

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

**Dumitru-Silviu Perijoc**

“Dunarea de Jos” University of Galati,  
 Faculty of Naval Architecture, Galati,  
 47 Domneasca Street, 800008, Romania,  
 E-mail: silviu.perijoc@ugal.ro

**Leonard Domnişoru**

“Dunarea de Jos” University of Galati,  
 Faculty of Naval Architecture, Galati,  
 47 Domneasca Street, 800008, Romania,  
 E-mail: leonard.domnisoru@ugal.ro

### ABSTRACT

*The design of the river-costal vehicles imposes the assessment by several hydrodynamic and structural criteria. This research involves the evaluation of a river-costal boat made of GRE composite materials at full load condition. The boat’s navigation area covers the Danube inland and costal 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 performances prediction of the river-costal boat.*

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

### 1. INTRODUCTION

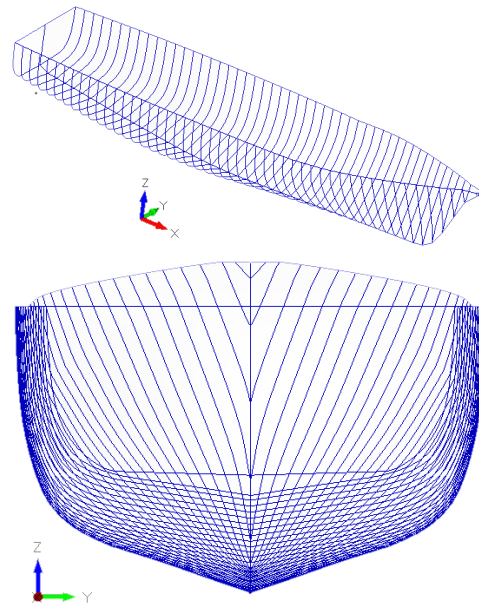
This study involves the prediction of the seakeeping performances of a river-costal boat made of composite materials GRE [1].

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

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

$L_{OA}$ [m]	24.660	Full load		
$L_{WL}$ [m]	23.500	$\Delta$ [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	
$\varphi_{maxGZ}$ [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
$\mu$ [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-costal boat GRE, offset-lines [1].

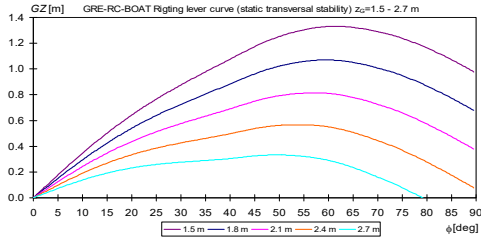


Fig.2 River-costal GRE boat, stability diagram.

The numerical analyses are carried out by eigen DYN [2] programs set, based on strip-theory hydrodynamic approach and 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 <sup>2</sup> ]	0.198
$RMS_{fore}$ [m]	2.450	$RMS_{roll}$ [rad]	0.087
$RMS_{heaveacc}$ [m/s <sup>2</sup> ]	1.472	$RMS_{rollacc}$ [rad/s <sup>2</sup> ]	0.164

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

The dynamic response analysis in regular waves lead to the computation in the frequency domain of the response amplitude operator functions (*RAO*) [4], for the main motion components of the river-costal 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 ( $\mu=135-180$  deg) waves, with speed influence noticed for  $\omega > 0.75$  rad/s.

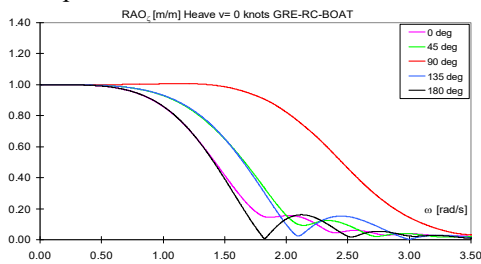


Fig.3.a RAO [m/m] boat heave, v=0 kn.

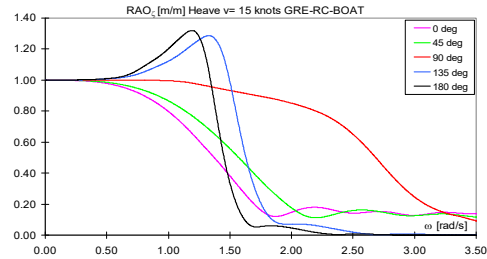


Fig.3.b RAO [m/m] boat heave, v=15 kn.

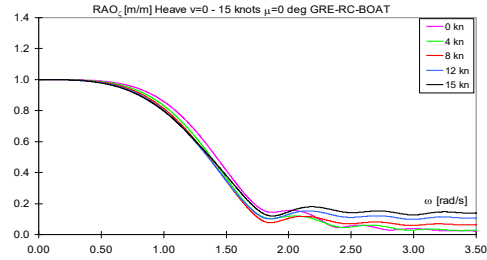


Fig.4.a RAO [m/m] boat heave,  $\mu=0$  deg.

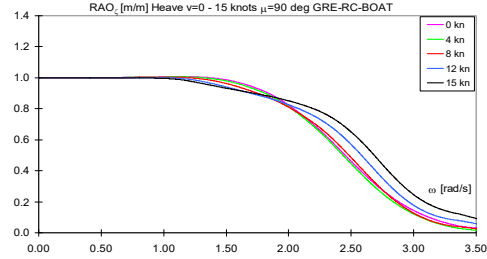


Fig.4.b RAO [m/m] boat heave,  $\mu=90$  deg.

