



## DYNAMIC RESPONSE PREDICTION OF A RESEARCH DESIGN CONCEPT VESSEL

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**Abstract:** Numerical dynamic response prediction refers to a research-passenger design concept vessel with the following specifications: 44.5m total length, 9.0m breadth, 3.0m height, mono-hull type, 20 km/h top speed, designed for navigation in the Danube River and Black Sea coastal areas, and with a maximum significant wave height of 2.5m. The multi-deck and compartment layout for research laboratories, as well as onboard rooms for crew and passengers, with specific equipment and provisions, necessitates a dynamic analysis for two loading cases with a draught of 1.5 m and 1.7 m. The vessel oscillation response in regular waves is computed using a frequency-domain linear strip approach, and the dynamic response in irregular waves using a statistical short-term approach, with seakeeping criteria assessment. The detailed parametric dynamic response analysis is solved using the eigen DYN\_OSC version 2025 program, which includes a wide range of specific navigation parameters. This research predicts navigation operational capabilities of the research passenger vessel.

**Key words:** research-passenger vessel, dynamic response, river-coastal, regular and irregular waves, seakeeping criteria.

### 1. INTRODUCTION

A new ship design concept, besides the structural criteria [1, 2, 3], has to be assessed by several hydrodynamic criteria, among which are the navigation operational capabilities by ship's dynamic response prediction for the specific waves' condition, and the seakeeping safety rules required criteria [4, 5, 6, 7].

The seakeeping analysis of a vessel design concept requires a hydrodynamic vessel motions method [8], ensuring a fast and accurate computational method capable of a wide range of navigation operational parameters for the vessel and wave system. For practical purposes, in the case of a slender shape mono-hull design concept vessel, the references [9, 10, 11] point out the best use of the two-analysis-part approach. In the first part, the vessel oscillations' response in regular waves is computed by a frequency domain linear strip approach. In the second part, the vessel dynamic response in irregular waves is computed by a short-term statistical approach [12, 13, 14] (section 2).

This study approaches the dynamic response prediction of a research-passenger design concept vessel for the river-coastal navigation area, with the structure previously assessed by strength criteria [3] for two reference loading cases with draughts of 1.5 m and 1.7 m, in accordance with onboard provisions and research equipment amounts. The research-passenger vessel satisfies the main requirements for the strip hydrodynamic method: the maximum vessel Froude number of 0.270, for top speed 20 km/h, is smaller than 0.4, and the vessel concept design has a mono-hull with slender shape, length over breadth ratio of 4.94 (44.5/9), which is almost 5 (section 3). For extended parametric dynamic response prediction, the vessel design concept includes a change in the vertical position  $z_G$  of onboard masses and the influence of the passive bilge keel system type on roll response.

The research-passenger vessel navigation area is the Danube River, IN(2.0), and the Black Sea Coast, C(2.5), waterways, with dynamic response prediction eigen DYN\_OSC versions 2025 [15] program, with integrated deterministic regular wave and statistical irregular wave solvers (section 2). The vessel's short-term dynamic response, on river-coastal routes, in terms of most probable oscillation motion and acceleration response amplitudes, is assessed by seakeeping criteria, resulting in the safety limits polar diagrams.

For both loading cases, the detailed parametric research-passenger vessel dynamic response analyses, in regular-irregular waves (section 4), include as navigation parameters: vessel speed, gravity center vertical position, and bilge keels type; wave frequencies, heading angles, and significant wave height for the river and coastal navigation scenarios.

The combination of navigation operational capabilities from seakeeping criteria with previous structural assessment results [3] provides practical safety limits for navigation in river-coastal conditions for the research-passenger vessel design concept (section 5).

## 2. METHODS AND SOFTWARE. THE ANALYSIS STEPS OF THE RESEARCH-PASSENGER VESSEL FOR THE RIVER-COASTAL NAVIGATION SAFETY EVALUATION BY SEAKEEPING CRITERIA

The river-coastal navigation safety evaluation of the research-passenger design concept is carried out according to the seakeeping *ITTC* procedures [4, 12], with eigen developed integrated program modules *DYN\_OSC* [15], improved in terms of computational accuracy, running time, and interface, with main analysis steps in Figure 1.

