THE ANNALS OF "DUNĂREA DE JOS" UNIVERSITY OF GALAȚI
FASCICLE V, TECHNOLOGIES IN MACHINE BUILDING,
ISSN 1221- 4566, 2012

COMPARASION BETWEEEN SEAKEEPING SHORT TERM RESPONSES FOR SEVERAL INPUT WAVE SPECTRA, OF A LPG CARRIER 100000 CBM

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ABSTRACT

This paper is focused on the seakeeping analysis of a LPG hull ship model, with 238.7 m length. The study includes the linear seakeeping analysis, coupled pitch and heave motions, uncoupled roll motion, in irregular oblique waves, heading angle 0 ÷ 360 deg., considering the sea described by four power density spectra: ITTC, ISSC, Pierson–Moskowitz and JONSWAP. Based on short term prediction statistical values and specific limits of seakeeping criteria, are obtained the dynamic response statistical polar diagrams, on each motion degree, power density spectrum and cumulative effect, pointing out the influence of the ship speed, heading angle and the difference between the four power density spectra for practical seakeeping assessment. The most restrictive results are obtained in the case using the JONSWAP wave spectrum. The numerical seakeeping analyses are carried out with DYN_OSC program code, in the frame of PhD POSDRU research activities.

KEYWORDS: numerical analysis, ship dynamics, seakeeping, irregular oblique waves, wave power density spectrum, heave, pitch, roll

1. INTRODUCTION

1.1. Problem definition

This study is focused on the seakeeping analysis in irregular oblique waves for a LPG Carrier 100000 cbm mono – hull ship model. The main objective of the study is to analyse the influences of ship speed, heading angle and the four wave power density spectra on the maximum RMS heave, pitch, roll motion and acceleration amplitudes.

The studies are carried on a LPG carrier 100000 cbm, with length of 238.7 m, under the rigid body hypothesis, analysed for linear seakeeping dynamic response (Bhattacharyya [2], Söding [6], Bertram [1], Domnisoru [3]) and statistical short term prediction response method [4], [5] (see Section 2), taking into account the main three ship oscillation degrees of freedom, heave and pitch, uncoupled roll.

The main dimensions of the analysed LPG carrier are presented in Table 1. The ship is designed to transport gas refinery in prismatic type cargo tanks, designed for a pressure of about 0.25 Bar and with a minimum temperature of $-48\,^{\circ}C$. This ship is symmetric in the centre line CL.

Table 1. *The LPG carrier 100000 cbm main characteristics*

Type of ship	LPG Carrier
Hull type	Mono-hull
L [m]	237.8 m
B [m]	38.2 m
H [m]	23.2 m
d [m]	13.8 m
C_B	0.77
h_0[m]	7.886
g [m/s^2]	9.81
Jx[t m^2]	8794162.997
$N_{sections}$	40
μ [deg.], $\delta\mu$	0÷360, 15
u_s[knots], δu_s	0÷18, 2,17
T_ζ [s]	8.326
T_θ [s]	8.3106
T_φ [s]	14.765

In Section 3 are presented the seakeeping and short term prediction statistical results, including transfer functions and polar diagrams (significant wave height and sea Beaufort level), for specific seakeeping criteria (14).

The conclusions of this analysis are included in Section 4, pointing out the practical design seakeeping restrictions, based on the resulting short term statistical polar diagrams.

2. THEORETICAL BACKGROUND

The seakeeping analysis from this study is carried out under the following hypotheses:

- the excitation source is the wave Airy model [2];
- the motion equations are linearized;
- the ship-sides are considered vertical;
- the motions amplitudes are considered small;
- the Lewis based on hydrodynamic coefficients [6];
- the strip theory based hydrodynamic forces [2].

The elevation of the equivalent wave, model Airy, with $f_s(x)$,$\varepsilon(x)$ average factors, is:

$$\bar{\zeta}_v^*(x,t) = a_w f_s(x)\varepsilon(x)\cos(kx\cos\mu - \omega_e t)$$
$$\omega_e = \omega - k\cdot u_s\cos\mu\,;\; k = \omega^2/g\,;\; \mu = 0^0 \div 360^0 \qquad (1)$$

where: a_w wave amplitude; ω_e encountering ship-wave equivalent circular frequency; g gravity acceleration; μ heading angle between the ship and wave main direction (0 & 360^0 following seas; 180^0 head seas; 90^0 beam seas); u_s ship speed.

The linear motion equations system of coupled heave $\zeta(t)$ and pitch $\theta(t)$ motions is:

$$A_{\zeta\zeta}\ddot{\zeta} + B_{\zeta\zeta}\dot{\zeta} + C_{\zeta\zeta}\zeta + A_{\zeta\theta}\ddot{\theta} + B_{\zeta\theta}\dot{\theta} + C_{\zeta\theta}\theta = F_w(t)$$
$$A_{\theta\zeta}\ddot{\zeta} + B_{\theta\zeta}\dot{\zeta} + C_{\theta\zeta}\zeta + A_{\theta\theta}\ddot{\theta} + B_{\theta\theta}\dot{\theta} + C_{\theta\theta}\theta = M_w(t) \qquad (2)$$

where: $A_{\zeta\zeta}$, $B_{\zeta\zeta}$, $C_{\zeta\zeta}$, $A_{\zeta\theta}$, $B_{\zeta\theta}$, $C_{\zeta\theta}$, $A_{\theta\zeta}$, $B_{\theta\zeta}$, $C_{\theta\zeta}$, $A_{\theta\theta}$, $B_{\theta\theta}$, $C_{\theta\theta}$ are the radiation terms; $F_w(t)$, $M_w(t)$ are the wave diffraction terms.

