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SEAKEEPING PERFORMANCE PREDICTION OF A RIVER-COASTAL BOAT MADE OF GRE COMPOSITE MATERIALS

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ABSTRACT

The design of the river-coastal vehicles imposes the assessment of several hydrodynamic and structural criteria. This research involves the evaluation of a river-coastal boat made of GRE composite materials at full load condition. The boat’s navigation area covers the Danube inland and coastal zones, modeled as irregular oblique waves. The analysis is based on a strip-theory hydrodynamic approach and short-term statistical dynamic response approach, delivering the seakeeping performance prediction of the river-coastal boat.

Keywords: river-coastal boat, seakeeping performances, oblique irregular waves.

1. INTRODUCTION

This study involves the prediction of the seakeeping performances of a river-coastal boat made of composite materials GRE [1].

The main data of the river-coastal boat is presented in Table 1 with the offset lines in Fig.1 and the transversal stability diagram in Fig.2, for a set of vertical positions of the gravity centre (z_G).

Table 1. The data of river-coastal boat GRE [1].

L_{OA}[m]	24.660		Full load	
L_{WL}[m]	23.500		Δ[t]	71.022
B[m]	6.000		T[m]	1.5
D[m]	3.650 / 4.250		x_G[m]	10.751
Sections	200		x_F[m]	9.786
v[knots]	0÷15 (4)		z_B[m]	1.026
r[m]	2.513		T_{heave}[s]	2.871
φ_{maxGZ}[deg]	49.50÷61.50		T_{pitch}[s]	2.830
H_s[m]	T_{roll}[s]	kd[%]	0%	5%
0÷2 (0.008)	z_G[m]	1.5	3.876	3.911
Wave		1.8	4.368	4.412
ITTC		2.1	4.963	5.018
μ [deg]		2.4	5.745	5.814
0÷180(5)		2.7	6.926	7.021

In order to include the bilge keels’ influence, an equivalent supplementary damping (k_d) formulation is applied, referenced to the roll critical damping values [2].

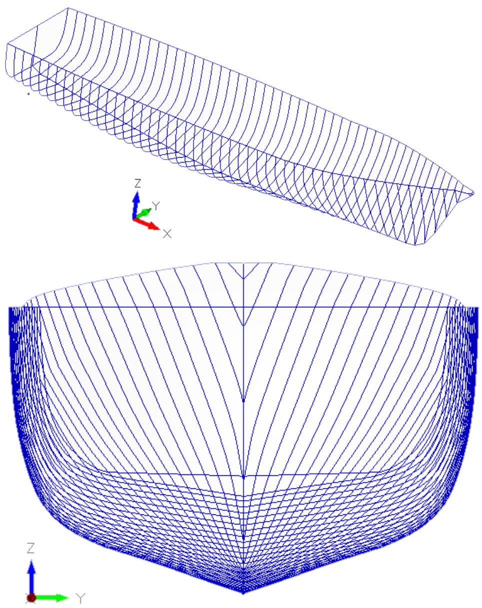

Fig.1 River-coastal boat GRE, offset-lines [1].

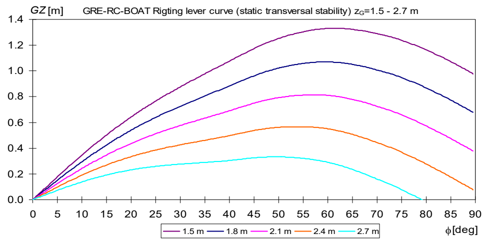

Fig.2 River-coastal GRE boat, stability diagram.

The numerical analyses are carried out by eigen DYN [2] programs set, based on a strip-theory hydrodynamic approach and a short-term statistical dynamic response approach [3],[4], with experimental validation [5]. The seakeeping criteria admissible values (Table 2) are formulated for the most probable response amplitudes *RMS* on main motions and accelerations (heave, pitch, roll).

Table 2 Seakeeping criteria admissible values.

RMS_{aft}[m]	1.850	RMS_{pitch}[rad]	0.052
RMS_{mid}[m]	1.850	$RMS_{pitchacc}$[rad/s^2]	0.198
RMS_{fore}[m]	2.450	RMS_{roll}[rad]	0.087
$RMS_{heaveacc}$[m/s^2]	1.472	$RMS_{rollacc}$[rad/s^2]	0.164

2. AMPLITUDE OPERATOR RESPONSE FUNCTIONS (RAO) OF THE RIVER-COASTAL BOAT

The dynamic response analysis in regular waves leads to the computation in the frequency domain of the response amplitude operator functions (*RAO*) [4], for the main motion components of the river-coastal boat.

The *RAO* functions for heave oscillations are presented in Figs. 3. a-b, Figs.4. a-c. The maximum *RAO* for heave results at oblique fore and head (μ=135-180 deg) waves, with speed influence noticed for ω>0.75 rad/s.

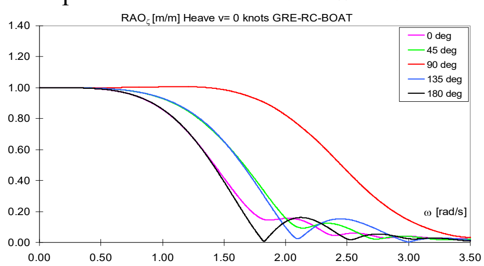

Fig.3.a *RAO*[m/m] boat heave, v=0 kn.

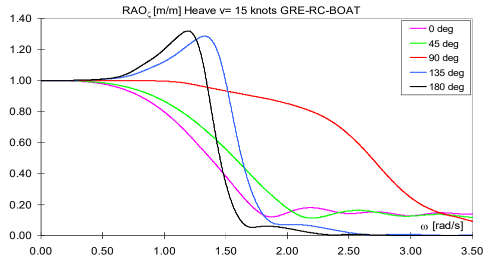

Fig.3.b *RAO*[m/m] boat heave, v=15 kn.