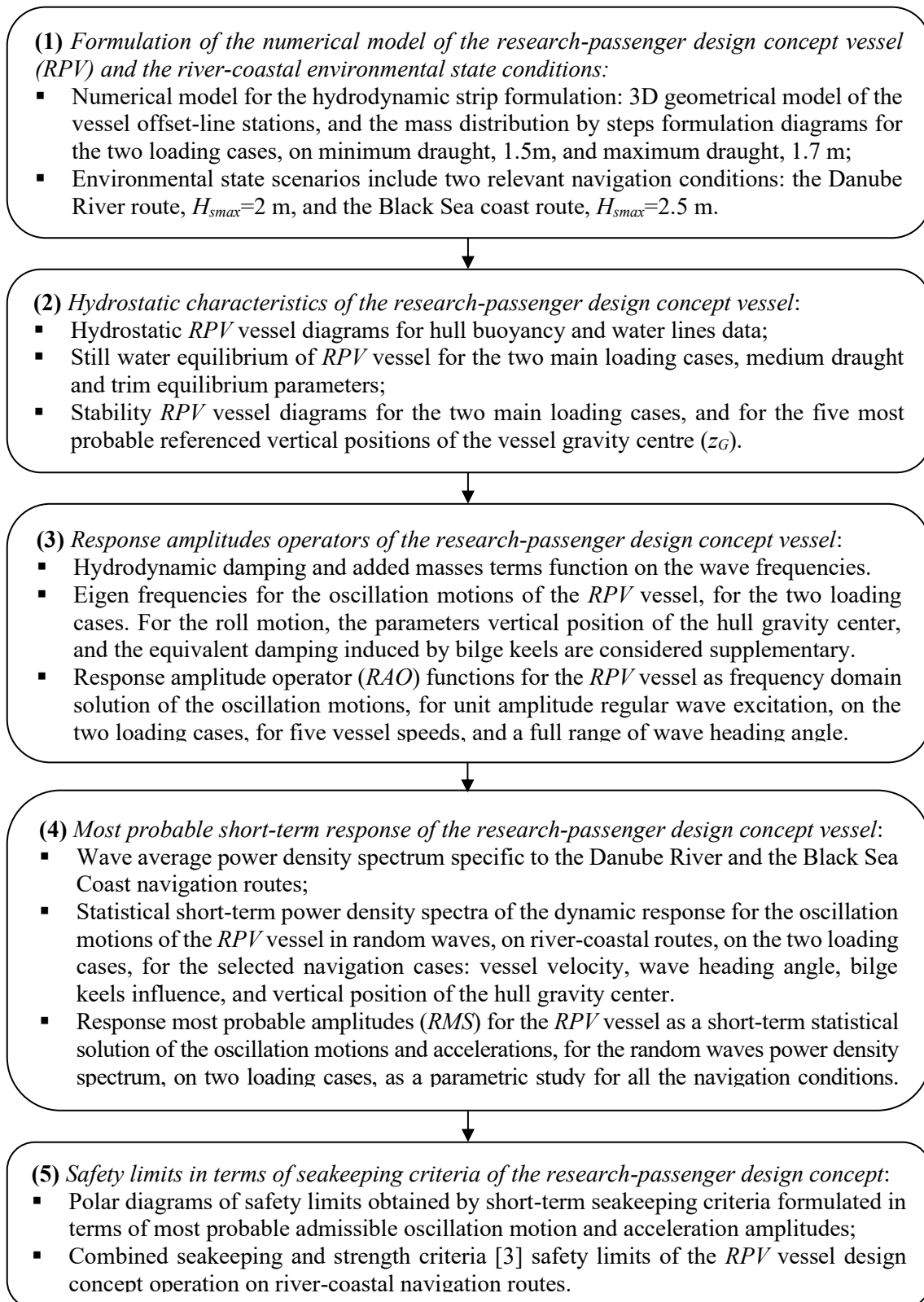


Fig. 1. The main analysis steps for navigation safety evaluation by seakeeping criteria and *DYN\_OSC vers.2025* [15] program modules of a research-passenger vessel design concept (*RPV*), in river-coastal environmental conditions.

(1) *Formulation of the numerical model of the research-passenger design concept vessel (RPV) and the river-coastal environmental state conditions*

The first step of the dynamic analysis involves the development of the *RPV* vessel numerical model, with the main data in Table 1, according to the hydrodynamic strip method formulation: the offset lines stations 3D geometrical model, with 30 points per station, imported from the vessel design concept [16, 3] (Figure 2), and the mass distribution diagram per unit hull length corresponding to the extreme loading cases, with minimum operational draught  $T_{min} = 1.5$  m, displacement  $\Delta = 434.725$  t (Figure 3a), reduced provisions and only essential research equipments, and maximum operational draught  $T_{max} = 1.7$  m, displacement  $\Delta = 501.750$  t (Figure 3. b), full provisions and research equipment. Although there are, by design, two structural construction versions of the *RPV* vessel [3], standard and enhanced structures, with the same hull external shape, the two extreme draught conditions are preserved, resulting in different effective mass capacities of  $42.795 \div 140.075$  t [3]. Also in this step, by design, the navigation area is set up for the *RPV* vessel: standard route on the Danube River, with a maximum significant wave height  $H_{smax} = 2$  m, and extended route on the Black Sea Coast with  $H_{smax} = 2.5$  m.

(2) *Hydrostatic characteristics of the research-passenger design concept vessel*

As the second step of the dynamic analysis setup, the hydrostatic characteristic diagrams of the *RPV* vessel are obtained using an incremental water line position procedure [17, 15] applied for the design concept offset lines stations (Figure 2), delivering the corresponding hull buoyancy initial data related to the two main loading cases. The oscillation motions are referenced to the *RPV* vessel's still water equilibrium state, obtained by an iterative nonlinear procedure [15], applied for each mass distribution (Figure 3) of the two loading cases. For the roll motion restoring capability assessment, the stability diagrams of the *RPV* vessel (Figure 4) by an enhanced iterative nonlinear procedure [15] are obtained, considering the most probable vertical positions of the vessel gravity center in the range  $z_G = 2.80 \div 3.40$  m (step  $\delta z_G = 0.15$  m).

(3) *Response amplitude operators of the research-passenger design concept vessel*

The third step of the dynamic analysis involves the hydrodynamic added masses ( $m_{33}, m_{55}, m_{35}, m_{44}$ ), and damping ( $N_{33}, N_{55}, N_{35}, N_{44}$ ), computation by a 2D hydrodynamic formulation on each *RPV* hull station [15], function to a complete range of the regular wave excitation frequencies ( $\omega = 0 \div 3$  rad/s, step  $\delta\omega = 0.001$  rad/s), the vessel-wave angle ( $\mu = 0 \div 180$  deg, and step  $\delta\mu = 5$  deg), and the vessel speeds ( $v = 0 \div 20$  km/h, step  $\delta v = 5$  km/h). For the two loading cases, in this step, the eigen frequencies (Table 3) for the oscillation motions of the *RPV* vessel are obtained as the first results of the dynamic analysis, defining the most sensitive frequency domains of the vessel and wave resonance conditions. In the case of roll motions, the eigen frequencies are function also to the vertical position of the vessel gravity centre ( $z_G = 2.80 \div 3.40$  m), and the equivalent damping induced by bilge keels system,  $k_{BK} = 0\%$  (no bilge keels),  $k_{BK} = 5\%$  (standard bilge keels), and  $k_{BK} = 10\%$  (extended bilge keels), as percent value of the critical specific roll damping [15]. For the selected navigation parameters ( $\Delta, v, \mu, \omega, z_G, k_{BK}$ ) and unit amplitude regular wave excitation, the response amplitude operators of the *RPV* vessel oscillations (Figures 6-11, 17-22) are computed by a frequency direct solution [15].