$$F_w(t) = a_w(F_{oc}\cos\omega_e t + F_{os}\sin\omega_e t)$$
$$M_w(t) = a_w(M_{oc}\cos\omega_e t + M_{os}\sin\omega_e t) \qquad (3)$$

The motion equations system (2) steady state solution has the following expression:

$$\zeta(t) = \zeta_1\cos\omega_e t + \zeta_2\sin\omega_e t = \zeta_a\cos(\omega_e t - \varepsilon_\zeta)$$
$$\theta(t) = \theta_1\cos\omega_e t + \theta_2\sin\omega_e t = \theta_a\cos(\omega_e t - \varepsilon_\theta) \qquad (4)$$

where $\zeta_1,\zeta_2,\theta_1,\theta_2$ result from the algebraic system:

$$[A(\omega_e)]\{X(\omega_e)\} = \{B(\omega_e)\}$$
$$\{X(\omega_e)\} = \{\zeta_1,\zeta_2,\theta_1,\theta_2\}^T \qquad (5)$$
$$\{B(\omega_e)\} = a_w\cdot\{F_{oc},F_{os},M_{oc},M_{os}\}^T$$

$$[A(\omega_e)] = \begin{bmatrix} C_{\zeta\zeta}-\omega_e^2A_{\zeta\zeta} & \omega_e B_{\zeta\zeta} & C_{\zeta\theta}-\omega_e^2A_{\zeta\theta} & \omega_e B_{\zeta\theta} \\ -\omega_e B_{\zeta\zeta} & C_{\zeta\zeta}-\omega_e^2A_{\zeta\zeta} & -\omega_e B_{\zeta\theta} & C_{\zeta\theta}-\omega_e^2A_{\zeta\theta} \\ C_{\theta\zeta}-\omega_e^2A_{\theta\zeta} & \omega_e B_{\theta\zeta} & C_{\theta\theta}-\omega_e^2A_{\theta\theta} & \omega_e B_{\theta\theta} \\ -\omega_e B_{\theta\zeta} & C_{\theta\zeta}-\omega_e^2A_{\theta\zeta} & -\omega_e B_{\theta\theta} & C_{\theta\theta}-\omega_e^2A_{\theta\theta} \end{bmatrix}$$

The transfer functions of the dynamic response at heave and pitch are the following:

$$H_{y_a}(\omega_e,\mu) = y_a(\omega_e,\mu)\big|_{a_w=1}\;;\; y\in\{\zeta,\theta\} \qquad (6)$$

The wave slope is as following:

$$\bar{\alpha}_y^*(x,t) = -a_w k\sin\mu f_x(x)\varepsilon(x)\sin(kx\cos\mu - \omega_e t) \qquad (7)$$

The differential equation for the linear uncoupled roll $\varphi(t)$ oscillation is:

$$a_\varphi\ddot{\varphi}(t) + b_\varphi\dot{\varphi}(t) + c_\varphi\varphi(t) = M_{\varphi w}(t) \qquad (8)$$

where: a_φ ,b_φ ,c_φ , are the radiation terms and the diffraction $M_{\varphi w}(t)$ wave excitation term is:

$$M_\varphi(t) = M_o\sin(\omega_e t + \beta_\varphi) \qquad (9)$$

The motion equation (8) steady state solution has the following expression:

$$\varphi(t) = \varphi_a\sin(\omega_e t - \varepsilon_\varphi);\; H_{\varphi_a}(\omega_e,\mu) = \varphi_a(\omega_e,\mu)\big|_{a_w=1} \qquad (10)$$

The short term ship dynamic response of the ship (the linear analysis) can be determined knowing the transfer function and the wave spectrum.

$$\Phi_{yy\_i}(\omega_e,\mu) = \left|H_{y\zeta v}(\omega_e,\mu)\right|^2\Phi_{\zeta v\zeta v\_i}(\omega_e,\mu) \qquad (11)$$

$$m_{ny\_i}(\mu) = \int_0^\infty \omega^n\,\Phi_{yy\_i}(\omega_e,\mu)\,d\omega_e \quad n = 0,2,4,.. \qquad (12)$$

where i represent the wave spectrum type (ISSC, ITTC, Pierson – Moskowitz and JONSWAP)

Dynamic response short term statistical values are:

$$RMS_y(\mu) = \sqrt{m_{0y}(\mu)}\,;\; RMS_{acy}(\mu) = \sqrt{m_{4y}(\mu)} \qquad (13)$$

where the following limits are considered:

$$RMS_{\zeta\max} = F_{fore} - z_{fore\theta}\,;\; RMSac_{\zeta\max} = 0.1g$$
$$RMS_{\theta\max} = 3^o;\; z_{fore\theta} = L/2\cdot RMS_{\theta\max} \qquad (14)$$
$$RMSac_{\theta fore}(\mu) = \frac{L}{2}RMSac_\theta(\mu);\; F = H - d\big|_{fore}$$
$$RMSac_{\theta fore\max} = RMSac_{\varphi sb\max} = 0.15g$$
$$RMSac_{\varphi sb}(\mu) = \frac{B}{2}RMSac_\varphi(\mu)\,;\; RMS_{\varphi\max} = 6^o$$

Based on limit values RMS_{max}, $RMSac_{max}$, result the polar diagrams $h_{1/3\max}(\mu,y)$ and Beaufort $B_{\max}(\mu,y)$, for several ship speeds u_s and wave spectra.