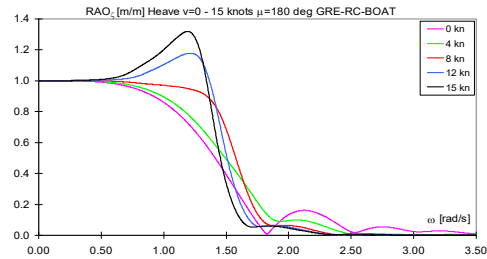


Fig.4.c RAO [m/m] boat heave,  $\mu=180$  deg.

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 ( $\mu=135-180$  deg) waves, for speed  $v \geq 8$  knots. Noticeable pitch results also at follow waves ( $\mu=0$  deg). The minimum pitch motion is at beam ( $\mu=90$  deg) waves. The boat speed influence is significant in the range of  $\omega=1.00-2.50$  rad/s.

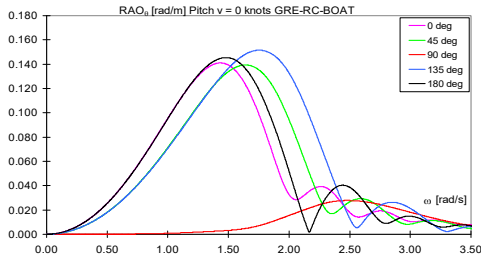


Fig.5.a RAO [rad/m] boat pitch,  $v=0$  kn.

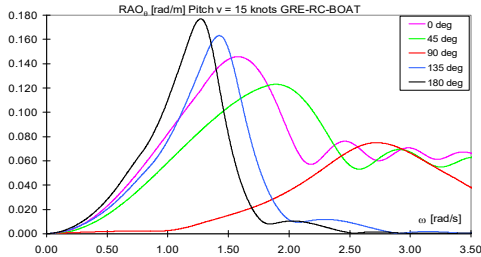


Fig.5.b RAO [rad/m] boat pitch,  $v=15$  kn.

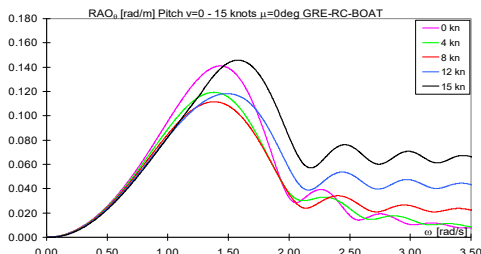


Fig.6.a RAO [rad/m] boat pitch,  $\mu=0$  deg.

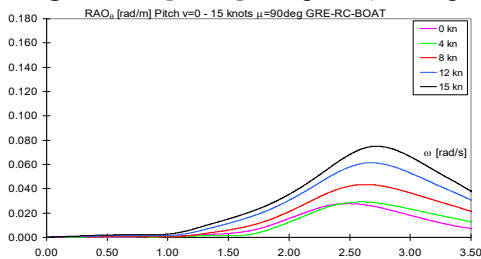


Fig.6.b RAO [rad/m] boat pitch,  $\mu=90$  deg.

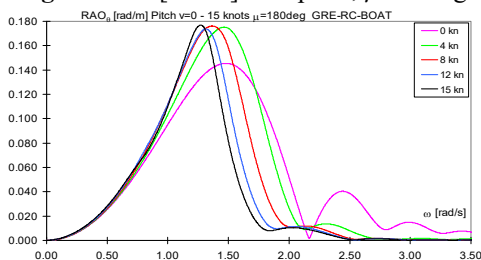


Fig.6.c RAO [rad/m] boat pitch,  $\mu=180$  deg.

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 ( $\mu=70-120$  deg), with a noticeable speed influence in the range of  $\omega=0.50-1.50$  rad/s. The influence of the bilge keels and the increase of  $z_G$  are positive, reducing the roll response.

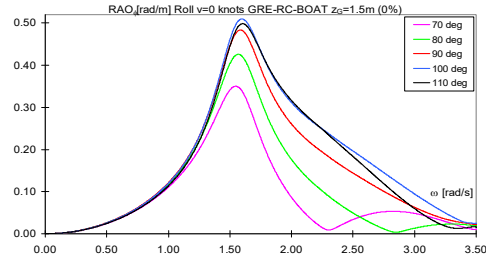


Fig.7.a RAO [rad/m] roll,  $v=0$  kn,  $z_G=1.5$ m, 0%.

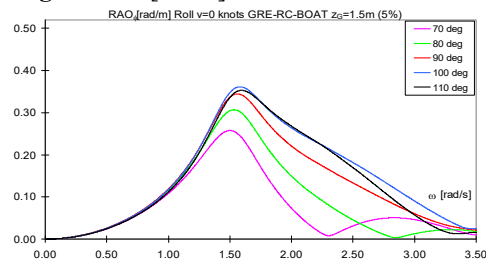


Fig.7.b RAO [rad/m] roll,  $v=0$  kn,  $z_G=1.5$ m, 5%.