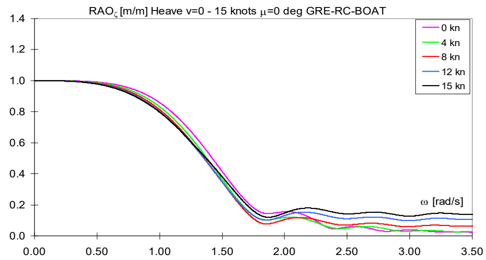

Fig.4.a *RAO* [m/m] boat heave, μ=0 deg.

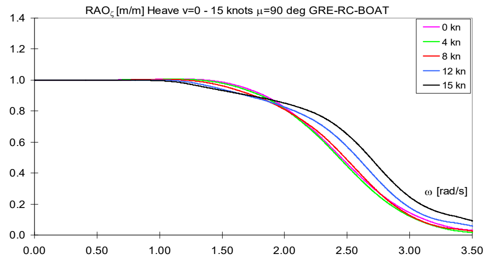

Fig.4.b *RAO* [m/m] boat heave, μ=90 deg.

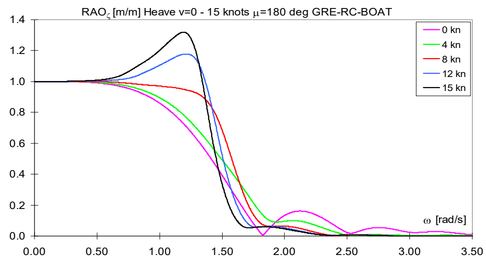

Fig.4.c *RAO* [m/m] boat heave, μ=180 deg.

The *RAO* functions for pitch oscillations are presented in Figs. 5. a-b and Figs.6. a-c. The maximum *RAO* for pitch motion results at oblique fore and head (μ=135-180 deg) waves, for speed v≥8 knots. Noticeable pitch results also for the following waves (μ=0 deg). The minimum pitch motion is at beam (μ=90 deg) waves. The boat speed influence is significant in the range of ω=1.00-2.50 rad/s.

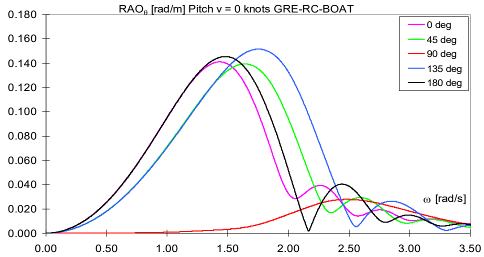

Fig.5.a *RAO* [rad/m] boat pitch, v=0 kn.

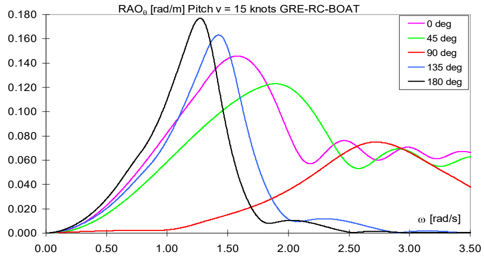

Fig.5.b *RAO* [rad/m] boat pitch, v=15 kn.

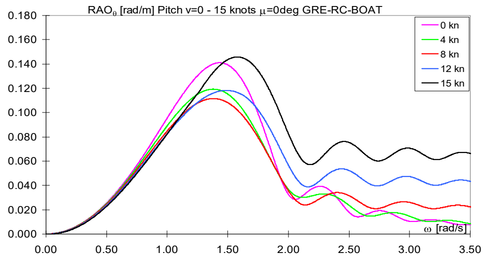

Fig.6.a *RAO* [rad/m] boat pitch, μ=0 deg.

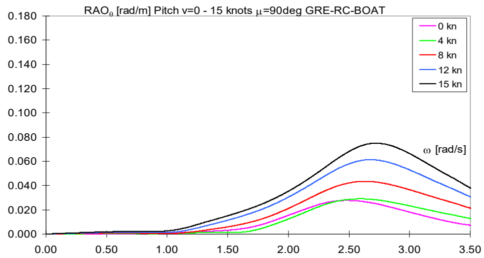

Fig.6.b *RAO* [rad/m] boat pitch, μ=90 deg.

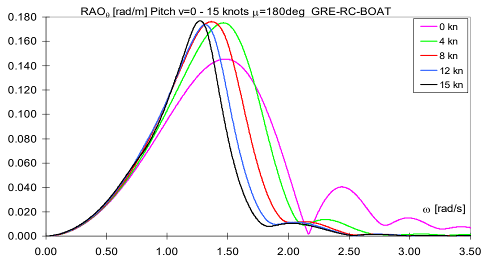

Fig.6.c *RAO* [rad/m] boat pitch, μ=180 deg.

The RAO functions for roll oscillations are presented in Figs. 7. a-f, Figs.8. a-f and Fig.9. a-b, for boat speed v=0 and 15 knots, z_G=1.5-2.7 m, without (0%) and with (5%) bilge keels. The maximum RAO for roll motion results around the beam waves domain (μ=70-120 deg), with a noticeable speed influence in the range of ω=0.50-1.50 rad/s. The influence of the bilge keels and the increase of z_G are positive, reducing the roll response.

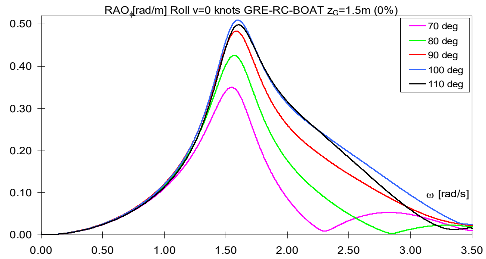

Fig.7.a *RAO* [rad/m] roll,v=0 kn,z_G=1.5m,0%.

