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NUMERICAL EVALUATION OF OPERABILITY ENVELOPE FOR ULTRA LARGE CONTAINER SHIP IN EXTREME SEAS AND INFLUENCE OF MANEUVERING ON WAVE LOADS

Abstract

This paper presents two interconnected parts of ship navigation in extreme seas. Possibilities and advices for ship maneuvering for seafarers are one part. Another part is influence of ship maneuvering on wave loads. Principle for making advices is made on operability criteria platform. Influence of maneuvering on wave loads is defined through amount of wave bending moment amidship. Practical example is made for 9200 TEU container ship. Numerical evaluation is carried out via 3D panel method. 2-P Pierson–Moskowitz wave spectrum is used for short term spectral analysis. Rough weather is described according to the IACS recommendation Note No.34. Closed-form expressions are used for quick estimate of wave induced bending moment. Results are presented in operability polar plots, operability diagram and speed diagram. In the conclusion, suggestions for better approach in maneuvering calculations are provided and connection of ship operability and amount of wave loads is commented with guidelines for the future research.

Key words: container ship, operational criteria, 3D panel method, wave induced bending moment

NUMERIČKA ANALIZA OPERATIVNOSTI KONTEJNERSKOG BRODA NA VALOVITOM MORU TE UTJECAJ UPRAVLJANJA NA VALNA OPTEREĆENJA

Sažetak

Rad prikazuje spoj dva međusobno povezana pristupa upravljanju brodom u nevremenu. Savjeti pomorcima za upravljanje brodom su prvi dio. Drugi dio je utjecaj upravljanja na iznos opterećenja od valova. Savjeti pomorcima su prikazani zadovoljavanjem ili premašivanjem kriterija operativnosti broda. Utjecaj upravljanja brodom na iznos valnog opterećenja je prikazan preko iznosa momenta savijanja na glavnom rebru. Za praktični prikaz poslužio je 9200 TEU brod za prijevoz kontejnera. Numeričkom 3D panel metodom su izračunate prijenosne funkcije komponenti gibanja te su iskorištene za analizu operativnosti u nevremenu opisanom prema preporuci IACS No. 34. Za spektralnu analizu kratkotrajnog stanja mora korišten je 2-P Pierson-Moskowitz spektar valova. Momenti savijanja izračunati su preko „closed-form“ jednadžbi. Rezultati su dijagrami operativnosti i brzina te polarni dijagram. Zaključak rada su prijedlozi za unaprijeđenje pristupa upravljanja brodom u nevremenu te podloge za daljna istraživanja.

Ključne riječ: kontejnerski brod, kriteriji operativnosti, 3D panel metoda, moment savijanja

1. Introduction

Open sea ship maneuvering for seafarers is largely a routine when weather conditions are calm. Problems appear when environmental conditions are extreme. To prevent cargo, equipment or even ship structure and finally human lives, ship speed has to be reduced or route has to be changed during navigation in extreme seas. Voluntary speed reduction and route changing is considered as maneuvering in extreme seas. However, the moment when maneuvering will have to be done is still open question.

Naval architects and seafarers have detected important criteria which describe seakeeping of the ship on rough sea and have effect on operability envelope of the ship. Seakeeping criteria, also known as operability criteria, considered in this paper are slamming, deck wetness, and vertical acceleration at bow. Moment when operability criterion reaches limiting value is point when maneuvering is good to be done.

Limiting values of the operability criteria are another questionable field investigated and reviewed by many authors [1- 4].

Numerical evaluation of operability envelope is shown on example of 9200 TEU container ship. Results of calculation are polar plots and other types of operability diagrams which are useful for seafarers to provide safe maneuvering.

Correct maneuvering reduces wave loads on ship structure in heavy sea and makes navigation safer. One of the most important wave load components is the vertical wave bending moment (VWBM) along the ship, especially in the midship section. Limiting value of VWBM can be calculated by IACS formula [5]. The most probable VWBM for short term sea state of certain duration can be easily calculated using closed form expressions [6]. Relation between calculated moment and IACS moment is given in terms of percentage and conveniently included in the operability polar plots.