3. NUMERICAL ANALYSIS

This calculation has been made for different heading angle 0 ÷ 360 deg. (step used 15 deg.), different speed of the ship (0 to 18 knots with step equal with 2 and 17 Knots – speed of ship), two load cases: full cargo, ballast, and four wave power density spectra, as following: ITTC, ISSC, Pierson – Moskowitz and JONSWAP.

The transfer function of heave, pitch and roll oscillation of the ship are obtained for each speed of the ship, each heading angle and for each load case (Fig.1 to Fig.6).

Knowing the transfer function of heave, pitch and roll of the ship, the next step is for each wave spectrum to obtain the short term ship dynamic response of the ship at the linear analysis.

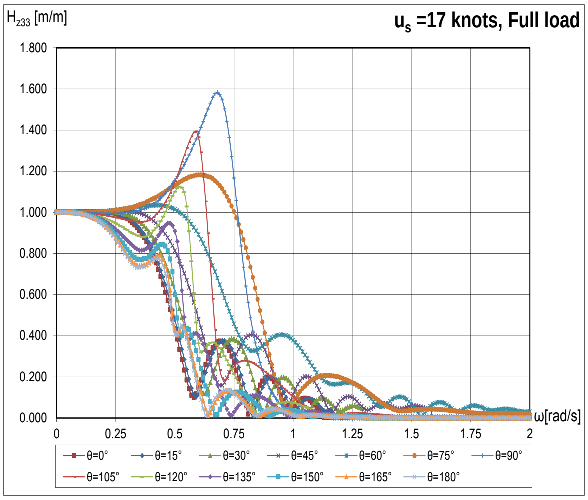

Fig. 1. *Heave transfer function H_{Z3}[m/m], full cargo*

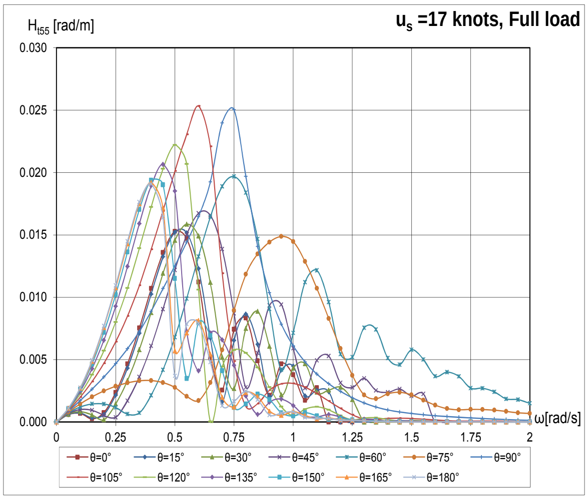

Fig. 2. *Pitch transfer function H_{T5}[m/m], full cargo*

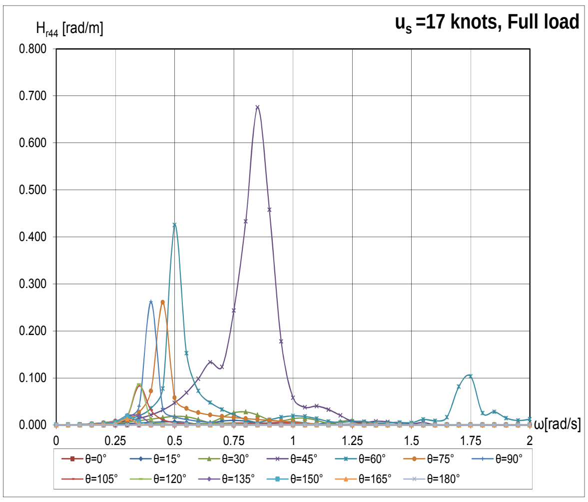

Fig. 3. *Roll transfer function H_{R4}[m/m], full cargo*

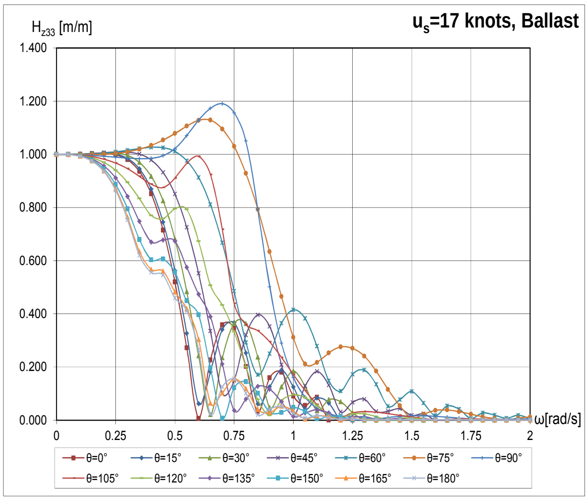

Fig. 4. *Heave transfer function H_{Z3}[m/m], ballast*

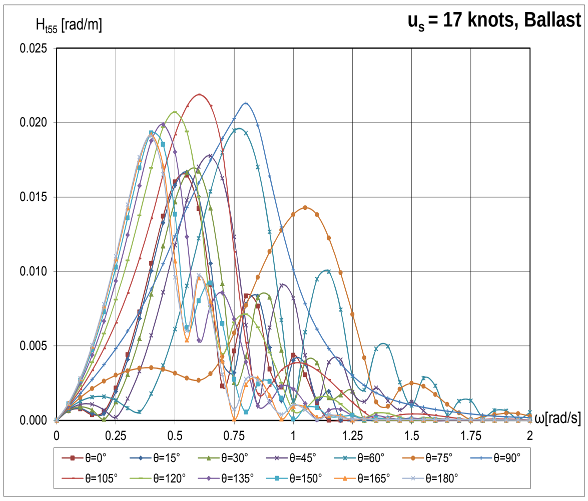

Fig. 5. *Pitch transfer function H_{T5}[m/m], ballast*

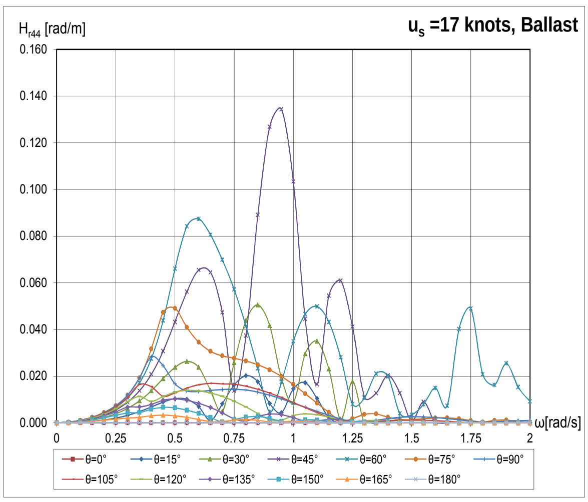