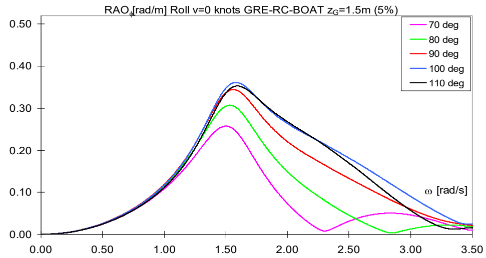

Fig.7.b *RAO* [rad/m] roll,v=0 kn,z_G=1.5m,5%.

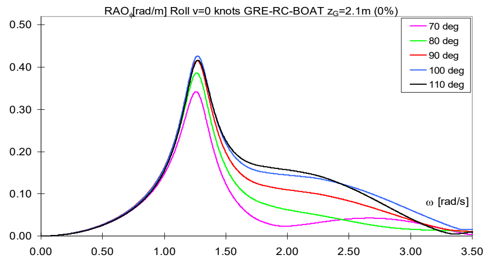

Fig.7.c *RAO* [rad/m] roll,v=0 kn,z_G=2.1m,0%.

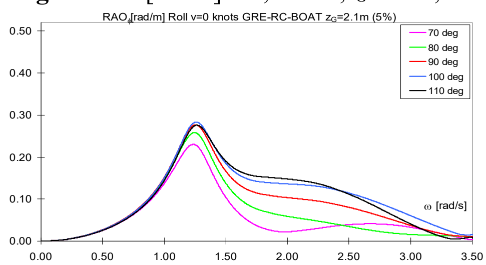

Fig.7.d *RAO* [rad/m] roll,v=0 kn,z_G=2.1m,5%.

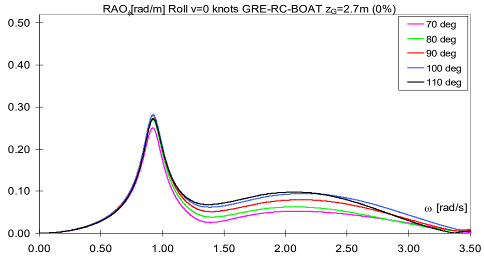

Fig.7.e *RAO* [rad/m] roll, v=0 kn, z_G=2.7m, 0%.

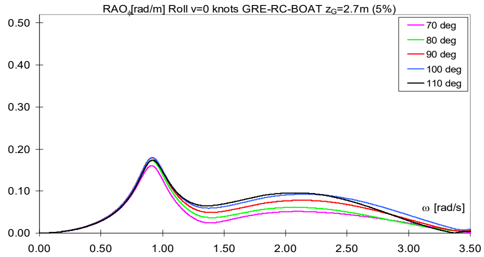

Fig.7.f *RAO* [rad/m] roll, v=0 kn, z_G=2.7m, 5%.

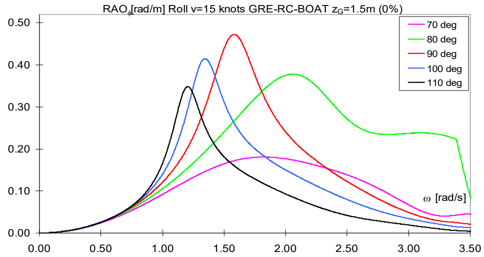

Fig.8.a *RAO* [rad/m] roll, v=15 kn, z_G=1.5m, 0%.

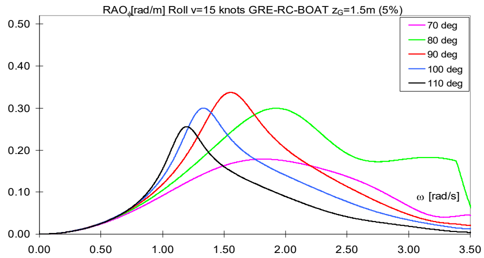

Fig.8.b *RAO* [rad/m] roll, v=15 kn, z_G=1.5m, 5%.

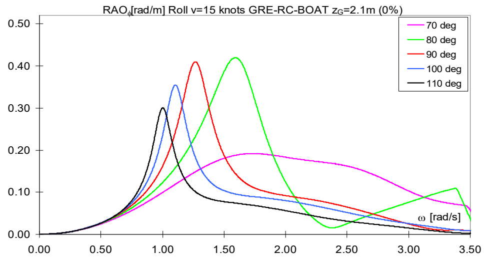

Fig.8.c *RAO* [rad/m] roll, v=15 kn, z_G=2.1m, 0%.

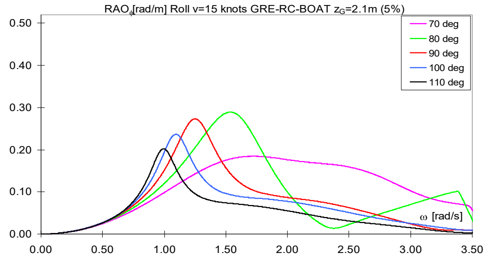

Fig.8.d *RAO* [rad/m] roll, v=15 kn, z_G=2.1m, 5%.

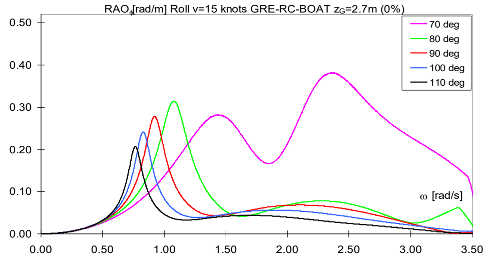

Fig.8.e *RAO* [rad/m] roll, v=15 kn, z_G=2.7m, 0%.

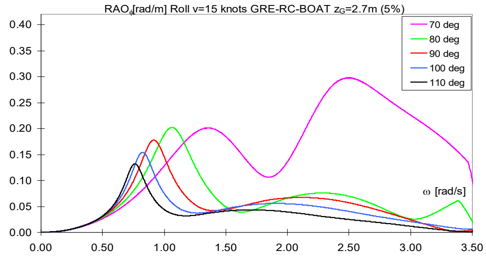

Fig.8.f *RAO* [rad/m] roll, v=15 kn, z_G=2.7m, 5%.