2. Criteria for ship maneuvering in extreme seas

Speed reduction and route changing are maneuvering actions done by seafarers in extreme seas when operability criteria reach limiting values. Limiting values of operability criteria are used in seakeeping studies to validate ship response on different sea states. Operability limiting values represent border between acceptable and unacceptable phenomena such as number of bottom slams in one minute or amount of vertical acceleration on fore perpendicular, etc.

2.1. Slamming

Slamming is operability criteria that can be clearly felt by seafarers because results of the slamming are vibrations of the hull. Seafarers can feel that vibrations very good because they 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. Slamming is quite obvious because every impact of the bow results with dispersion of the huge amount of water around the ship so can be recognized by seafarers onboard and by observers outside the ship. Limiting values of probability of slamming provided by different authors [3, 4, 7- 10] are presented in Table 1.

Table 15. Limiting values of probability for slamming

Author	Moan [3]	Ochi and Motter [4]	Aertssen [7-10]
Limiting value	0.03	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. Usually happens at fore part when bow submerge under rough sea surface. Limiting values of probability of deck wetness provided by different authors [2-4] are presented in Table 2.

Table 16. Limiting values of probability for deck wetness

Author	Lloyd [2]	Moan et al. [3]	Ochi and Motter [4]
Limiting value	0.02	0.05	0.07

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. Transversal accelerations on the bridge are also very important for seafarers but are not taken under considerations when calculating operability in the present study. Proposal of limiting root mean square (RMS) of vertical acceleration for different ship types is given by Moan et al. [3] and presented in Table 3.

Table 17. Root mean square (RMS) of vertical accelerations at FP:

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 for ship maneuvering

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

Table 18. Characteristics of 9200 TEU container ship

Lpp	335 m
B (Breadth)	42.8 m
T (Draught)	13.17 m
v	25 kn
Capacity	9200 TEU

Seakeeping calculation is performed in the present study to find out which is sustainable speed of the 9200 TEU container ship on different sea states. For that purpose, limiting values presented in Table 5 are used.

Table 19. Limiting values used in operability calculation

Limiting probability of slamming	0.03
Limiting probability of deck wetness	0.05
Limiting RMS of vertical bow accelerations	0.108 g

3.1. Methodology of numerical evaluation

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 [12]. Sea states of interest are given for North Atlantic sea environment (Table 6) according to the IACS recommendation Note No.34 [13].

Table 6. Probability of sea states of interest in the North Atlantic described as occurrence per 100000 observations. Derived from wave scatter diagram - IACS recommendation Note No.34

		Tz - zero crossing 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

RAOs are calculated using seakeeping software Hydrostar [14] while results are post processed using program Starspec [15]. Calculations are based on 3D panel numerical method and linear potential theory.

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

- relative vertical motion,
- relative vertical speed,
- absolute bow acceleration.

All three RAOs are calculated for four speeds (U represents normal service speed):

$U_1 = 1/4\ U = 6.25$ kn

$U_2 = 1/2\ U = 12.50$ kn

$U_3 = 3/4\ U = 18.75$ kn

$U_4 = U = 25.00$ kn

3.2. Results

Practical results, useful to seafarers, are generated in program Starspec. Calculations carried out in Starspec connect significant wave heights and limiting values of operability criteria. Results are shown in two ways:

- operability polar plots,
- operability diagram.