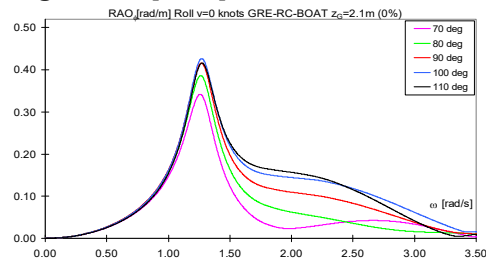


Fig.7.c RAO [rad/m] roll,  $v=0$  kn,  $z_G=2.1$ m, 0%.

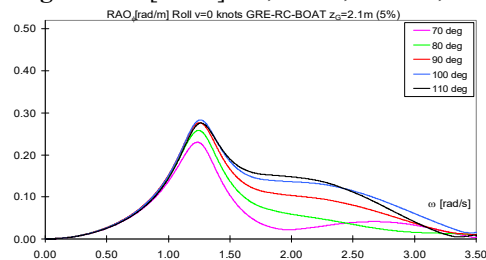


Fig.7.d RAO [rad/m] roll,  $v=0$  kn,  $z_G=2.1$ m, 5%.

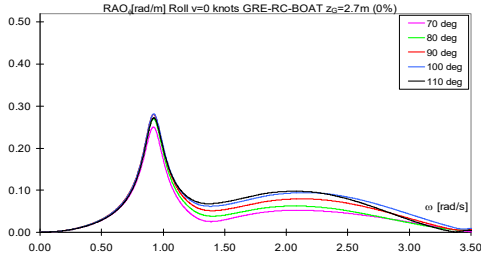


Fig. 7.e RAO [rad/m] roll,  $v=0$  kn,  $z_G=2.7$ m, 0%.

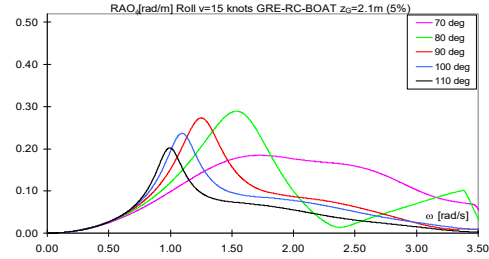


Fig. 8.d RAO [rad/m] roll,  $v=15$  kn,  $z_G=2.1$ m, 5%.

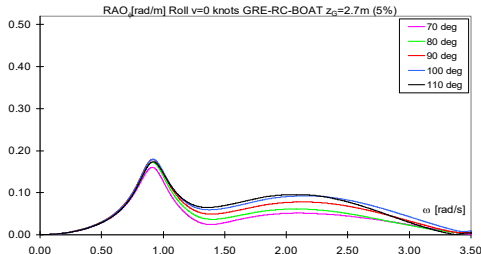


Fig. 7.f RAO [rad/m] roll,  $v=0$  kn,  $z_G=2.7$ m, 5%.

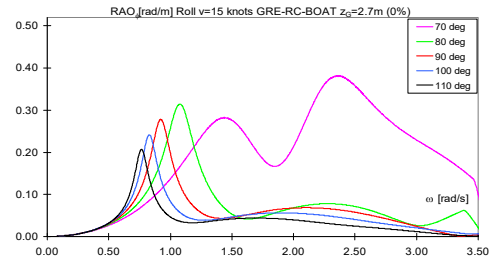


Fig. 8.e RAO [rad/m] roll,  $v=15$  kn,  $z_G=2.7$ m, 0%.

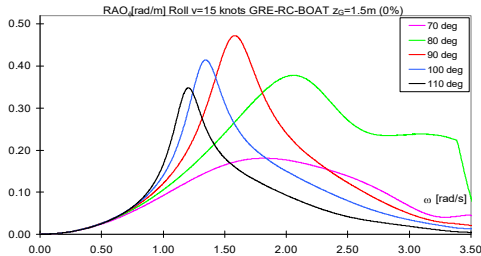


Fig. 8.a RAO [rad/m] roll,  $v=15$  kn,  $z_G=1.5$ m, 0%.

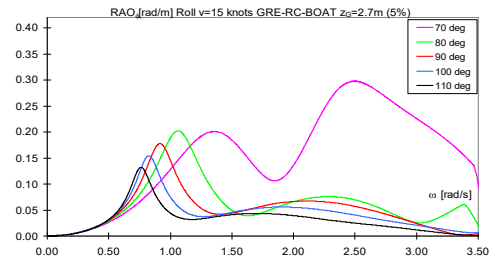


Fig. 8.f RAO [rad/m] roll,  $v=15$  kn,  $z_G=2.7$ m, 5%.

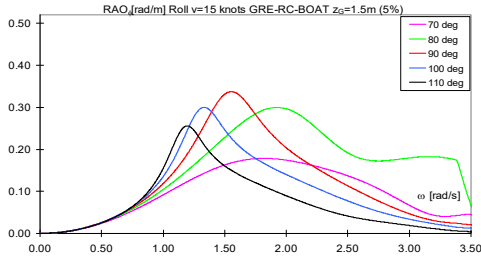


Fig. 8.b RAO [rad/m] roll,  $v=15$  kn,  $z_G=1.5$ m, 5%.

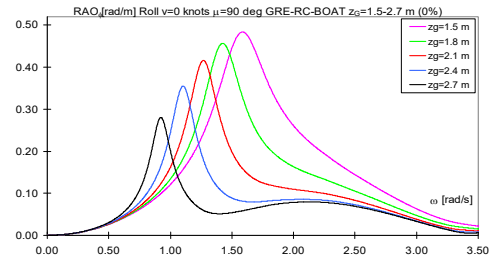


Fig. 9.a RAO [rad/m] boat roll,  $\mu=90$ ,  $v=0$  kn, 0%.