(4) *Most probable short-term response of the research-passenger design concept vessel*

The *RPV* vessel is designed to operate on river-coastal routes, using the *ISSC* average power density spectrum for the irregular waves' energy model (Figure 5) [1, 7], with the wave significant height range  $H_s = 0 \div 2.5$  m (step  $\delta H_s = 0.01$  m), having maximum for the Danube River  $H_s = 2$  m, and for the Black Sea coastal  $H_s = 2.5$  m.

In the fourth step, for the selected navigation parameters ( $\Delta, v, \mu, \omega, z_G, k_{BK}$ ), based on the *RAO* operators (unit amplitude regular waves' dynamic response) and the wave power density spectrum (irregular waves energy formulation), the short-term statistical analyses deliver the motions spectra and the most probable short-term oscillation motions ( $RMS_{osc}$ ) and accelerations ( $RMS_{osc\_acc}$ ) amplitudes (Tables 5, 8 and Figures 12-14, 23-25).

(5) *Safety limits in terms of seakeeping criteria of the research passenger vessel design concept*

The fifth step of the dynamic analysis includes the prediction of the polar diagrams safety  $H_s(m)$  limits (Tables 6, 9, Figures 15, 16, 26, 27) of the *RPV* vessel function to the selected navigation parameters ( $\Delta, v, \mu, \omega, z_G, k_{BK}$ ), by the short-term seakeeping criteria formulated in terms of most probable admissible oscillation motions ( $RMS_{osc\_adm}$ ), and accelerations ( $RMS_{osc\_acc\_adm}$ ) vertical combined, pitch and roll amplitudes (Table 4).

In a previous study [3], the safety operational limits of the *RPV* vessel were determined using strength criteria, with a structural FEM model with oblique design wave loads. Combining the limit results, seakeeping and strength criteria, the practical safety limits on the river-coastal navigation routes of the *RPV* research passenger vessel design concept are obtained (Tables 7, 10).

The accuracy and robustness of eigen *DYN\_OSC* [15] strip approach hydrodynamic modules have been validated by experimental scaled models at the towing tank test laboratory [18], and also by numerical benchmark full-scale models [19], satisfying the rules requests [5, 6, 7], the new version adds supplementary facilities for data processing and optimized numerical code.

### 3. HYDRODYNAMIC MODEL DATA OF THE RESEARCH-PASSENGER VESSEL DESIGN CONCEPT

The research-passenger vessel *RPV* numerical model for the strip hydrodynamic analysis includes two main data items: the offset lines 3D geometrical model of the hull external shape [16], and the vessel mass distribution for each selected loading case [3]. The *RPV* numerical data (Table 1) and geometry are imported from the vessel's 3D design concept structural model, which was previously assessed using strength criteria [3, 16].

Based on the *Parasolid* geometrical model implemented in the Femap [20] program, intersections of the hull surface with transversal planes at 200 mm intervals are applied to extract the preliminary geometry of the offset lines, comprising 229 stations. Each station is processed with an eigen geometrical module, resulting in a uniform distribution of 30 points on each station, and a numerical parameterization by *Lewis* conformal transformation [15] for the *RPV* vessel offset lines geometry (Figure 2).

Applying user macro-command files [3] for the structural *RPV* vessel model in the Femap [20] program results in mass step distribution diagrams per unit length for each loading case. Two specific displacement conditions are considered, corresponding to the limit vessel draughts, related to the onboard added provisions and research equipment. The two structural vessel versions [3] (standard *T1*, enhanced *T2*) have the vessel light displacement  $\Delta_{light(T1)} = 361.675$  t and  $\Delta_{light(T2)} = 391.750$  t, resulting by the vessel hydrostatic diagrams the total displacement in the range  $\Delta = 434.725 \div 501.750$  t ( $T = 1.5 \div 1.7$  m), with associated mass diagrams (Figure 3), and different effective carrying mass capacities of  $42.795 \div 140.075$  t, that satisfies in any condition the necessity of onboard masses of the vessel research missions.

By design layout, the vertical position of the *RPV* vessel gravity center can be changed from  $z_{Gmin} = 2.80$  m to  $z_{Gmax} = 3.40$  m, affecting the roll inertial mass moment ( $J_{xx}$ ) and the metacentric height ( $GM_0$ )  $> 0.1$  m. The stability diagrams [17] for the two loading cases (Figure 4) are linear curves up to 15 deg roll angle, with a maximum for angles between  $22.50 \div 25.50$  deg  $> 15$  deg, in accordance with the rules [2, 17] (Table 2). The transversal stability of the *RPV* vessel increases the restoring roll moment for the first loading case compared to the second loading case, and, related to reduced onboard masses (Table 1, Figure 3), leads to higher roll frequencies for the minimum draught case (Table 3).

Figure 5 presents the irregular waves' *ISSC* power density spectrum [1, 7] formulation, for the Danube River,  $H_{smax} = 2.0$  m, and the Black Sea Coast,  $H_{smax} = 2.5$  m, waterways. The significant wave energy is recorded in the frequency range of  $\omega = 0.6 \div 1.8$  rad/s, peak values are in the range of  $\omega = 0.7 \div 1.2$  rad/s, with the spectral domain being extended up to 2.8 rad/s, for both navigation areas.

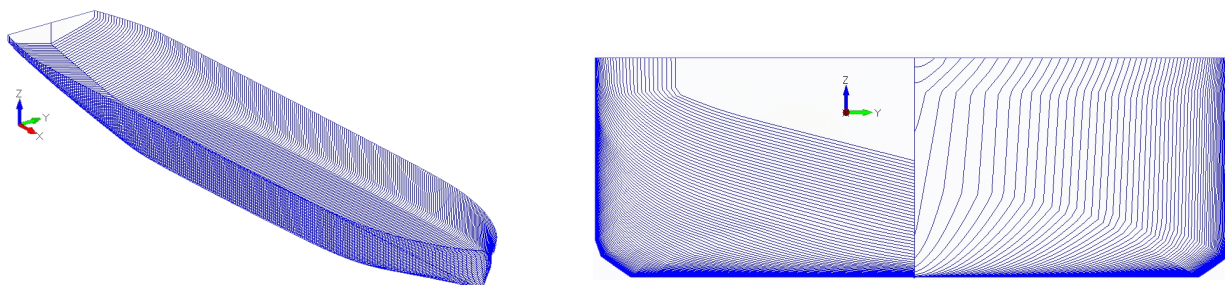


Fig. 2. The *RPV* research-passenger design concept vessel 3D offset lines stations [16, 3].