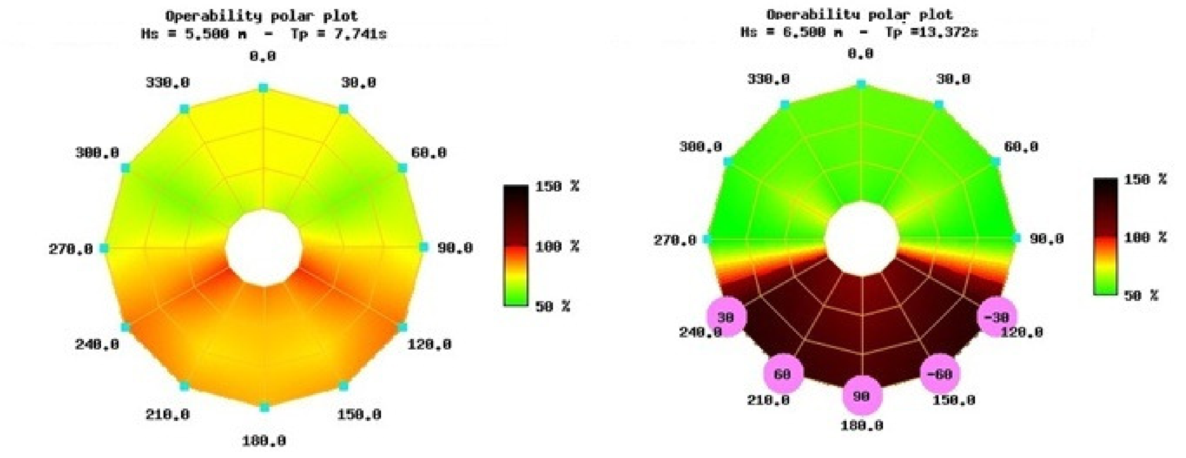

Figure 1. Percentage of limiting values for sea state 1(H_s=5.5 m, T_p=7.741 s) and sea state 2 (H_s=6.5 m, T_p=13.372 s)

Operability polar plots (Figure 1) show which navigating azimuth and which speed is sustainable for each sea state. Heading 180^0 means head seas. For calculation presented in this paper only sea states having considerable probability of appearance in the North Atlantic scatter diagram from IACS recommendation Note No.34 (Table 6) are used. Each sea state has its own operability polar plot. For presentation in this paper two characteristic sea states are chosen (Figure 1). Sea state 1 is described by significant wave height H_s=5.5 m and peak wave period T_p=7.741 s, while sea state 2 is described by H_s=6.5 m and T_p=13.372 s. It is obvious on polar plots that for sea state 1 limiting values are not exceeded, while for sea state 2 limits are exceeded for certain cases and speed reducing and azimuth change has to be done. Value and direction of azimuth change is shown in purple circle.

Operability polar plots are not user friendly for seafarers. More useful could be operability diagram and speed diagram. Operability diagram (Figure 2) shows appropriate maneuvers for bow heading navigation on different sea states. Blue colour in Figure 2 indicates sea states for which no maneuvers are required. Green colour indicates sea states for which speed reduction maneuver has to be done while yellow colour shows sea states for which route change maneuver is essential.

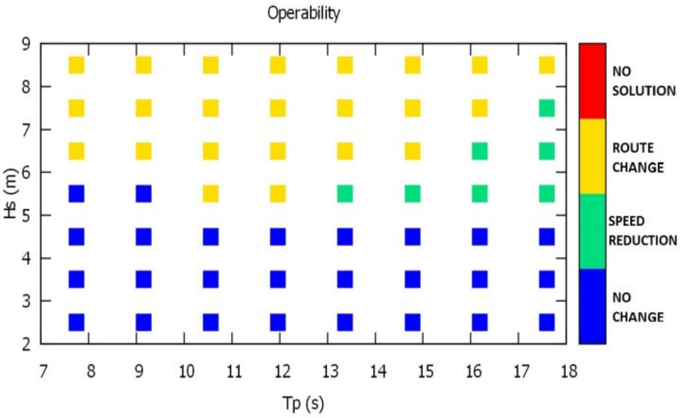

Figure 2. Operability diagram for 9200 TEU container ship

Interesting maneuvers are speed reduction and route change. Operability diagram groups all polar plots for all important sea states in one place.

Speed diagram for different sea states, assuming head seas (Figure 3), shows limiting speed if seafarers do not want to exceed operability criteria. It is obvious that for sea state H_s=6.5 m and T_p=13.372 s azimuth has to be changed as it is not possible to keep operability limits by reducing speed.