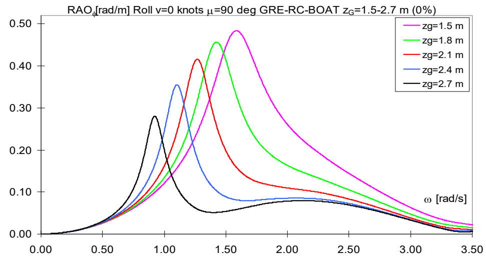

Fig.9.a *RAO* [rad/m] boat roll, μ=90, v=0 kn, 0%.

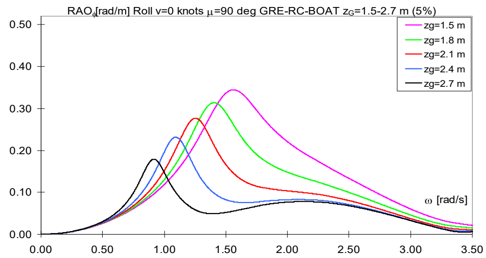

Fig.9.b *RAO* [rad/m] boat roll, μ=90, v=0 kn, 5%.

3. MOST PROBABLE SHORT-TERM AMPLITUDE RESPONSE (RMS) OF THE RIVER-COASTAL BOAT

The statistical response analysis in irregular waves (ITTC spectrum) leads to the computation of the short-term most probable amplitudes (*RMS*) [4], for the main motions and acceleration components of the river-coastal boat, used for the assessment of the navigation limits by seakeeping criteria (Table 2).

The *RMS* maximum short-term most probable response values for combined vertical motions at the aft, mid, and fore of the boat (heave-pitch-roll) are presented in Figs. 10. a-c, having a moderate influence from the roll motion parameters. For all the navigation conditions the combined vertical motions criterion is satisfied.

The heave acceleration *RMS* maximum short-term most probable response is presented in Fig.11, and the criterion is not satisfied for $v \geq 12$ knots and μ=115-180 deg.

The pitch motion *RMS* maximum short-term most probable response is presented in Fig.12, and the criterion is not satisfied for $v \geq 4$ knots and μ=140-180 deg.

The pitch acceleration *RMS* maximum short-term most probable response is presented in Fig.13, and the criterion is not satisfied for $v \geq 8$ knots and μ=110-180 deg.

The roll motion *RMS* maximum short-term most probable response is presented in Figs.14. a-f, and the criterion is not satisfied for the case without bilge keels (0%) at beam sea (μ=75-120 deg) waves, whole range of z_G=1.5-2.7 and boat speed v=0-15 knots. In the case of bilge keels (5%) the criterion is satisfied at a limit of z_G=1.5m, with a small overpass for v=0 knots, and no restrictions for z_G>1.5m and boat speed v=0-15 knots.

The roll acceleration *RMS* maximum response is presented in Figs.15.a-f, and the criterion is not satisfied for z_G=1.5m, with or without keels, and for z_G=2.1m without keels, at beam sea waves. In the case without keels (0%) and z_G>2.1 m, the criterion is satisfied. In the case of bilge keels (5%) the criterion has no restrictions for z_G>1.5m.

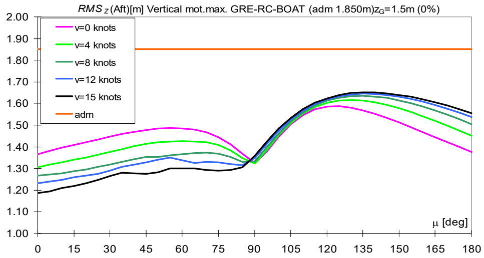

Fig.10.a RMS_{aft}[m] max. boat combined aft.

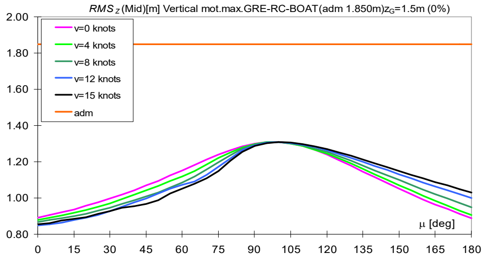

Fig.10.b RMS_{mid}[m] max. boat combined mid.

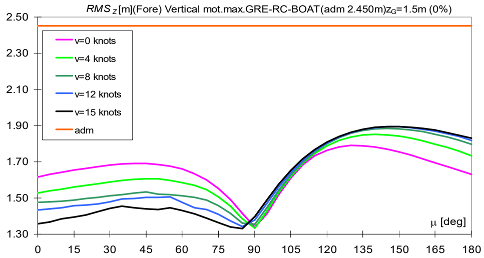

Fig.10.c RMS_{fore} [m] max. boat combined fore.

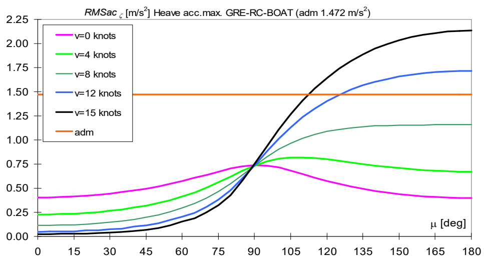

Fig.11 $RMS_{heaveacc}$[m/s^2] max. boat vertical acc.

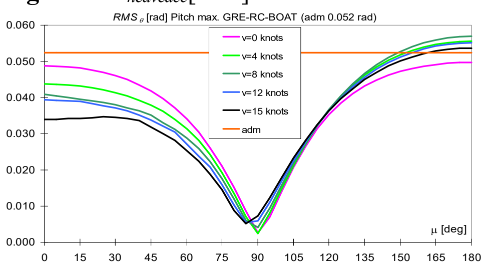

Fig.12 RMS_{pitch} [rad] max. boat pitch motion.