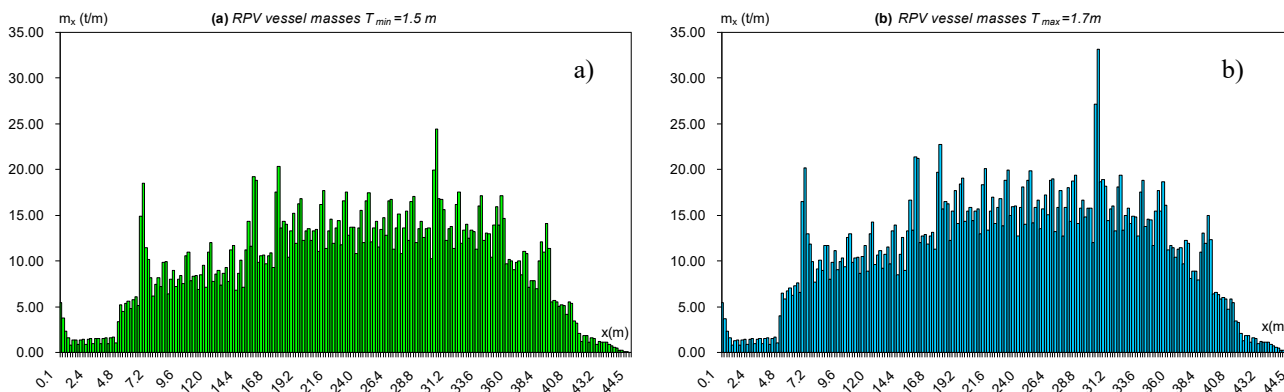


Fig. 3. The *RPV* research-passenger design concept vessel mass diagrams  $m_x(t/m)$ , (a)  $T_{min} = 1.5$  m and (b)  $T_{max} = 1.7$  m [3].

Table 1. The numerical data of the *RPV* vessel [3].

$L_{max}$ (m)	$B_{max}$ (m)	$\delta L$ (m)	Stations	$z_G$ (m)	$v$ (km/h)
44.500	9.000	0.200	229	2.80÷3.40	0÷20
$H_{mid}$ (m)		$H_{aft}$ (m)		$H_{fore}$ (m)	
initial	+parapet	initial	+parapet	initial	+parapet
3.000	3.200	3.100	3.500	3.450	3.700
Case	$T$ (m)	trim(rad)	$\Delta$ (t)	$x_G=x_B$ (m)	$x_F$ (m)
$T_{min}$	1.500	0.000	434.725	23.359	21.916
$T_{max}$	1.700	0.000	501.750	23.177	21.485
$H_s$ (m)	$\delta H_s$ (m)	$\mu$ (deg)	$\delta\mu$ (deg)	spectrum	$\rho_w$ (t/m <sup>3</sup> )
0÷2.50	0.010	0÷180	5	ISSC	1.025

Table 2. Transversal stability data of the *RPV* vessel.

Case	$z_G$ (m)	$J_{xx}$ (tm <sup>2</sup> )	$\phi_{max}$ (deg)	$GZ_{max}$ (m)	$GM_0$ (m)
$T_{min}$	2.80	5827	25.50	0.945	2.464
	2.95	6006	25.00	0.881	2.314
	= 3.10	6205	24.50	0.819	2.164
1.5m	3.25	6424	24.00	0.757	2.014
	3.40	6662	23.50	0.696	1.864
	2.80	6294	24.75	0.774	2.090
$T_{max}$	2.95	6471	24.00	0.712	1.940
	= 3.10	6670	23.50	0.651	1.790
	1.7m	3.25	6892	23.00	0.592
	3.40	7137	22.50	0.535	1.490

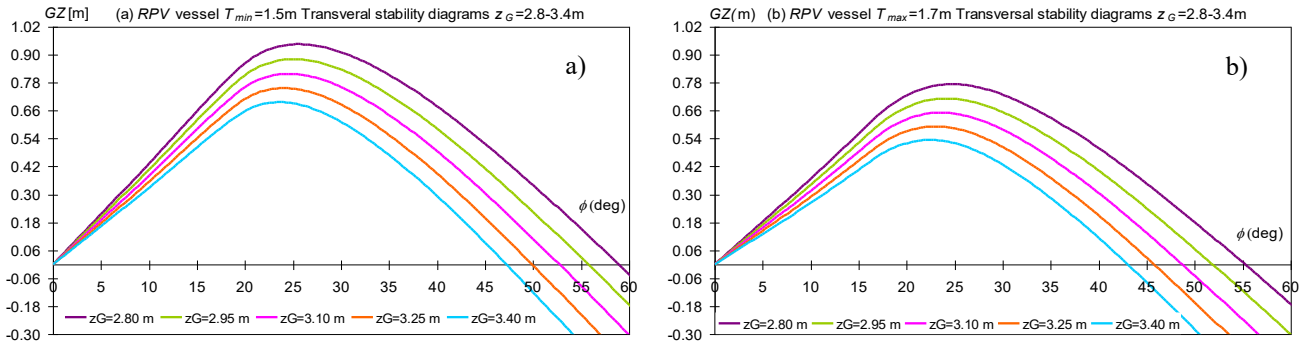


Fig. 4. The *RPV* research-passenger design concept vessel stability diagrams  $GZ$ (m), (a)  $T_{min}=1.5$  m and (b)  $T_{max}=1.7$  m.

Table 3. The oscillations natural circular frequencies, with hydrodynamic and bilge keels damping, of the *RPV* vessel.

