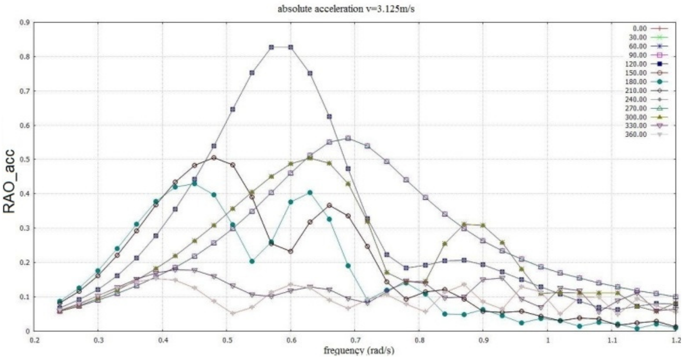

Figure 4. RAO for absolute acceleration, v=3.125m/s

Figures 2, 3 and 4 represent RAOs for different wave headings (0^0-360^0). RAOs are dimensionless values and in dependence of frequency.

3.2 *Calculation of significant response of the ship in rough sea states*

For assessment of ship operability in rough sea states, ship response is calculated by Starspec software for spectral analysis. In this calculation only short term ship response is investigated because of assumption that rough sea state represents storm that lasts a few hours (short term).

Some marginal sea states are excluded from IACS No.34 scatter diagram while interesting sea states presented in Table 5 are taken into account.

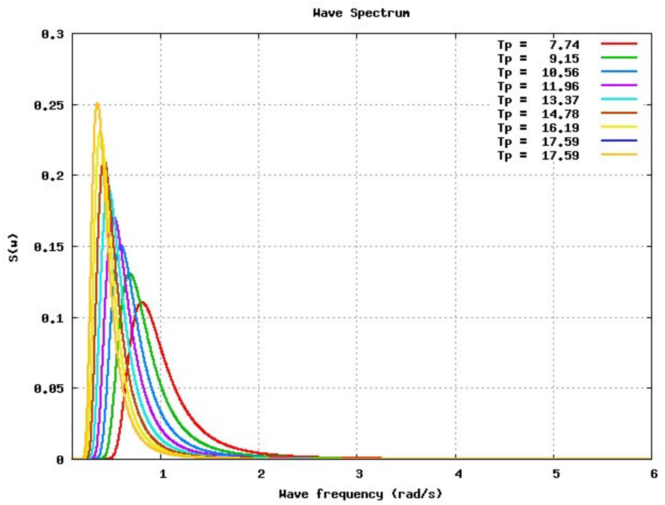

Figure 5. Relevant wave spectra for IACS No.34 scatter diagram (H_s=1m)

Figure 5 represents wave spectra (H_s=1m) for interesting sea states defined in Table 5. Relation between T_p (Fig.5) and T_z (Table5) reads:

$$T_p=1{,}41\ T_z \tag{4}$$

where T_p is peak wave period and T_z is zero wave period (Prpić-Oršić & Čorić 2006.).

2-P Pierson–Moskowitz wave spectrum formulation is used for short term spectral analysis. Formula for 2-P Pierson–Moskowitz wave spectrum reads:

$$S_w(\omega) = \frac{5}{16} H_S^2 \cdot \omega_p^4 \cdot \omega^{-5} \cdot e^{\frac{-5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}} \tag{5}$$

where H_s is significant wave height, ω is wave frequency and ω_p is given as:

$$\omega_p = \frac{2\pi}{1.27 \cdot T_Z} \tag{6}$$

180° means that ship is heading waves with bow. One of the results of spectral analysis is zero spectral moment which represents variance of wave process defined by wave spectrum. Significant response may be determined as:

$$R_S = 4 \cdot \sqrt{m_0} \tag{7}$$

where R_S is significant response (double amplitude) and m_0 is zero spectral moment Significant response is calculated for each combination of RAO and speed of the ship.