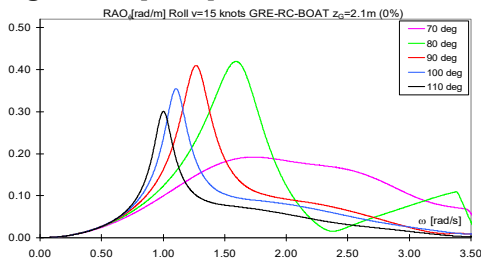


Fig. 8.c RAO [rad/m] roll,  $v=15$  kn,  $z_G=2.1$ m, 0%.

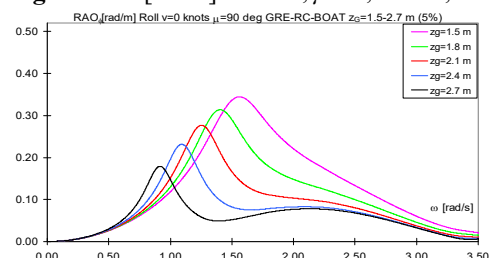


Fig. 9.b RAO [rad/m] boat roll,  $\mu=90$ ,  $v=0$  kn, 5%.

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

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

The *RMS* maximum short-term most probable response values for combine vertical motions at 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  $\mu = 115-180$  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  $\mu = 140-180$  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  $\mu = 110-180$  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 ( $\mu = 75-120$  deg) waves, whole range of  $z_G = 1.5-2.7$  and boat speed  $v = 0-15$  knots. In the case with bilge keels (5%) the criterion is satisfied at limit for  $z_G = 1.5$ m, with a small overpass for  $v = 0$  knots, and no restrictions for  $z_G > 1.5$ m 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  $z_G = 1.5$ m, with or without keels, and for  $z_G = 2.1$ m 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 with bilge keels (5%) the criterion has no restrictions for  $z_G > 1.5$ m.

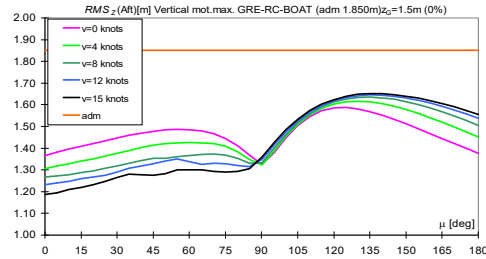


Fig.10.a  $RMS_{aft}$  [m] max. boat combined aft.

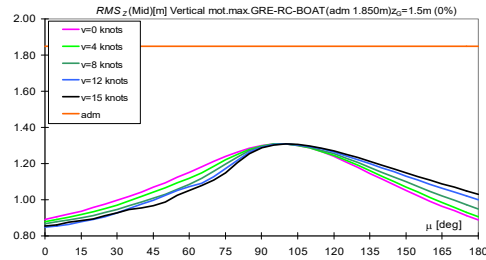


Fig.10.b  $RMS_{mid}$  [m] max. boat combined mid.

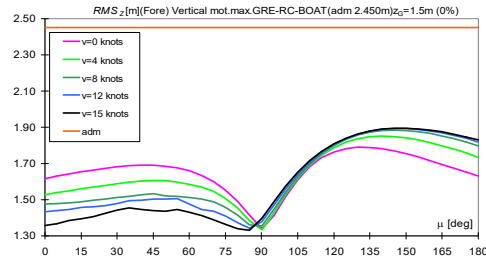


Fig.10.c  $RMS_{fore}$  [m] max. boat combined fore.

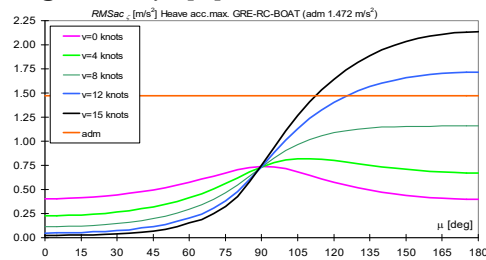


Fig.11  $RMS_{heaveacc}$  [m/s<sup>2</sup>] max. boat vertical acc.

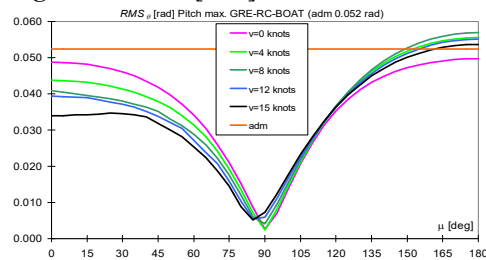


Fig.12  $RMS_{pitch}$  [rad] max. boat pitch motion.

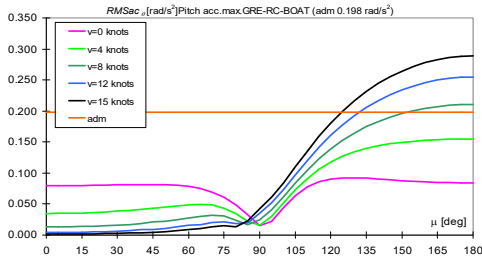


Fig.13  $RMS_{pitchacc}$  [rad/s<sup>2</sup>] max. boat pitch acc.