Heave motion			Pitch motion		
$\omega_{heave}$	$T$		$\omega_{pitch}$	$T$	
rad/s	$T_{min}$	1.611	rad/s	$T_{min}$	1.754
	$T_{max}$	1.559		$T_{max}$	1.714
Roll motion					
$\omega_{roll}$	Case	$z_G$ (m)	0% $k_{BK}$	5% $k_{BK}$	10% $k_{BK}$
rad/s	$T_{min}$	2.80	0.895	0.880	0.862
		2.95	0.859	0.844	0.827
		= 3.10	0.822	0.808	0.791
	1.5m	3.25	0.784	0.770	0.753
		3.40	0.745	0.731	0.715
		2.80	0.811	0.796	0.777
$T_{max}$	2.95	0.774	0.758	0.740	
	= 3.10	0.735	0.720	0.702	
	1.7m	3.25	0.695	0.680	0.662
		3.40	0.653	0.638	0.620

Table 4.  $RMS_{adm}$  admissible seakeeping criteria, *RPV* vessel.

Case	Aft	Mid	Fore	Pitch	Roll	Heave	Pitch	Roll
	m	m	m	rad	rad	m/s <sup>2</sup>	rad/s <sup>2</sup>	rad/s <sup>2</sup>
vertical combined rotations accelerations								
$T_{min}$	2.000	1.700	2.200	0.039	0.052	0.981	0.065	0.218
$T_{max}$	1.800	1.500	2.000					

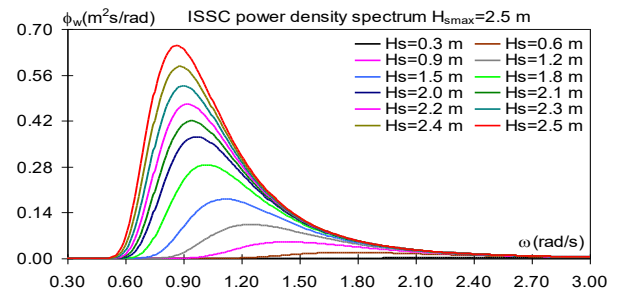


Fig. 5. ISSC power density spectrum, river-coastal waves [7].

A preliminary evaluation of the dynamic behavior of the *RPV* vessel in irregular waves is based on the correlation between the vessel's natural circular frequencies (Table 3) and the wave spectrum energy distribution in the spectral domain (Figure 5). The heave and pitch motions have similar natural circular frequencies for both loading cases, in the range  $\omega = 1.559 \div 1.754$  rad/s, which corresponds to a wave medium energy spectral domain (1.5÷1.8 rad/s). The roll motion is highly sensitive to the vertical position of the *RPV* vessel gravity centre ( $z_G$ ), and to the influence of the bilge keels' roll damping passive system ( $k_{BK}$ ). The roll frequencies are higher for the first loading case, due to the mass and stability characteristics, compared to the second loading case. The increase of the vertical position  $z_G$  of the gravity center, combined with the bilge keels damping effect ( $k_{BK}$ ), is reducing the roll natural circular frequencies, so that for the minimum draught case the roll natural circular frequencies are in the range of  $\omega = 0.715 \div 0.895$  rad/s, and for the maximum draught case in the range of  $\omega = 0.620 \div 0.811$  rad/s, that corresponds to a wave high energy spectral domain (0.7÷1.0 rad/s).

Table 4 presents the setup for the seakeeping criteria [15], vertical combined and individual motions, with the acceleration limits, considering the design concept with parapets at the main deck (Table 1).

The next sections (4-6) present the relevant results of the seakeeping assessment of the *RPV* vessel in regular and irregular waves, for the vessel data from this section and the integrated approach from section 2.

## 4. RESULTS AND DISCUSSIONS

### 4.1. THE RESEARCH-PASSENGER VESSEL DESIGN CONCEPT NAVIGATION SAFETY LIMITS FOR LOADING CASE 1 ( $T_{min}=1.5$ m)

The dynamic regular waves' analyses (module 3, section 2) for the minimum draught loading case, with reduced onboard provisions, deliver the main heave-pitch and roll  $RAO$  oscillation responses. The other motion components, sway-yaw, and surge, are not significant due to the slenderness of the vessel hull (Figure 2) [9, 10]. Figures 6, 7 present the selected  $RAO_{33}$  heave response functions for the  $RPV$  ( $T_{min}$ ) minimum draught vessel. The natural heave frequency is 1.611 rad/s (3.900 s) (Table 3), linked to the *ISSC* wave spectrum energy distribution (Figure 5,  $H_{smax}=2.5$ m), resulting in the heave motion relevant for the frequency range 0.6÷2.4 rad/s. The heave motion is maximum at beam sea wave (90 deg) for any vessel speed. For zero speed, the minimum heave motion is at follow and head (0, 180 deg) waves. As the vessel speed increases, mainly the heave motion at oblique-fore and head (135÷180 deg) waves is influenced, being lower than at the beam sea. The vessel speed influence is reduced on heave motion at follow and oblique-stern waves (0÷45 deg), being the minimum.

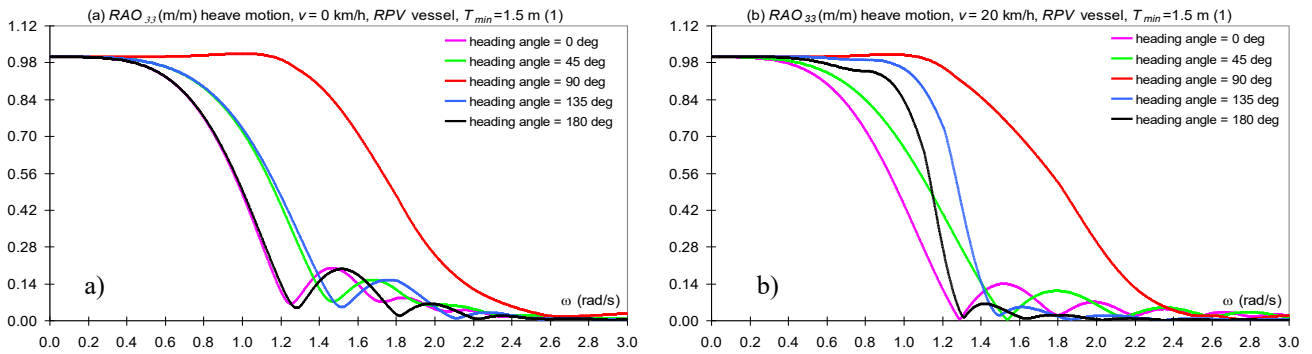


Fig. 6. The  $RPV$  research-passenger design concept heave  $RAO_{33}$ (m/m),  $T_{min}=1.5$  m (1), (a)  $v=0$  km/h and (b)  $v=20$  km/h.