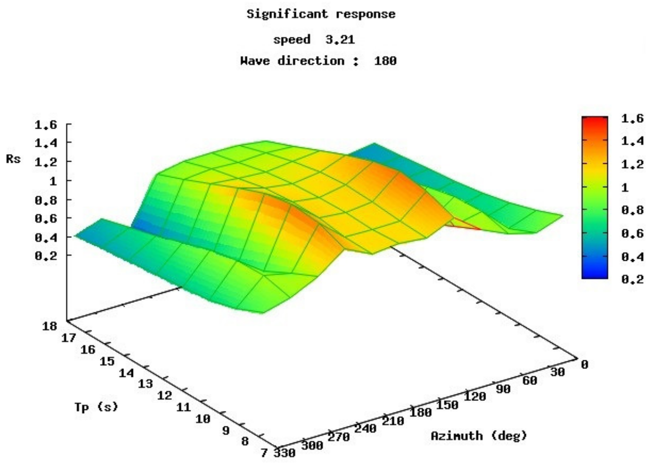

Figure 6. Significant response of relative velocity, v=3.125m/s, wave direction in bow (180) (for H_s=1m)

Figure 6 shows that maximum significant response of the ship occurs for peak period range between 7 and 13 seconds. That period range is recognized as significant and taken into calculation. Other wave periods (lower or higher) cause low values of significant response. Also, Figures 2, 3 and 4 shows that the highest values of the RAOs are for wave headings 120^0 and 240^0 which is in agreement with Figure 6.

3.3 *Limiting values of operability criteria*

Values of operability criteria i.e. slamming, deck wetness and vertical acceleration on F.P., representing margin between acceptable and unacceptable ship responses, are given in Table 5. Amongst many limiting values (Table1, Table 2 and Table3), values given by Moan et al. (2006) are chosen.

Table 6. Limiting values used in operability calculation (Moan et al. 2006)

Limiting probability of slamming	0.0112
Limiting probability of deck wetness	0.05
Limiting RMS of vertical bow accelerations	0.108g

3.4 *Results*

Calculations carried out in Starspec connect significant responses and limiting values of operability criteria. Results are practically shown in:

- operability polar plots showing which navigation azimuth is possible and safe for one sea state (Fig. 7),
- operability diagram that shows which maneuver should be done on each sea state (Fig. 8),
- speed diagram that shows which speed is sustainable for each sea state (Fig. 9).

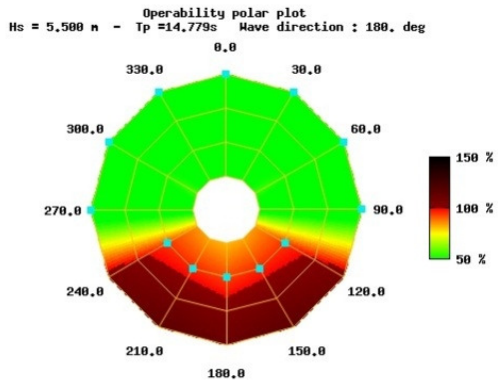

Figure 7. Polar diagram for different speeds and heading on one sea state.

Polar diagram in Figure 7 shows overshooting of criteria in percentage. Diagram is valid for H_s=5.5m and T_p=14.8s where it is obvious that speed needs to be reduced for head and bow seas (from 180 to 120 deg). Significant response shown on Figure 6 is maximum in azimuth range between 120° and 240° which is also shown on Figure 7. In mentioned azimuth range operability limiting values are reached or overshooted. Detailed calculations showed that the reason for overshooting criteria is slamming which is usually the most severe operability limiting criterion.

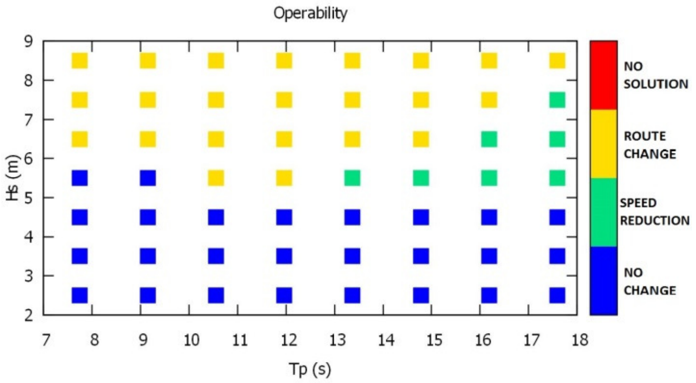

Figure 8. Operability diagram for different sea states

Operability diagram in Figure 8 shows appropriate maneuvers for navigation on different sea states. Interesting maneuvers are speed reduction and route change. Both lead to reduction of operability criteria under limiting value. Speed reduction is maneuver that is done first. Maneuver that is done when speed reduction is not enough is route change.