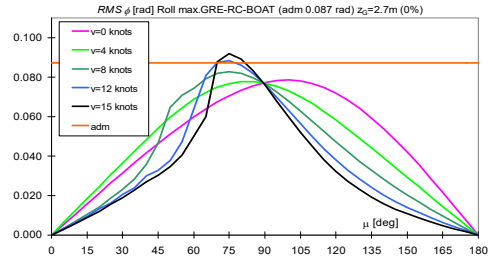


Fig.14.e  $RMS_{roll}$  [rad] max. boat roll,  $z_G=2.7m$ , 0%.

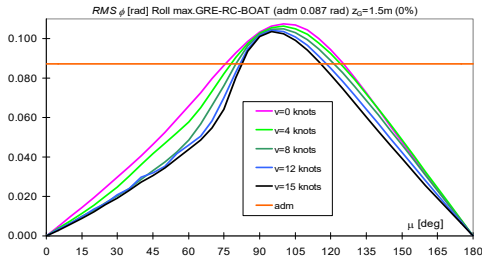


Fig.14.a  $RMS_{roll}$  [rad] max. boat roll,  $z_G=1.5m$ , 0%.

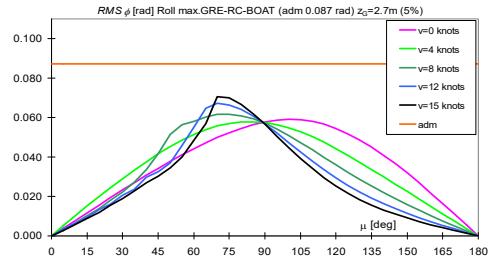


Fig.14.f  $RMS_{roll}$  [rad] max. boat roll,  $z_G=2.7m$ , 5%.

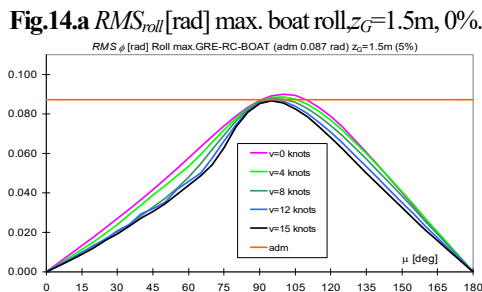


Fig.14.b  $RMS_{roll}$  [rad] max. boat roll,  $z_G=1.5m$ , 5%.

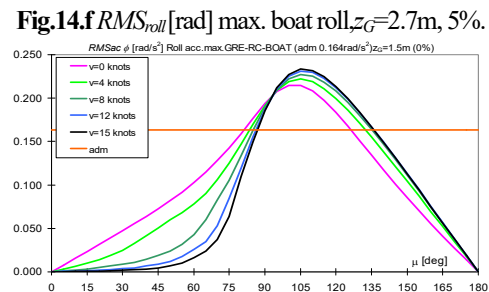


Fig.15.a  $RMS_{rollacc}$  [rad/s<sup>2</sup>] roll acc.,  $z_G=1.5m$ , 0%.

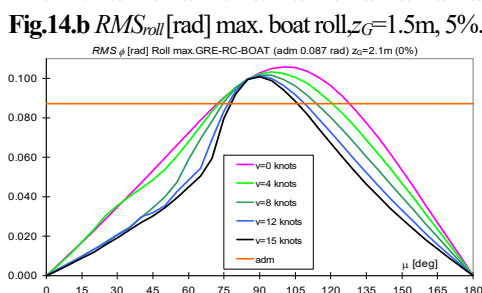


Fig.14.c  $RMS_{roll}$  [rad] max. boat roll,  $z_G=2.1m$ , 0%.

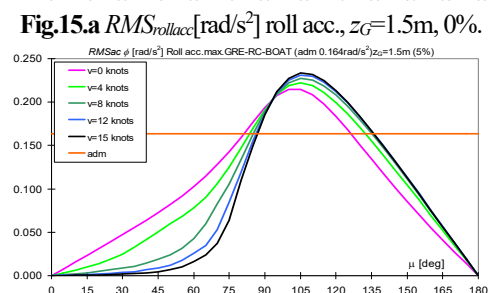


Fig.15.b  $RMS_{rollacc}$  [rad/s<sup>2</sup>] roll acc.,  $z_G=1.5m$ , 5%.

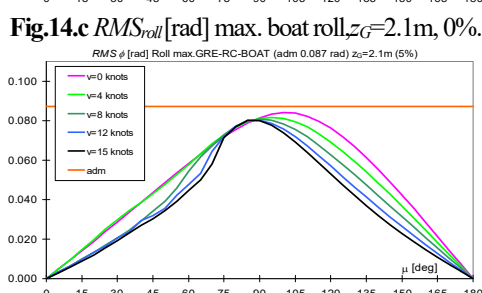


Fig.14.d  $RMS_{roll}$  [rad] max. boat roll,  $z_G=2.1m$ , 5%.

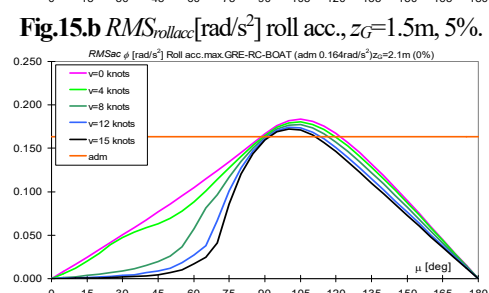


Fig.15.c  $RMS_{rollacc}$  [rad/s<sup>2</sup>] roll acc.,  $z_G=2.1m$ , 0%.