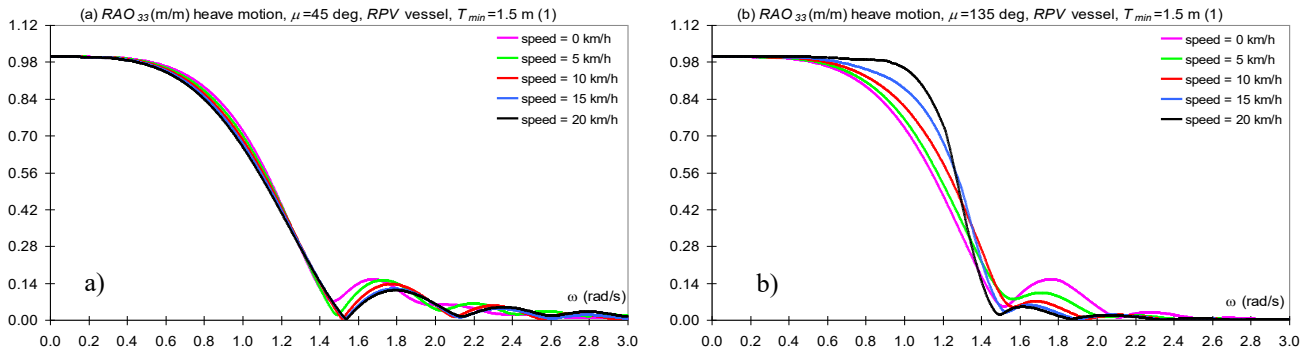


Fig. 7. The  $RPV$  research-passenger design concept heave  $RAO_{33}$ (m/m),  $T_{min}=1.5$  m (1), (a)  $\mu=45$  deg and (b)  $\mu=135$  deg.

Figures 8, 9 present the selected  $RAO_{55}$  pitch response functions for the  $RPV$  ( $T_{min}$ ) minimum draught vessel. The natural pitch frequency is 1.754 rad/s (3.582 s) (Table 3), linked to the *ISSC* wave spectrum energy distribution (Figure 5,  $H_{smax}=2.5$ m), resulting in the pitch motion relevant for the frequency range 0.3÷2.6 rad/s.

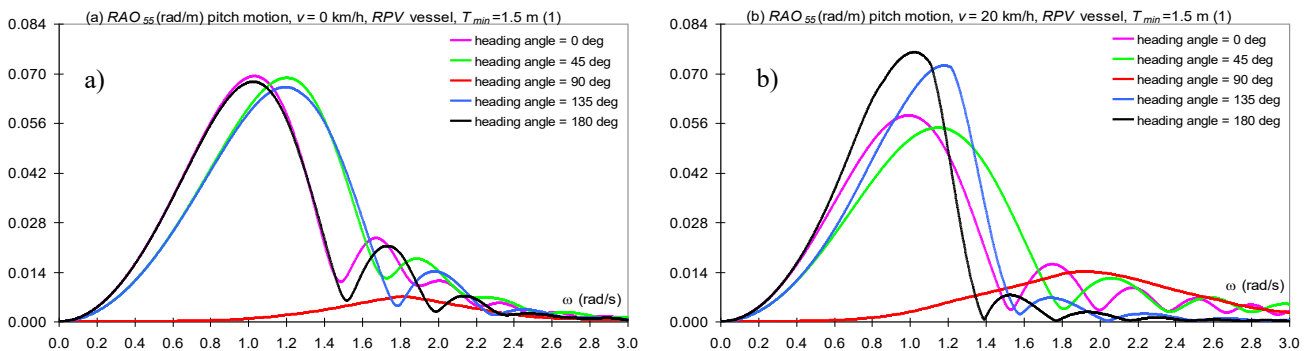


Fig. 8. The  $RPV$  research-passenger design concept pitch  $RAO_{55}$ (rad/m),  $T_{min}=1.5$  m (1), (a)  $v=0$  km/h and (b)  $v=20$  km/h.

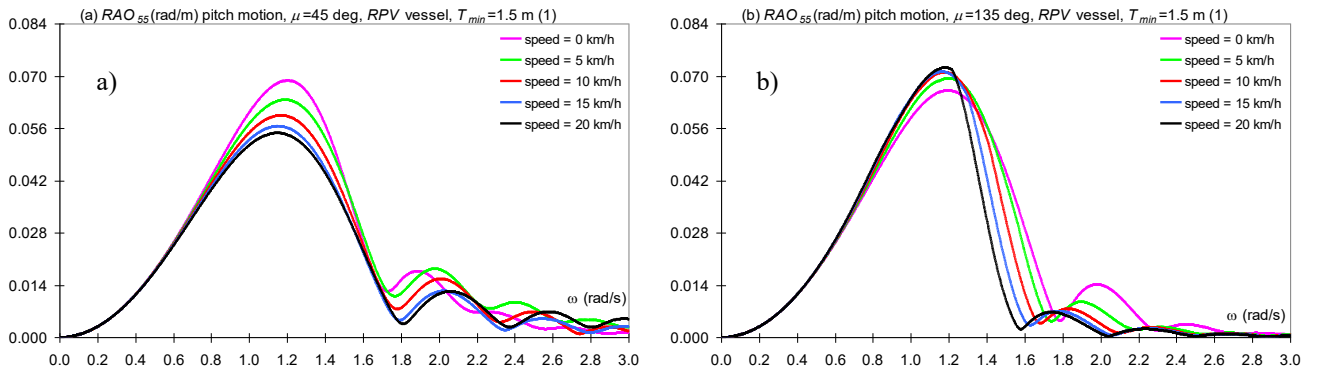


Fig. 9. The *RPV* research-passenger design concept pitch  $RAO_{55}$ (rad/m),  $T_{min}=1.5$  m (1), (a)  $\mu=45$  deg and (b)  $\mu=135$  deg.