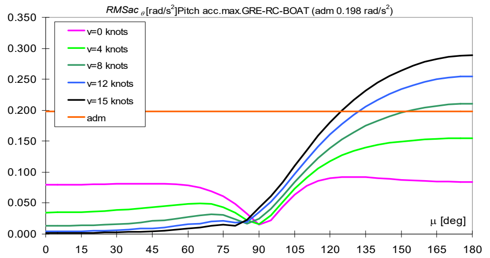

Fig.13 $RMS_{pitchacc}$[rad/s^2] max. boat pitch acc.

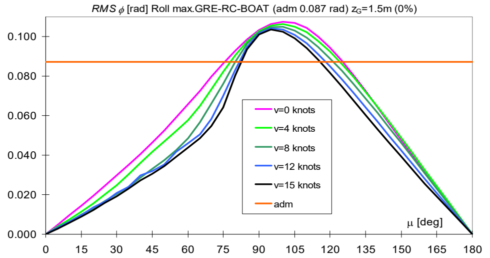

Fig.14.a RMS_{roll}[rad] max. boat roll,z_G=1.5m, 0%.

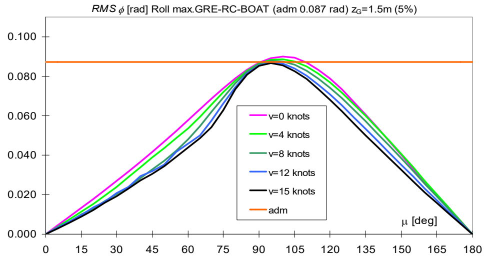

Fig.14.b RMS_{roll}[rad] max. boat roll,z_G=1.5m, 5%.

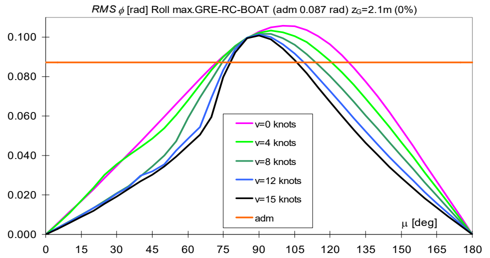

Fig.14.c RMS_{roll}[rad] max. boat roll,z_G=2.1m, 0%.

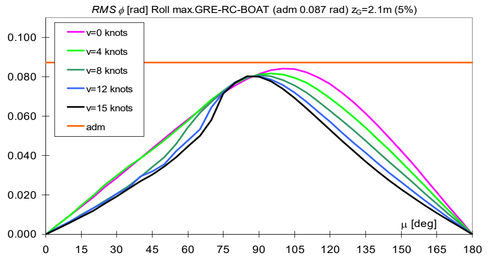

Fig.14.d RMS_{roll}[rad] max. boat roll,z_G=2.1m, 5%.

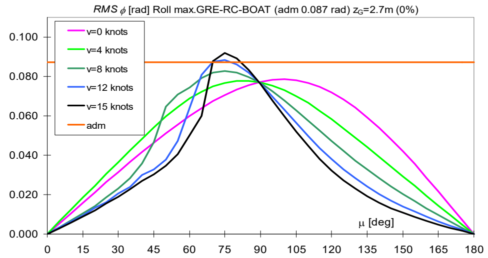

Fig.14.e RMS_{roll}[rad] max. boat roll,z_G=2.7m, 0%.

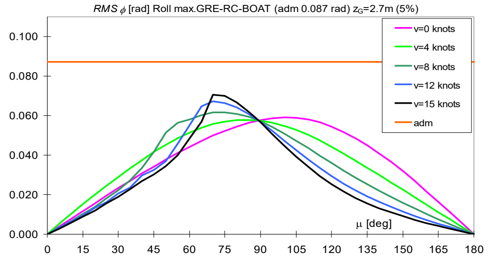

Fig.14.f RMS_{roll}[rad] max. boat roll,z_G=2.7m, 5%.

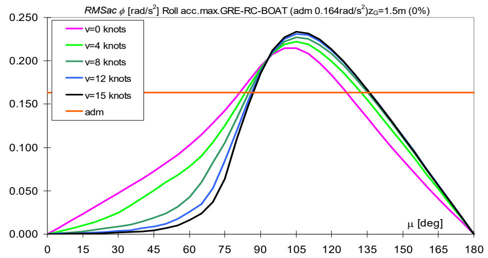

Fig.15.a $RMS_{rollacc}$[rad/s^2] roll acc., z_G=1.5m, 0%.

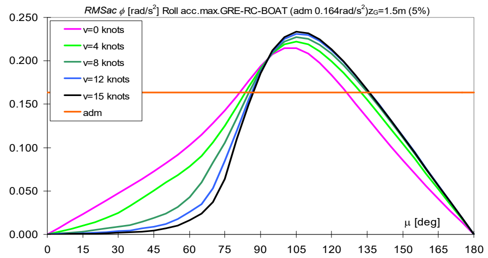

Fig.15.b $RMS_{rollacc}$[rad/s^2] roll acc., z_G=1.5m, 5%.

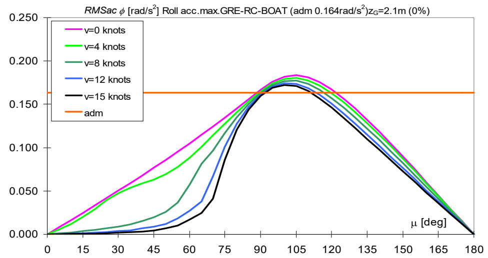

Fig.15.c $RMS_{rollacc}$[rad/s^2] roll acc., z_G=2.1m, 0%.

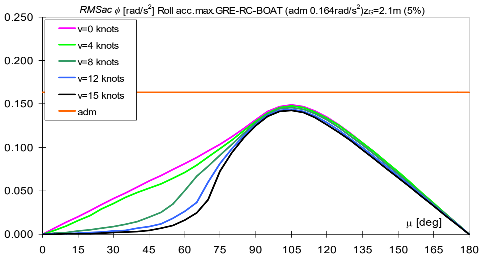

Fig.15.d $RMS_{rollacc}$[rad/s^2] roll acc., z_G=2.1m, 5%.