Fig. 6. *Roll transfer function H_{R4}[m/m], ballast*

Table 2. *Cumulative limit using ISSC spectrum, full load*

μ [deg.]	heave	pitch	roll	$h_{1/3max}$	Beaufort
0	3.584	10.000	10.000	12.000	11.00
15	3.519	10.000	10.000	12.000	11.00
30	3.326	10.000	7.337	12.000	11.00
45	3.009	10.000	4.955	1.817	4.20
60	2.561	10.000	4.234	4.214	7.05
75	2.041	10.000	3.929	5.697	8.07
90	1.802	10.000	3.840	4.349	7.14
105	2.041	10.000	3.929	5.466	7.91
120	2.561	10.000	4.234	6.738	8.72
135	3.009	10.000	4.955	7.884	9.33
150	3.326	10.000	7.337	8.759	9.75
165	3.519	10.000	10.000	9.302	10.01
180	3.584	10.000	10.000	9.480	10.07
180 ÷ 360 deg. same as for 180 ÷ 0 deg. due sym.					

Table 3. *Cumulative limit using ISSC spectrum, ballast*

μ [deg.]	heave	pitch	roll	$h_{1/3max}$	Beaufort
0	3.584	10.000	10.000	12.000	11.00
15	3.519	10.000	10.000	12.000	11.00
30	3.326	10.000	7.337	12.000	11.00
45	3.009	10.000	4.955	7.503	9.15
60	2.561	10.000	4.234	6.554	8.60
75	2.041	10.000	3.929	7.061	8.92
90	1.802	10.000	3.840	4.376	7.16
105	2.041	10.000	3.929	5.331	7.82
120	2.561	10.000	4.234	6.579	8.62
135	3.009	10.000	4.955	7.912	9.34
150	3.326	10.000	7.337	8.478	9.61
165	3.519	10.000	10.000	8.807	9.77
180	3.584	10.000	10.000	8.918	9.83
180 ÷ 360 deg. same as for 180 ÷ 0 deg. due sym.					