For zero vessel speed, the maximum pitch motion is at follow and oblique-stern ( $0\div 45$  deg) waves. As the vessel speed increases, the pitch motion becomes maximum at oblique-fore and head ( $135\div 180$  deg) waves. The pitch motion is minimum at beam sea wave (90 deg). For the whole range of the vessel speed, the influence is significant on pitch motion for any wave heading angle ( $0\div 180$  deg).

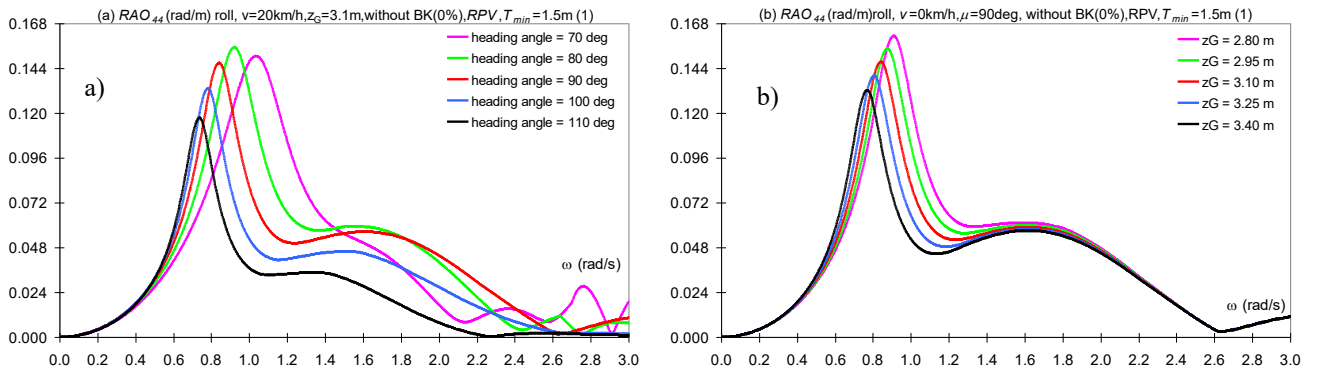


Fig. 10. The *RPV* vessel roll  $RAO_{44}$ (rad/m),  $T_{min}=1.5$  m (1), (a)  $z_G=3.10$  m,  $v=20$  km/h (0%) and (b)  $\mu=90$  deg,  $v=0$  km/h (0%).

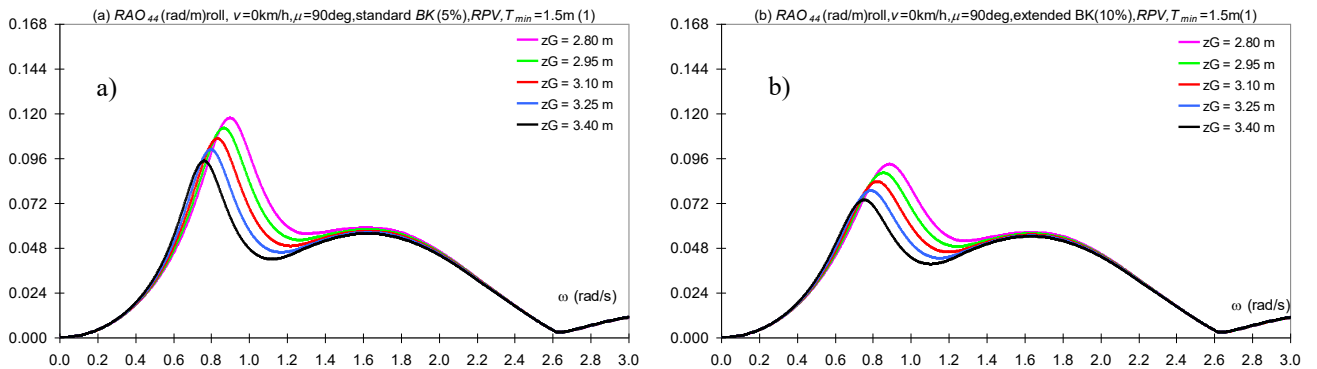


Fig. 11. The *RPV* vessel roll  $RAO_{44}$ (rad/m),  $T_{min}=1.5$  m (1), (a)  $\mu=90$  deg,  $v=0$  km/h (5%) and (b)  $\mu=90$  deg,  $v=0$  km/h (10%).

Figures 10 and 11 present the selected  $RAO_{44}$  roll response functions for the *RPV* ( $T_{min}$ ) minimum draught vessel. The natural roll frequencies are  $0.715\div 0.895$  rad/s ( $7.020\div 8.788$  s) (Table 3), having a significant influence from the vessel gravity centre vertical position for the preliminary design concept with several onboard mass vertical distribution,  $z_G=2.80\div 3.40$  m, and the selected design for the bilge keels, without  $k_{BK}=0\%$ , standard  $k_{BK}=5\%$ , and extended  $k_{BK}=10\%$ .

Similar to the heave and pitch, the  $RAO_{44}$  roll response functions have a wide frequency band, being relevant for the range of  $0.2\div 2.6$  rad/s. The vessel speed influence is mainly at oblique and beam sea waves ( $60\div 120$  deg), where the maximum roll response is also recorded. At follow (0 deg) and head (180 deg), the roll response becomes zero. The  $z_G$  gravity centre increases, changes the vessel roll characteristics, hydrodynamic and hydrostatic terms, and has a significant influence on reducing the roll response. The bilge keels increase the hydrodynamic roll damping with a supplementary damping component. Results in a noticeable reduction of the roll response for standard bilge keels, and especially for extended bilge keels.

The dynamic irregular waves' analyses (modules 4 and 5, section 2) for the minimum draught loading case deliver the short-term *RMS* statistical vessel response, for the *ISSC* wave spectrum power density distribution (Figure 5), averaged for Danube River ( $H_{smax}=2m$ ) and Black Sea Coast ( $H_{smax}=2.5m$ ) navigation conditions. The *RPV* ( $T_{min}$ ) minimum draught vessel safety navigation limits are obtained by seakeeping criteria (Table 4).