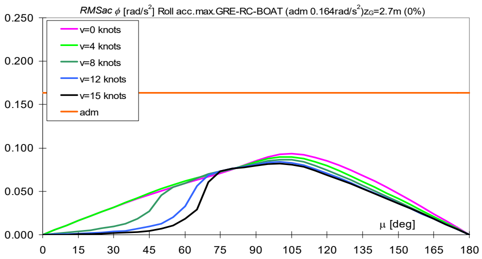

Fig.15.e $RMS_{rollacc}$[rad/s^2] roll acc., z_G=2.7m, 0%.

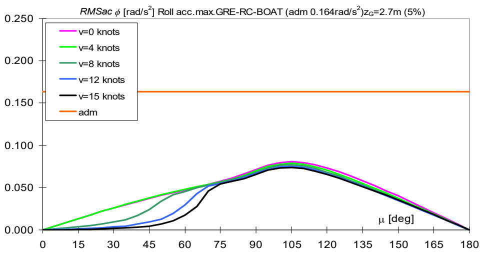

Fig.15.f $RMS_{rollacc}$[rad/s^2] roll acc., z_G=2.7m, 5%.

4. THE NAVIGATION SAFETY LIMITS OF THE RIVER-COASTAL BOAT

The seakeeping criteria applied for the motions and accelerations obtained by short-term analysis delivering the most probable amplitudes (*RMS)*, leads to the evaluation of the safety limits of the river-coastal boat, expressed as polar diagrams in H_{slimit} wave significant height and B_{limit} Beaufort sea state [4].

Figs.16. a-f, Figs.17. a-f, Figs.18. a-d present the safety navigation limits H_{slimit}, B_{limit} polar diagrams, function to the boat speed v=0-15 knots, heading angle μ=0-180(360) deg, vertical position of the gravity center z_G=1.5-2.7m, bilge keels (k_d=0% or 5%).

A synthesis of the navigation limits by seakeeping criteria (Table 2) is presented in Table 3 for the river-coastal boat (Table 1).

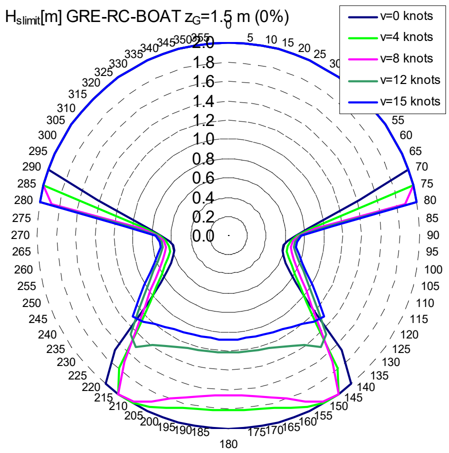

Fig.16.a H_{slimit}[m] boat, z_G=1.5 m, 0%.

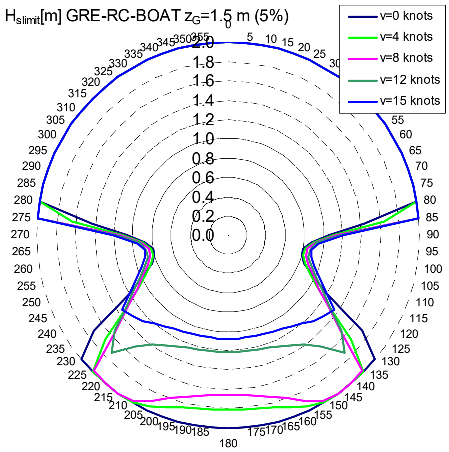

Fig.16.b H_{slimit}[m] boat, z_G=1.5 m, 5%.

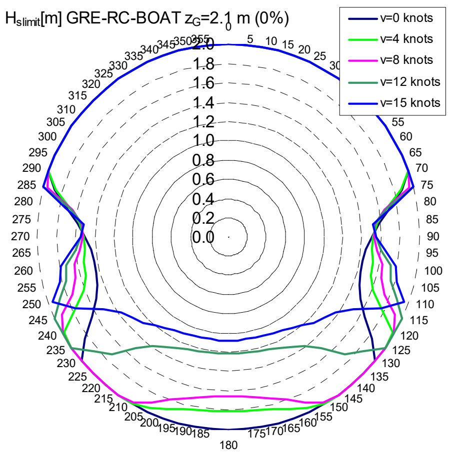

Fig.16.c H_{slimit}[m] boat, z_G=2.1 m, 0%.

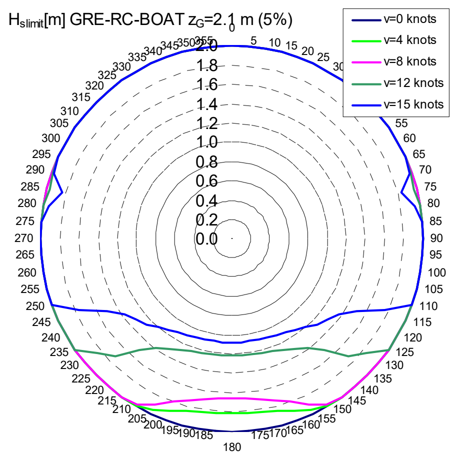

Fig.16.d H_{slimit}[m] boat, z_G=2.1 m, 5%.

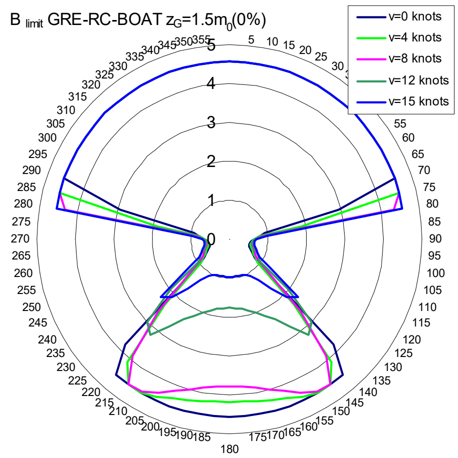

Fig.17.a B_{limit} boat, z_G=1.5 m, 0%.