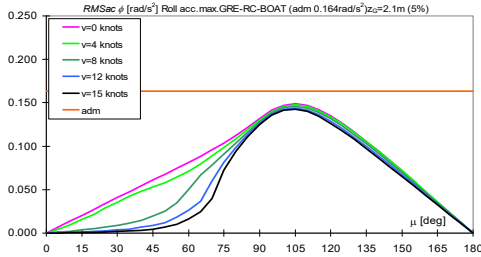


Fig.15.d  $RMS_{rollacc}$  [rad/s<sup>2</sup>] roll acc.,  $z_G=2.1m$ , 5%.

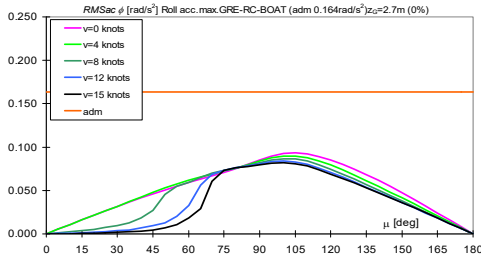


Fig.15.e  $RMS_{rollacc}$  [rad/s<sup>2</sup>] roll acc.,  $z_G=2.7m$ , 0%.

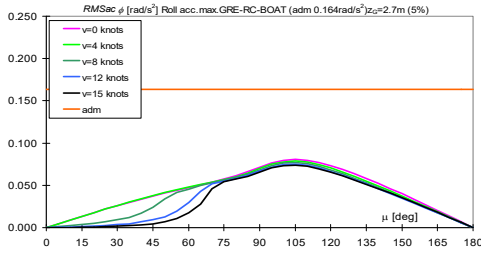


Fig.15.f  $RMS_{rollacc}$  [rad/s<sup>2</sup>] roll acc.,  $z_G=2.7m$ , 5%.

#### 4. THE NAVIGATION SAFETY LIMITS OF THE RIVER-COSTAL 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-costal 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  $\mu=0-180(360)$  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) are presented in Table 3 for the river-costal boat (Table 1).

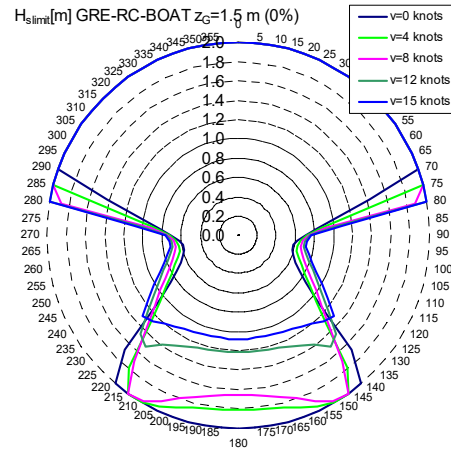


Fig.16.a  $H_{slimit}$  [m] boat,  $z_G=1.5m$ , 0%.

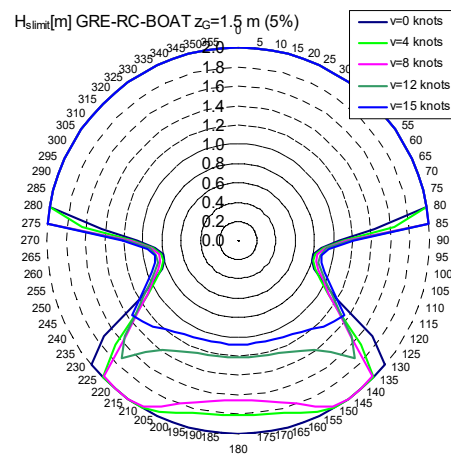


Fig.16.b  $H_{slimit}$  [m] boat,  $z_G=1.5m$ , 5%.

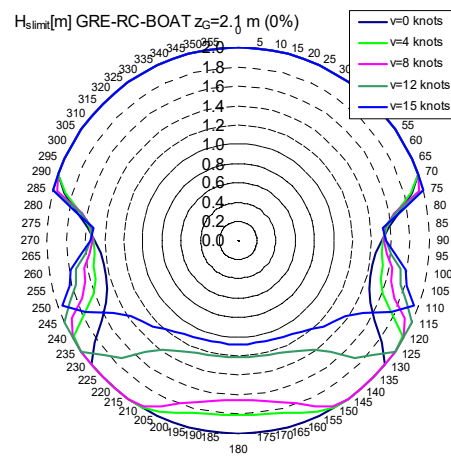


Fig.16.c  $H_{slimit}$  [m] boat,  $z_G=2.1m$ , 0%.

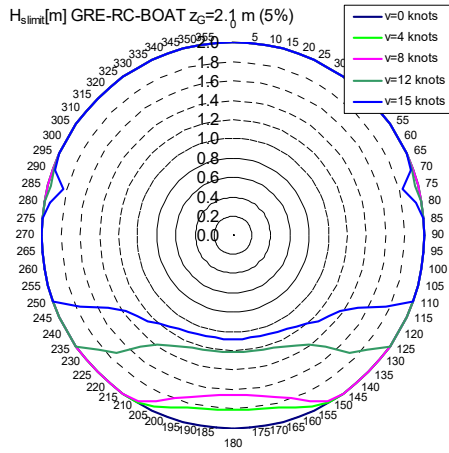


Fig.16.d  $H_{slimit}$ [m] boat,  $z_G=2.1$  m, 5%.