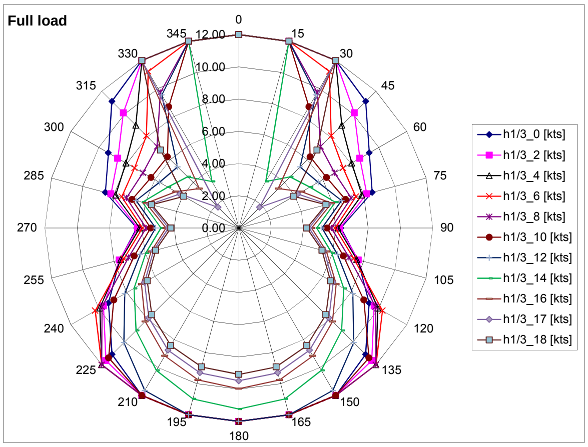

Fig. 7. *Cumulative $h_{1/3}$[m] polar diagram, ISSC spectrum*

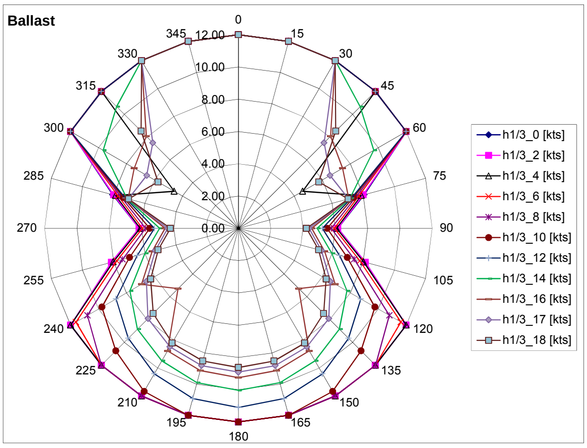

Fig. 9. *Cumulative $h_{1/3}$[m] polar diagram, ISSC spectrum*

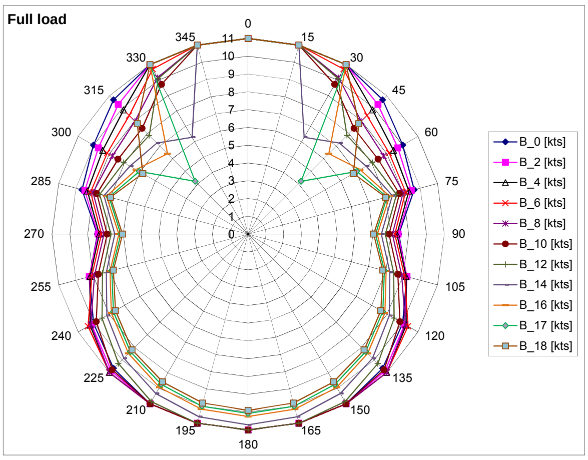

Fig. 8. *Cumulative Beaufort polar diagram, ISSC spectrum*

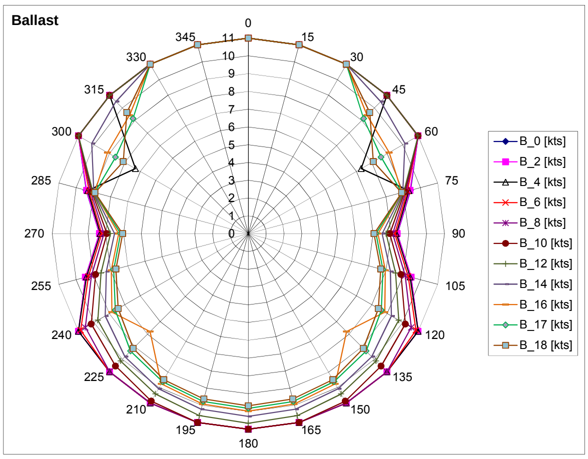

Fig. 10. *Cumulative Beaufort polar diagram, ISSC spectrum*

Table 4. *Cumulative limit using ITTC spectrum, full load*

μ [deg.]	heave	pitch	roll	$h_{1/3max}$	Beaufort
0	3.584	10.000	10.000	12.000	11.00
15	3.519	10.000	10.000	12.000	11.00
30	3.326	10.000	7.337	12.000	11.00
45	3.009	10.000	4.955	1.647	3.74
60	2.561	10.000	4.234	3.761	6.66
75	2.041	10.000	3.929	5.080	7.65
90	1.802	10.000	3.840	4.302	7.11
105	2.041	10.000	3.929	5.345	7.83
120	2.561	10.000	4.234	6.621	8.64
135	3.009	10.000	4.955	7.794	9.29
150	3.326	10.000	7.337	8.702	9.72
165	3.519	10.000	10.000	9.269	9.99
180	3.584	10.000	10.000	9.454	10.06
180 ÷ 360 deg. same as for 180 ÷ 0 deg. due sym.					

Table.5. *Cumulative limit using ITTC spectrum, ballast*

μ [deg.]	heave	pitch	roll	$h_{1/3max}$	Beaufort
0	3.584	10.000	10.000	12.000	11.000
15	3.519	10.000	10.000	12.000	11.000
30	3.326	10.000	7.337	12.000	11.000
45	3.009	10.000	4.955	9.223	9.971
60	2.561	10.000	4.234	6.775	8.740
75	2.041	10.000	3.929	7.996	9.385
90	1.802	10.000	3.840	4.504	7.251
105	2.041	10.000	3.929	5.448	7.901
120	2.561	10.000	4.234	6.771	8.737
135	3.009	10.000	4.955	8.212	9.488
150	3.326	10.000	7.337	8.694	9.718
165	3.519	10.000	10.000	9.003	9.866
180	3.584	10.000	10.000	9.106	9.915
180 ÷ 360 deg. same as for 180 ÷ 0 deg. due sym.					