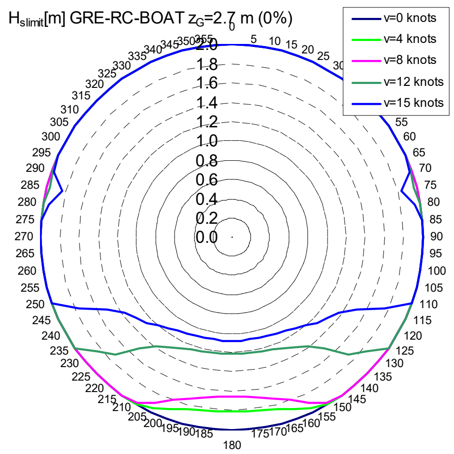

Fig.16.e H_{slimit}[m] boat, z_G=2.7 m, 0%.

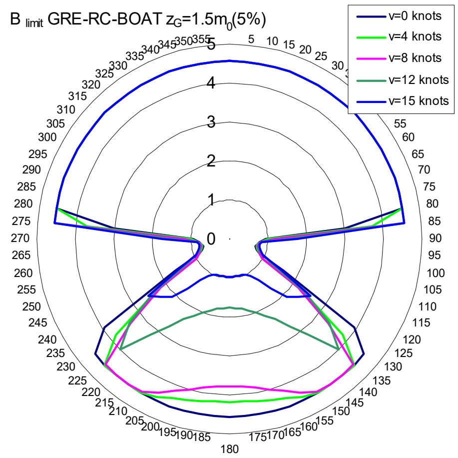

Fig.17.b B_{limit} boat, z_G=1.5 m, 5%.

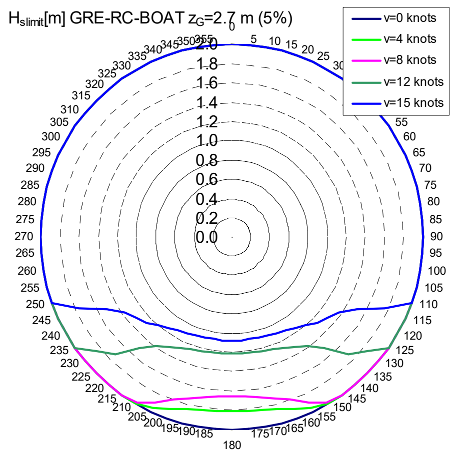

Fig.16.f H_{slimit}[m] boat, z_G=2.7 m, 5%.

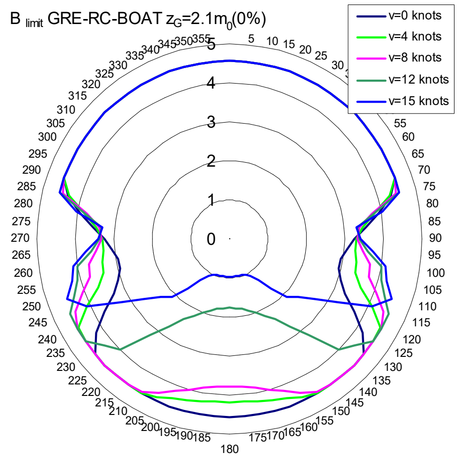

Fig.17.c B_{limit} boat, z_G=2.1 m, 0%.

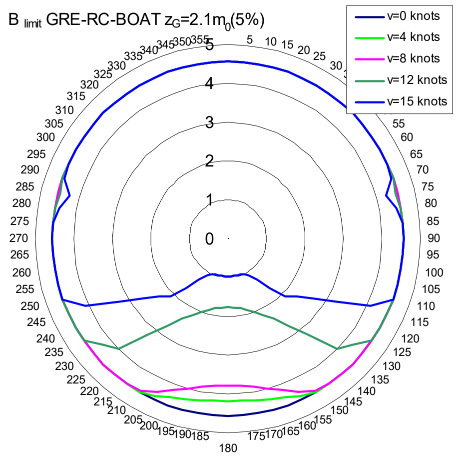

Fig.17.d B_{limit} boat, z_G=2.1 m, 5%.

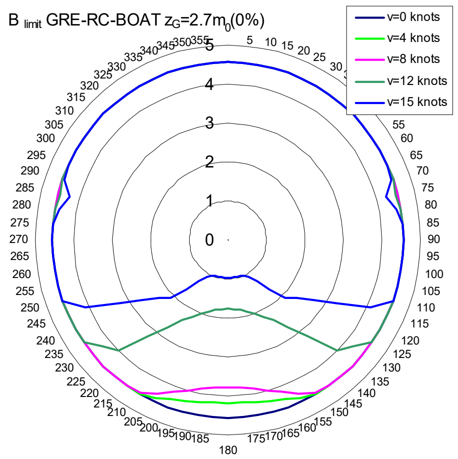

Fig.17.e B_{limit} boat, z_G=2.7 m, 0%.

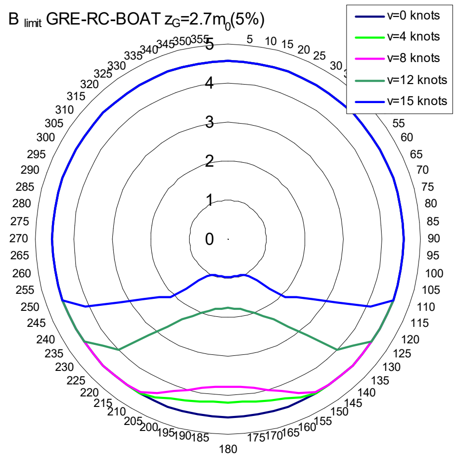

Fig.17.f B_{limit} boat, z_G=2.7 m, 5%.