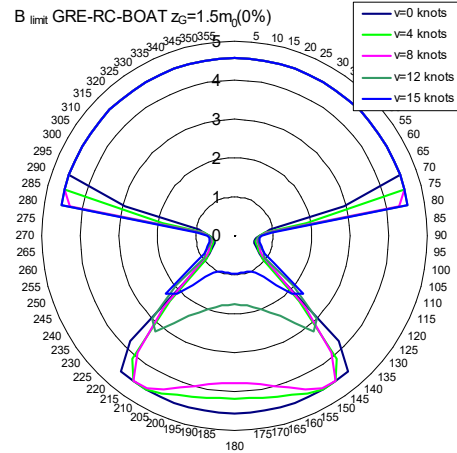


Fig.17.a  $B_{limit}$  boat,  $z_G=1.5$  m, 0%.

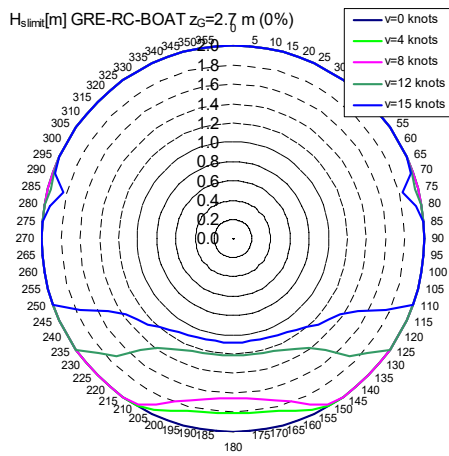


Fig.16.e  $H_{slimit}$ [m] boat,  $z_G=2.7$  m, 0%.

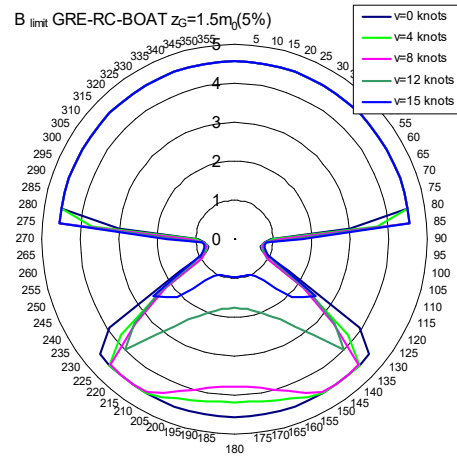


Fig.17.b  $B_{limit}$  boat,  $z_G=1.5$  m, 5%.

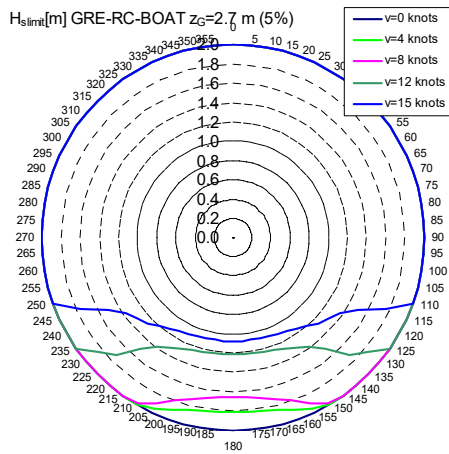


Fig.16.f  $H_{slimit}$ [m] boat,  $z_G=2.7$  m, 5%.

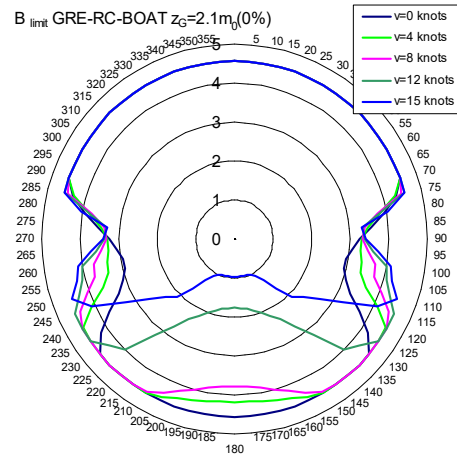


Fig.17.c  $B_{limit}$  boat,  $z_G=2.1$  m, 0%.



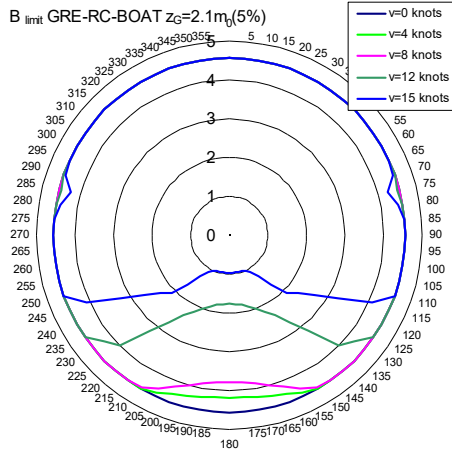


Fig.17.d  $B_{limit}$  boat,  $z_G=2.1$  m, 5%.