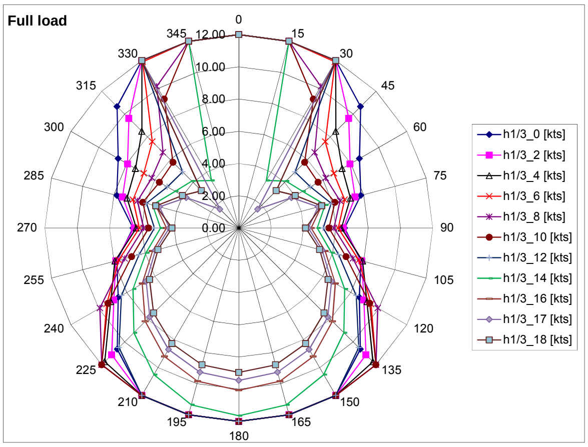

Fig. 11. *Cumulative $h_{1/3}$[m] polar diagram, ITTC spectrum*

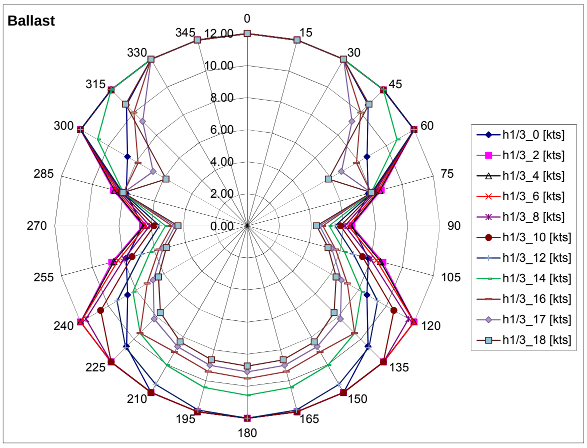

Fig. 13. *Cumulative $h_{1/3}$[m] polar diagram, ITTC spectrum*

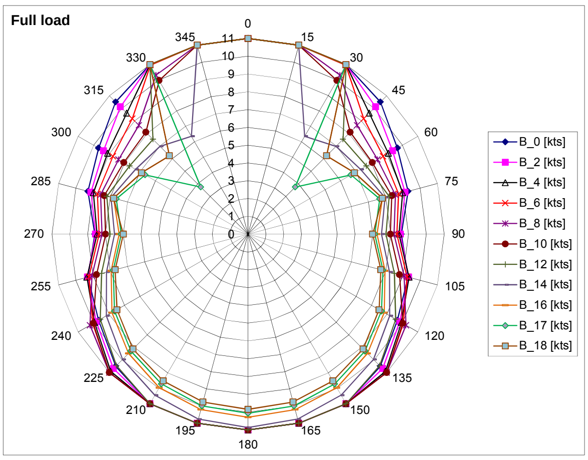

Fig. 12. *Cumulative Beaufort polar diagram, ITTC spectrum*

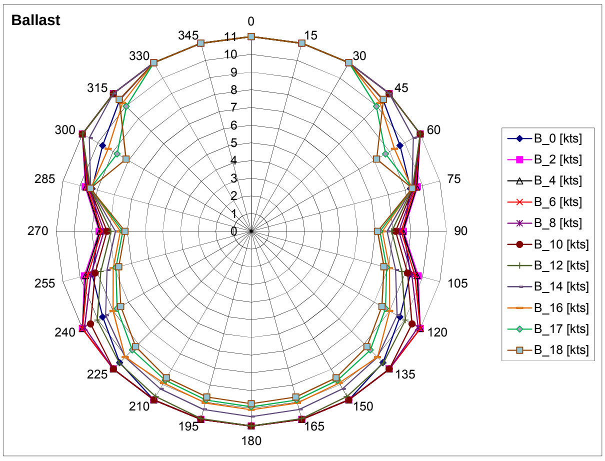

Fig. 14. *Cumulative Beaufort polar diagram, ITTC spectrum*

Table 6. *Cumulative limit using PM spectrum, full load*

μ [deg.]	heave	pitch	roll	$h_{1/3max}$	Beaufort
0	3.584	10.000	10.000	12.000	11.00
15	3.519	10.000	10.000	12.000	11.00
30	3.326	10.000	7.337	12.000	11.00
45	3.009	10.000	4.955	1.818	4.20
60	2.561	10.000	4.234	4.216	7.05
75	2.041	10.000	3.929	5.701	8.07
90	1.802	10.000	3.840	4.352	7.15
105	2.041	10.000	3.929	5.470	7.92
120	2.561	10.000	4.234	6.742	8.72
135	3.009	10.000	4.955	7.890	9.33
150	3.326	10.000	7.337	8.765	9.75
165	3.519	10.000	10.000	9.308	10.01
180	3.584	10.000	10.000	9.487	10.07
180 ÷ 360 deg. same as for 180 ÷ 0 deg. due sym.					

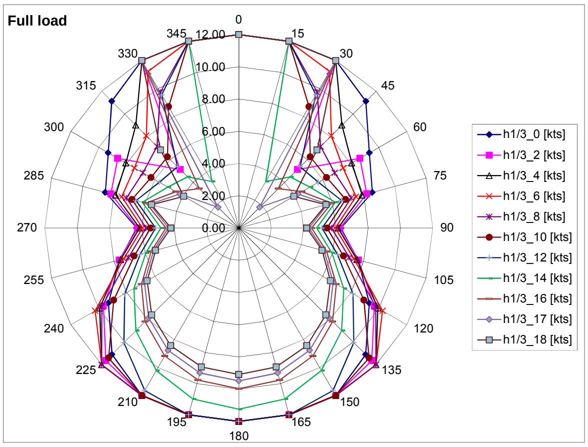

Fig. 15. *Cumulative $h_{1/3}$[m] polar diagram, PM spectrum*

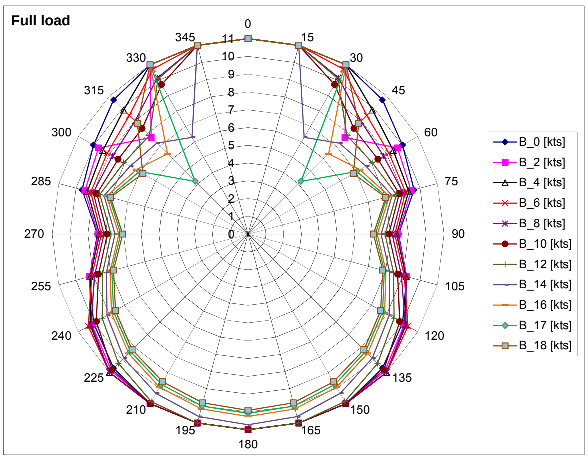

Fig. 16. *Cumulative Beaufort polar diagram, PM spectrum*

Table 7. *Cumulative limit using PM spectrum, ballast*

μ [deg.]	heave	pitch	roll	$h_{1/3max}$	Beaufort
0	3.584	10.000	10.000	12.000	11.00
15	3.519	10.000	10.000	12.000	11.00
30	3.326	10.000	7.337	12.000	11.00
45	3.009	10.000	4.955	7.509	9.15
60	2.561	10.000	4.234	6.559	8.60
75	2.041	10.000	3.929	7.066	8.92
90	1.802	10.000	3.840	4.379	7.16
105	2.041	10.000	3.929	5.335	7.82
120	2.561	10.000	4.234	6.584	8.62
135	3.009	10.000	4.955	7.918	9.35
150	3.326	10.000	7.337	8.484	9.62
165	3.519	10.000	10.000	9.003	9.77
180	3.584	10.000	10.000	9.106	9.83
180 ÷ 360 deg. same as for 180 ÷ 0 deg. due sym.					