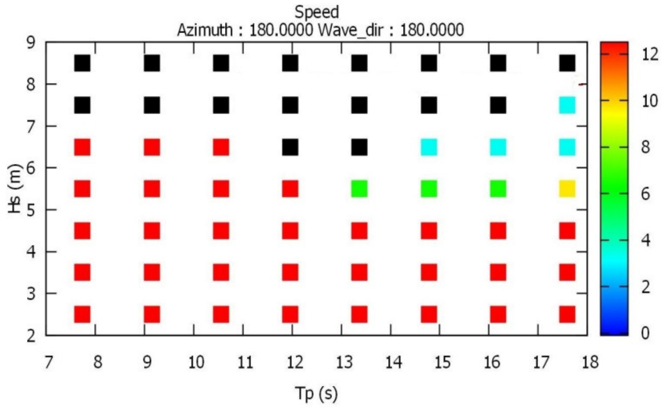

Figure 3. Speed diagram for different sea states assuming head seas

4. Influence of ship maneuvering on wave loads

Vertical wave induced bending moment is calculated for 9200 TEU container ship presented in previous chapter. Transfer functions of VWBM are calculated using closed-form expresions derived by Jensen et al. [6]. The most probable extreme VWBM for short term sea states with duration of three hours is then easily calculated using spreadsheet.Although closed-form expressions are extremely simple for application, their accuracy is surprisingly high when compared to numerical methods such as 3D panel method or strip method [16].

Results are compared with IACS bending moment and presented in Table 7 in terms of percentage of IACS rule VWBM.

Table 7. Relation between calculated closed-form moment and IACS moment for two characteristic sea states

speed (kn)	wave heading (^{o})	results, sea state 1 (%)	results, sea state 2 (%)
U_1=6.25	120	31	34
U_1=6.25	150	45	55
U_1=6.25	180	45	58
U_2=12.50	120	32	35
U_2=12.50	150	46	57
U_2=12.50	180	47	61
U_3=18.75	120	33	37
U_3=18.75	150	49	60
U_3=18.75	180	50	64
U_4=25.00	120	35	39
U_4=25.00	150	52	65
U_4=25.00	180	53	68

Sea states used in analysis are the same as described in Section 3.2. Wave headings considered in the analysis are 120^0, 150^0 and 180^0. 180^0means head seas, while 90^0 denotes beam seas. Ship speeds used in calculation are same as in Section 3.

Results presented in Table 6 show percentage of the most probable VWBM with respect to IACS rule VWBM for defined sea state, speed and wave heading.

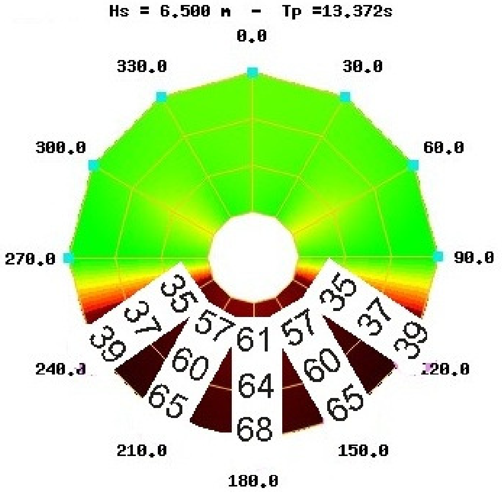

Figure 4. Combination of the operability polar plot and values of the calculated results (sea state 2)

Figure 4 shows results of the VWBM calculation presented in the form of the operability polar plots

Numbers in white squares are results from Table 6 (only for first three velocities because of the clear presentation, sea state 1), while operability polar plots are described in Chapter 3.

Values in white squares in operability plots in Figure 4 show that in the worst case (head seas and full ship speed) VWBM in concerned sea state will reach 68% of the IACS rule VWBM. Results look reasonable, as the sea state with H_s=6.5 m is lower than extreme sea states for which IACS rule VWBM is derived. Route change maneuver leads to lower values more than speed reduction, especially between 150^0 and 120^0 heading seas Phenomena that will occur with mentioned headings is rolling and should be analyzed in future research.