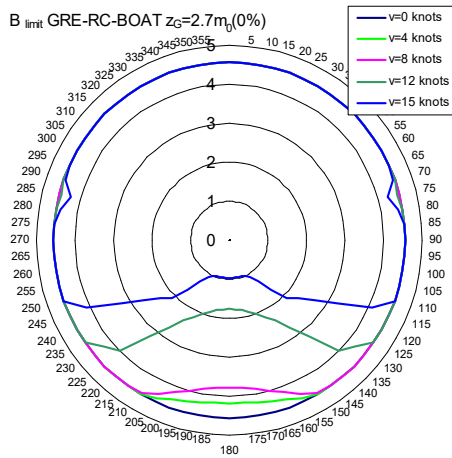


Fig.17.e  $B_{limit}$  boat,  $z_G=2.7$  m, 0%.

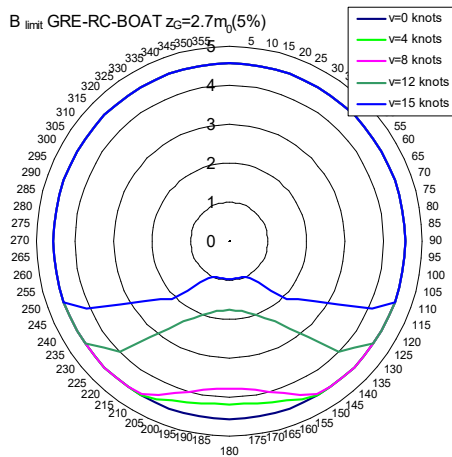


Fig.17.f  $B_{limit}$  boat,  $z_G=2.7$  m, 5%.

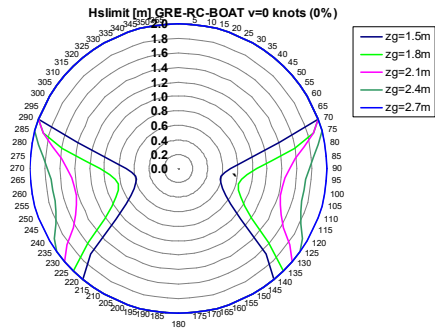


Fig.18.a  $H_{slimit}$  [m] boat,  $v=0$  kn, 0%,  $z_G=1.5-2.7$  m.

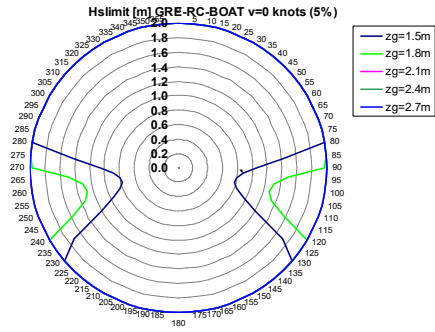


Fig.18.b  $H_{slimit}$  [m] boat,  $v=0$  kn, 5%,  $z_G=1.5-2.7$  m.

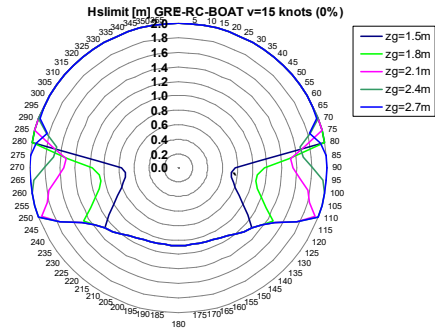


Fig.18.c  $H_{slimit}$  [m] boat,  $v=15$  kn, 0%,  $z_G=1.5-2.7$  m.

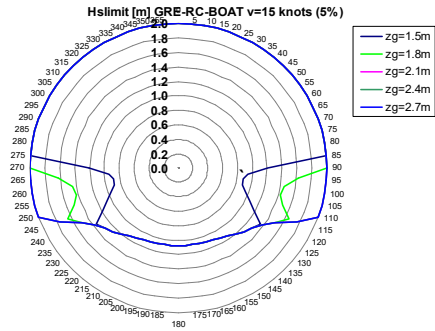


Fig.18.d  $H_{slimit}$  [m] boat,  $v=15$  kn, 5%,  $z_G=1.5-2.7$  m.

**Table.3** River-costal boat seakeeping limits.

$z_G$ [m]	$k_d$ [%]	$H_{slimit}$ [m]	$B_{limit}$ [m]	$\mu$ [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	<b>2.000</b>	<b>4.58</b>	-	-
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	<b>1.809</b>	<b>4.18</b>	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	<b>1.657</b>	<b>3.78</b>	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	<b>1.206</b>	<b>1.76</b>	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	<b>1.072</b>	<b>0.97</b>	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-costal boat, speed, heading angle, vertical position of the gravity center and bilge keels are in detail analyzed, leading to the safety limits (Table 3), on Danube and costal waterways by seakeeping criteria.

For  $z_G=1.5-2.1$  m the main restrictions occur from roll criterion and for  $z_G=2.1-2.7$  m the pitch criterion becomes dominant. So that, for  $z_G \geq 2.4$  m the bilge keels are improving the dynamic boat behavior only for 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  $z_G=2.1$  m with bilge keels (Figs.16-17.d) is recommended as design for the river-costal boat. For  $v=0$  knots are no restrictions ( $H_s=2$  m), and for  $v \geq 4$  knots the major restrictions are recorded at head ( $\mu=180$  deg) waves,  $H_{slimit}=1.809$  m to 1.022 m.

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