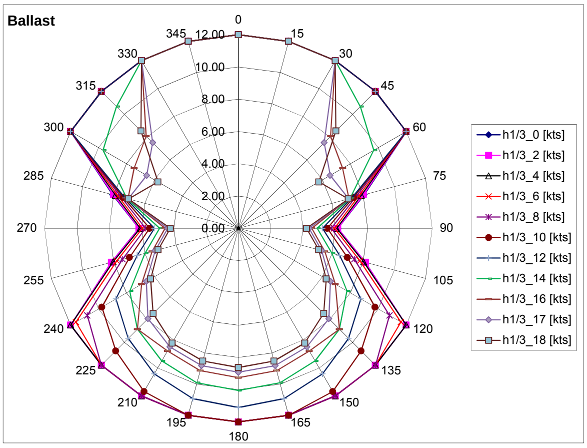

Fig. 17. *Cumulative $h_{1/3}$[m] polar diagram, PM spectrum*

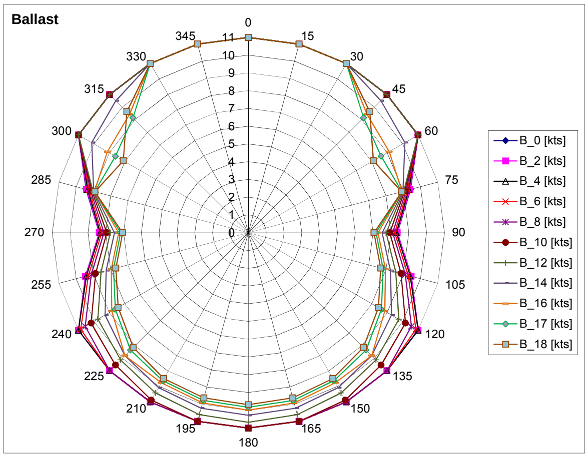

Fig. 18. *Cumulative Beaufort polar diagram, PM spectrum*

Table 8. *Cumulative limit using JONSWAP spectrum, full load*

μ [deg.]	heave	pitch	roll	$h_{1/3max}$	Beaufort
0	3.584	10.000	10.000	12.000	11.00
15	3.519	10.000	10.000	12.000	11.00
30	3.326	10.000	7.337	12.000	11.00
45	3.009	10.000	4.955	2.166	4.92
60	2.561	10.000	4.234	5.101	7.66
75	2.041	10.000	3.929	6.911	8.83
90	1.802	10.000	3.840	4.233	7.06
105	2.041	10.000	3.929	5.548	7.97
120	2.561	10.000	4.234	6.914	8.83
135	3.009	10.000	4.955	8.092	9.43
150	3.326	10.000	7.337	8.994	9.86
165	3.519	10.000	10.000	9.563	10.10
180	3.584	10.000	10.000	9.757	10.17
180 ÷ 360 deg. same as for 180 ÷ 0 deg. due sym.					

Table 9. *Cumulative limit using JONSWAP spectrum, ballast*

μ [deg.]	heave	pitch	roll	$h_{1/3max}$	Beaufort
0	3.584	10.000	10.000	12.000	11.00
15	3.519	10.000	10.000	12.000	11.00
30	3.326	10.000	7.337	12.000	11.00
45	3.009	10.000	4.955	9.362	10.03
60	2.561	10.000	4.234	6.558	8.60
75	2.041	10.000	3.929	8.457	9.60
90	1.802	10.000	3.840	4.375	7.16
105	2.041	10.000	3.929	5.364	7.84
120	2.561	10.000	4.234	6.740	8.72
135	3.009	10.000	4.955	8.198	9.48
150	3.326	10.000	7.337	9.164	9.94
165	3.519	10.000	10.000	9.655	10.14
180	3.584	10.000	10.000	9.822	10.20
180 ÷ 360 deg. same as for 180 ÷ 0 deg. due sym.					