On comment should be put on results shown in Figure 4. Namely, presented results represent rigid-body VWBM, while contribution due to ship vibratory transient response (whipping) is neglected. It should be noted, however, that whipping bending moment for full ship speed and H_s=6.5 m can be rather high, even as high as the rigid-body VWBM [17]. Future research should include operability plots with whipping contributions.

5. Conclusion

Presented polar plots, operability diagram and speed diagram 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. Understanding and reading of presented diagrams depend on the experience of seafarers because recognition of importance of sea states is subjective.

Existing limiting values are based on ship geometry that is outdated nowadays. 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.

Evaluation is made for combination of all three criteria. Another point of interest would be which single criterion has the biggest influence on operability for ship used in presentation.

Combination of ship operability and wave induced bending moments is shown as interesting part that is going to be point of interest for the authors. Presented results are calculated by simple closed-form expressions, while calculations with numerical methods such as strip method and/or 3D panel method would lead to more confident results.

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 which is main goal of the presented research.

References

[1] JOURNÈE, J.M.J.: "Prediction of speed and behaviour of a ship in a seaway", Rapport 0427-P, Delft, 1976.

[2] LLOYD, A.R.J.M.: "Seakeeping: Ship Behaviour in Rough Weather", Ellis Horwood Limited, Chichester, England, 1989.

[3] MOAN et al.: "Comparative reliability analysis of ships-considering different ship types and the effect of ship operations on loads", Annual Meeting (SMTC&E), SNAME, Fort Lauderdale, 2006.

[4] OCHI, M.K., MOTTER, E.: "Prediction of extreme ship responses in rough seas of the north Atlantic", International Symposium on the Dynamics of Marine Vehicles and Structures in Waves: paper 20, London 1974.

[5] ...: INTERNATIONAL ASSOCIATION OF CLASSIFICATION SOCIETIES (IACS): "Common Structural Rules for Double Hull Oil Tankers", 2006.

[6] JENSEN, J.J., MANSOUR, A.E., OLSEN A.S.: "Estimation of ship motions using closed-form expressions", Ocean Engineering 31 (2004), p.61-85.

[7] AERTSEN, G.: "Service, performance and seakeeping trials on MV Lukuga", TRINA 105, 1963.

[8] AERTSEN, G.: "Service, performance and seakeeping trials on MV Jordaens", TRINA 108, 1966.

[9] AERTSEN, G.: “Labouring of ships in rough weather seas with special emphasis on the fast ship”, SNAME Diamond Jubilee International Meeting, 1968.

[10] AERTSEN, G., van SLUYS, M.F.: “Service, performance and seakeeping trials on a large container ship”, TRINA 114, 1972.

[11] ...: LLOYD, ARJM: “Seakeeping: Ship behaviour in rough weather”, ARJM Lloyd, Gosport, United Kingdom, 1998.

[12] PRPIĆ-ORŠIĆ, J., ČORIĆ, V.: ”Seakeeping”, Rijeka: University of Rijeka, Croatia, 2006.

[13] ...: INTERNATIONAL ASSOCIATION OF CLASSIFICATION SOCIETIES (IACS): “IACS Recommendation No.34”, Standard Wave Data. Rev.1, 2000.

[14] ...: BUREAU VERITAS: “Hydrostar User Manual”, Bureau Veritas, Paris, 2010.

[15] ...: BUREAU VERITAS: “Starspec User Manual”, Bureau Veritas, Paris, 2010.

[16] ĐIGAŠ, A., ĆORAK, M.; PARUNOV, J. 2012.: “Comparison of Linear Seakeeping Tools For Containerships”, XX. Symposium Theory and Practice of Naval Architecture (SORTA), Shipping Institute, Zagreb, 2012.

[17] ĆORAK, M., PARUNOV, J., GUEDES SOARES, C.: “Long-term prediction of combined wave and whipping bending moments of container ships”, Ships and Offshore Structures (2014.), article in press.