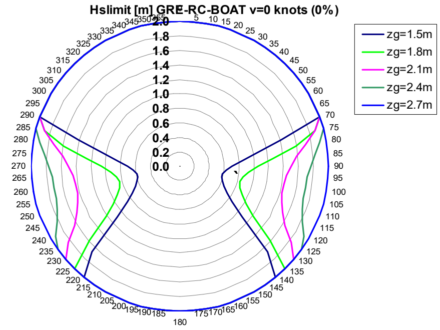

Fig.18 .a H_{slimit}[m] boat, v=0 kn,0%, z_G=1.5-2.7m.

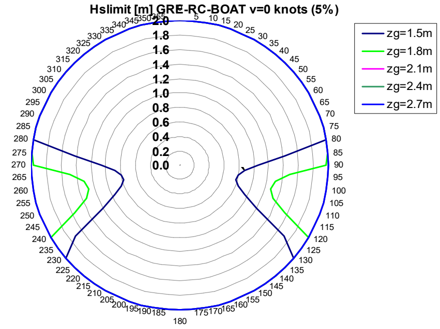

Fig.18 .b H_{slimit}[m] boat, v=0 kn,5%, z_G=1.5-2.7m.

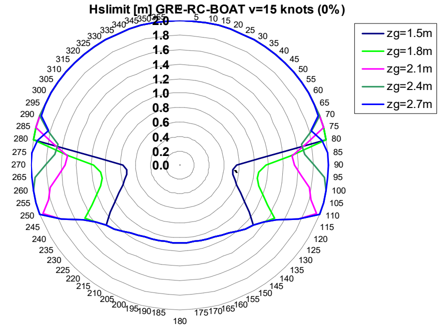

Fig.18 .c H_{slimit}[m] boat,v=15kn,0%, z_G=1.5-2.7m.

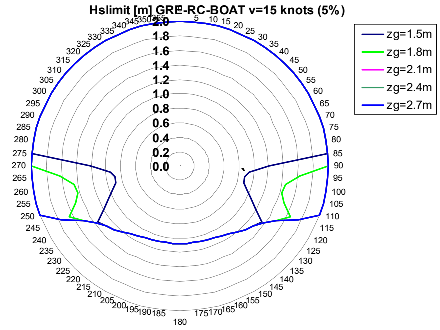

Fig.18 .d H_{slimit}[m] boat,v=15kn,5%, z_G=1.5-2.7m.

Table.3 River-coastal boat seakeeping limits.

z_G[m]	k_d[%]	H_{slimit}[m]	B_{limit}[m]	μ[deg]	Criteria
v=0 knots					
1.5	0	0.585	0.53	105	roll
	5	0.792	0.72	105	roll
1.8	0	0.841	0.76	105	roll
	5	1.271	2.17	105	roll
2.1	0	1.423	2.96	100	roll
	5	**2.000**	**4.58**	-	-
2.4	0	1.710	3.96	100	roll
	5	2.000	4.58	-	-
2.7	0	2.000	4.58	-	-
	5	2.000	4.58	-	-
v=4 knots					
1.5	0	0.627	0.57	100	roll
	5	0.814	0.73	105	roll
1.8	0	0.916	0.83	100	roll
	5	1.308	2.36	105	roll
2.1	0	1.507	3.26	95	roll
	5	**1.809**	**4.18**	180	pitch
2.4	0	1.777	4.11	90	roll
	5	1.809	4.18	180	pitch
2.7	0	1.809	4.18	180	pitch
	5	1.809	4.18	180	pitch
v=8 kn					
1.5	0	0.663	0.60	100	roll
	5	0.842	0.76	100	roll
1.8	0	0.971	0.88	100	roll
	5	1.351	2.59	105	roll
2.1	0	1.527	3.33	90	roll
	5	**1.657**	**3.78**	180	pitch
2.4	0	1.657	3.78	180	pitch
	5	1.657	3.78	180	pitch
2.7	0	1.657	3.78	180	pitch
	5	1.657	3.78	180	pitch
v=12 knots					
1.5	0	0.698	0.63	95	roll
	5	0.866	0.78	100	roll
1.8	0	1.022	0.92	100	roll
	5	1.206	1.76	180	pitch
2.1	0	1.206	1.76	180	pitch
	5	**1.206**	**1.76**	180	pitch
2.4	0	1.206	1.76	180	pitch
	5	1.206	1.76	180	pitch
2.7	0	1.206	1.76	180	pitch
	5	1.206	1.76	180	pitch
v=15 knots					
1.5	0	0.714	0.64	95	roll
	5	0.883	0.80	100	roll
1.8	0	1.059	0.96	100	roll
	5	1.072	0.97	180	pitch
2.1	0	1.072	0.97	180	pitch
	5	**1.072**	**0.97**	180	pitch
2.4	0	1.072	0.97	180	pitch
	5	1.072	0.97	180	pitch
2.7	0	1.072	0.97	180	pitch
	5	1.072	0.97	180	pitch

5. CONCLUSIONS

The influence of the navigation parameters on the river-coastal boat, speed, heading angle, vertical position of the gravity center, and bilge keels are analyzed in detail, leading to the safety limits (Table 3) on the Danube and coastal waterways by seakeeping criteria.

For z_G=1.5-2.1 m the main restrictions occur from the roll criterion and for z_G=2.1-2.7 m the pitch criterion becomes dominant. So, for $z_G \geq 2.4$m the bilge keels are improving the dynamic boat behavior only for a small speed range v=0-4 knots. For the high-speed range v=12-15 knots, the main restrictions are from the pitch criterion.

In conclusion, for a well balance between the boat's stability (Fig.2) and the navigation capabilities, an average value of z_G=2.1m with bilge keels (Figs.16-17. d) is recommended as design for the river-coastal boat. For v=0 knots there are no restrictions (H_s=2m), and for $v \geq 4$ knots, the major restrictions are recorded at the head (μ=180 deg) waves, H_{slimit}=1.809 m to 1.022m.

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