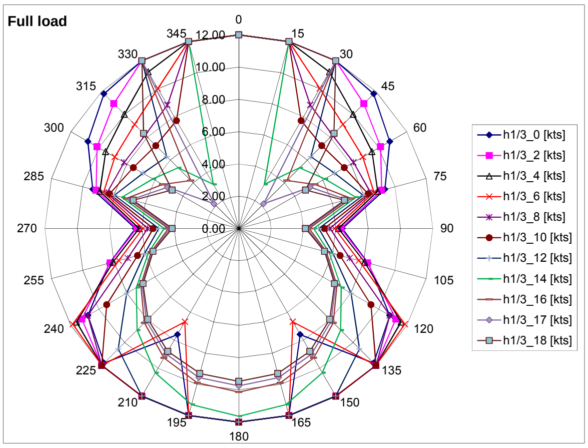

Fig. 19. *Cumulative $h_{1/3}$[m] polar diagram, JONSWAP spectrum*

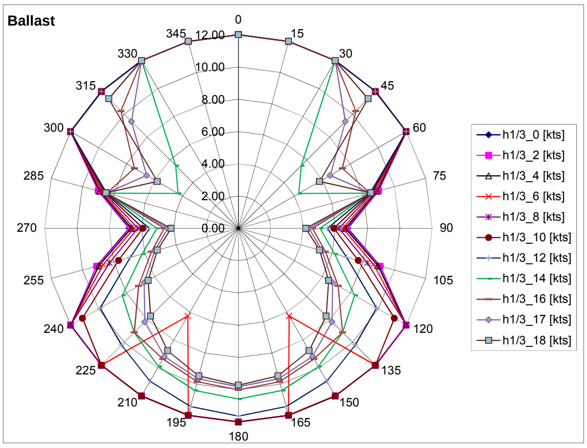

Fig. 21. *Cumulative h1/3[m] polar diagram, JONSWAP spectrum*

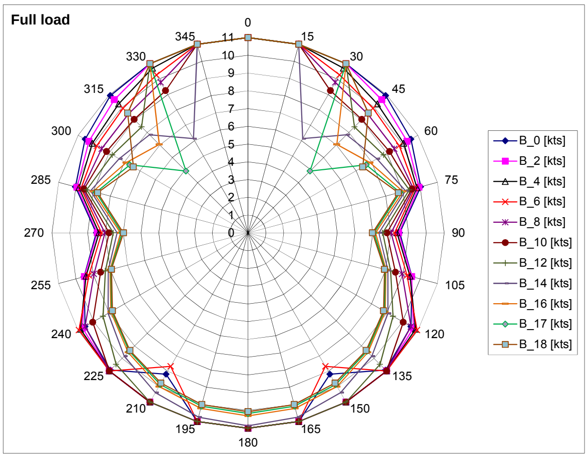

Fig. 20. *Cumulative Beaufort polar diagram, JONSWAP spectrum*

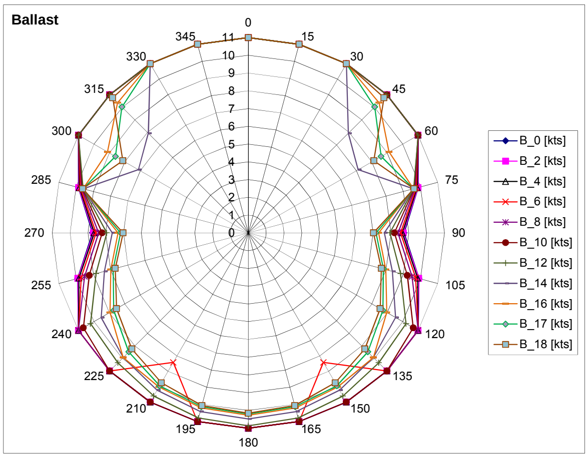

Fig. 22. *Cumulative Beaufort polar diagram, JONSWAP spectrum*

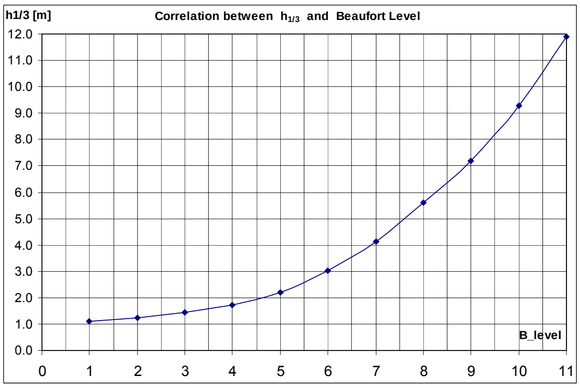

Fig. 23. *The correlation diagram between the significant wave height $h_{1/3}$[m] and the sea state condition expressed in Beaufort level*

The significant dynamic response on short term prediction has some limits presented in Chapter 2, according to the seakeeping restrictions practical criteria (Fig.7 to Fig.21 and Table 2 to Table 9).

4. CONCLUDING REMARKS

Based on the numerical results from Section 3, it results the following conclusions:

1. The maximum significant amplitudes for heave and roll are recorded at μ=90 deg. and for pitch at μ=180 deg (Table 2 to Table 9).

2. From Fig.7 and Fig.9 (Table 2 and Table 3 only $h_{1/3max}$), it results that the maximum significant wave height limit $h_{1/3max}$ has the following values: full load 4.349 ÷ 12.000 m and ballast 4.376 ÷ 12.000 m; the B_{max} obtained from cumulative Beaufort polar diagrams in Fig. 8 and Fig.10 for which case it has the following values: full load 7.140 ÷ 11.000 m and ballast 7.160 ÷ 11.000 m.

3. From Fig.11 and Fig.13 (Table 4 and Table 5 only $h_{1/3max}$), it results that the maximum significant wave height limit $h_{1/3max}$ has the following values: full load 4.302 ÷ 12.000 m and ballast 4.504 ÷ 12.000 m; the B_{max} obtained from cumulative Beaufort polar diagrams in Fig. 12 and Fig.14 for which case it has the following values: full load 7.110 ÷ 11.000 m and ballast 7.251 ÷ 11.000 m.

4. From Fig.15 and Fig.17 (Table 6 and Table 7 only $h_{1/3max}$), it results that the maximum significant wave height limit $h_{1/3max}$ has the following values: full load 4.352 ÷ 12.000 m and ballast 4.379 ÷ 12.000 m; the B_{max} obtained from cumulative Beaufort polar diagrams in Fig. 16 and Fig.18 for which case it has the following values: full load 7.150 ÷ 11.000 m and ballast 7.160 ÷ 11.000 m.

5. From Fig.19 and Fig.21 (Table 8 and Table 9 only $h_{1/3max}$), it results that the maximum significant wave height limit $h_{1/3max}$ has the following values: full load 4.233 ÷ 12.000 m and ballast 4.375 ÷ 12.000 m; the B_{max} obtained from cumulative Beaufort polar diagrams in Fig. 20 and Fig.22 for which case it has the following values: full load 7.060 ÷ 11.000 m and ballast 7.160 ÷ 11.000 m.

6. From conclusion 2) to 5) it results that the most restrictive seakeeping state is recorded on JONSWAP wave spectrum.

Acknowledgements

This study has been accomplished in the frame of the national grants EFICIENT POSDRU 88/1.5/S ID-61445 2009-2011 and TOP ACADEMIC POSDRU 107/1.5/S ID-76822 2010-2011.

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