It is obvious that for H_s=5.5m and T_p=14.8s speed reduction has to be done. That can also be seen on Figure 7.

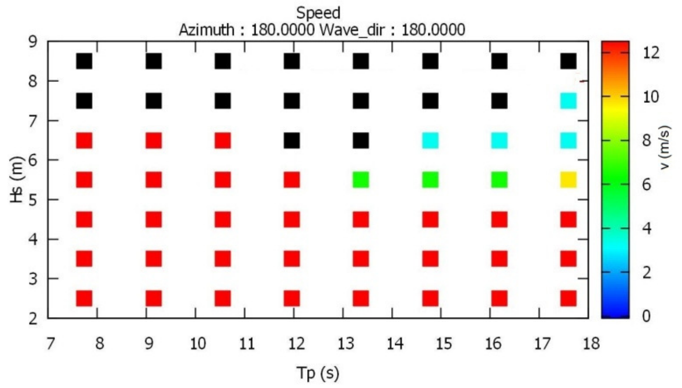

Figure 9. Speed diagram for different sea states assuming head seas

Speed diagram for different sea states, assuming head seas are shown in Figure 9. Diagram represents speed limit for not overshooting operability criteria. It is obvious that for H_s=5.5m and T_p=14.8s ship speed has to be under 6m/s.

4 CONCLUSION

Polar plot, operability diagrams and speed diagrams presented in the paper represent orientation mark for seafarers how to maneuver ship on rough sea. A lot of uncertainties exist in this field of navigation and naval architecture. Ship structural design and safety depends on the extreme wave induced loads. Those loads depend a lot on the maneuvering in heavy seas. Maneuvers are based on the experience and practice of ship master. Therefore, maritime navigation and naval architecture are closely related fields that are the main issue of the research described in the present paper.

Polar plots are given for each sea state. Number of sea states is large which makes list of polar plots unusable for seafarers in practice. Operability and speed diagrams are more useful. Aggravating circumstance is recognizing of sea state from the bridge of the boat. Experienced seafarer much better recognizes real parameters of the sea state. The identification of sea state parameters is difficult because of the complex interaction of short-crested waves and swell waves.

Seafarers are trained on simulators where rough sea state is simulated. In that way they get used to operate in such conditions. Reaction just in time often leads to prevention of cargo, equipment or even life. During school time and practice on simulator, seafarers learn about maneuvering in rough sea but do not learn impact of bad maneuvering on safety of ship structure. That makes indispensable better connection and communication between seafarers and naval architects.

Maneuvering in rough sea is a part of International Safety Management Code (ISM Code). ISM Code includes check list for reaction of seafarers during navigation in rough sea but with lack of ship construction safety part and lack of operability criteria.

Limiting values were established in past based on experience and changes of ship design, especially changing of bow geometry, leads to new calculations of limiting values. Example is bowflare slamming that appears on container ships which is totally different from bottom slamming and requires other approach to determining criteria. Also order of maneuvers (first speed reduction, than route change) is result of experience and can be changed depending on master's decision.

The method which calculates 3D seakeeping parameters is based on the Green function of wave diffraction-radiation problem, using wave encounter approximation in a case of small forward speed. Such linear seakeeping theory, expressed in frequency domain, is applicable for ships advancing with relatively low speed on small wave heights. Consequently, there are some inaccuracies and uncertainties when applying linear theory in extreme sea conditions. Ideally, uncertainties of the operational conditions needs to be accounted based on a probabilistic assessment of seakeeping events, expressed by random variables in defined limit state functions, which are used for the evaluation of different seakeeping hazards (Papanikolaou et al. 2014). Such considerations are outside the scope of the present study.

Future research of authors will be related to the connection of wave loads with operability criteria and exploring possibilities of improvement of existing and future operability criteria limiting values. The mentioned field is of interest for both naval architecture and maritime research disciplines which will lead to better incorporation of reaction of seafarers on rough sea maneuvering in ship structural design.

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