Table 5. The *RPV* research-passenger design concept,  $T_{min}=1.5$  m (1), maximum most probable amplitudes, seakeeping response.

Criteria	Adm.	$z_G(m)$	$k_{BK}(\%)$	$v=0$ km/h		$v=5$ km/h		$v=10$ km/h		$v=15$ km/h		$v=20$ km/h		
<b>Comb. Vertical Aft <i>RMS</i><sub>aft</sub> (m)</b>	2.000	2.80	0%	1.967	-1.65%	1.966	-1.70%	1.963	-1.87%	1.960	-2.02%	1.957	-2.16%	
			5%	1.921	-3.95%	1.926	-3.70%	1.930	-3.48%	1.934	-3.32%	1.937	-3.15%	
			10%	1.891	-5.44%	1.900	-5.01%	1.910	-4.50%	1.918	-4.11%	1.925	-3.75%	
		3.10	0%	1.942	-2.89%	1.939	-3.04%	1.936	-3.20%	1.935	-3.27%	1.934	-3.29%	
			5%	1.901	-4.95%	1.905	-4.77%	1.911	-4.47%	1.916	-4.22%	1.921	-3.95%	
			10%	1.874	-6.28%	1.884	-5.81%	1.894	-5.29%	1.904	-4.78%	1.913	-4.36%	
	3.40	0%	1.908	-4.60%	1.905	-4.76%	1.906	-4.68%	1.909	-4.55%	1.913	-4.33%		
		5%	1.875	-6.27%	1.881	-5.97%	1.889	-5.57%	1.898	-5.10%	1.907	-4.66%		
		10%	1.853	-7.34%	1.865	-6.73%	1.878	-6.09%	1.891	-5.46%	1.903	-4.87%		
	<b>Comb. Vertical Mid <i>RMS</i><sub>mid</sub> (m)</b>	1.700	2.80	0%	1.511	-11.09%	1.510	-11.20%	1.508	-11.31%	1.505	-11.45%	1.507	-11.35%
				5%	1.455	-14.44%	1.453	-14.53%	1.451	-14.63%	1.449	-14.77%	1.448	-14.84%
				10%	1.417	-16.64%	1.416	-16.71%	1.414	-16.82%	1.412	-16.95%	1.409	-17.10%
3.10			0%	1.477	-13.14%	1.475	-13.22%	1.473	-13.33%	1.474	-13.31%	1.476	-13.16%	
			5%	1.426	-16.11%	1.425	-16.19%	1.423	-16.29%	1.421	-16.42%	1.422	-16.38%	
			10%	1.394	-18.02%	1.392	-18.10%	1.391	-18.10%	1.388	-18.20%	1.388	-18.46%	
3.40		0%	1.432	-15.76%	1.431	-15.84%	1.429	-15.95%	1.431	-15.84%	1.435	-15.60%		
		5%	1.392	-18.10%	1.391	-18.18%	1.389	-18.28%	1.387	-18.41%	1.388	-18.33%		
		10%	1.367	-19.58%	1.366	-19.66%	1.364	-19.76%	1.362	-19.89%	1.360	-20.02%		
<b>Comb. Vertical Fore <i>RMS</i><sub>fore</sub> (m)</b>		2.200	2.80	0%	1.986	-9.74%	1.986	-9.73%	1.983	-9.88%	1.981	-9.97%	1.978	-10.10%
				5%	1.940	-11.80%	1.946	-11.54%	1.952	-11.29%	1.955	-11.15%	1.959	-10.97%
				10%	1.911	-13.15%	1.921	-12.69%	1.931	-12.22%	1.940	-11.82%	1.947	-11.51%
	3.10		0%	1.962	-10.83%	1.959	-10.95%	1.957	-11.03%	1.956	-11.11%	1.956	-11.09%	
			5%	1.921	-12.70%	1.925	-12.49%	1.932	-12.19%	1.938	-11.93%	1.943	-11.69%	
			10%	1.894	-13.91%	1.905	-13.41%	1.915	-12.93%	1.926	-12.44%	1.935	-12.04%	
	3.40	0%	1.927	-12.39%	1.925	-12.48%	1.928	-12.39%	1.931	-12.23%	1.935	-12.03%		
		5%	1.894	-13.90%	1.902	-13.56%	1.910	-13.17%	1.920	-12.72%	1.929	-12.31%		
		10%	1.873	-14.87%	1.886	-14.25%	1.900	-13.62%	1.913	-13.04%	1.925	-12.50%		
	<b><i>RMS</i><sub>pitch</sub> (rad)</b>	0.039	-	-	0.034	-13.34%	0.035	-10.26%	0.036	-7.50%	0.036	-7.35%	0.036	-8.97%
	<b><i>RMS</i><sub>roll</sub> (rad)</b>	0.052	2.80	0%	<b>0.066</b>	<b>26.16%</b>	<b>0.065</b>	<b>24.55%</b>	<b>0.066</b>	<b>25.78%</b>	<b>0.068</b>	<b>29.04%</b>	<b>0.070</b>	<b>33.00%</b>
				5%	<b>0.053</b>	<b>2.02%</b>	<b>0.052</b>	<b>0.55%</b>	<b>0.053</b>	<b>1.39%</b>	<b>0.054</b>	<b>4.06%</b>	<b>0.056</b>	<b>7.46%</b>
10%				0.045	-13.87%	0.044	-15.23%	0.045	-14.70%	0.046	-12.51%	0.047	-9.55%	
3.10			0%	<b>0.058</b>	<b>11.31%</b>	<b>0.057</b>	<b>9.95%</b>	<b>0.059</b>	<b>12.75%</b>	<b>0.062</b>	<b>18.07%</b>	<b>0.065</b>	<b>24.66%</b>	
			5%	0.047	-10.14%	0.046	-11.43%	0.047	-9.88%	0.049	-5.86%	0.052	-0.43%	
			10%	0.040	-23.98%	0.039	-25.20%	0.040	-24.32%	0.041	-21.38%	0.044	-16.88%	
3.40		0%	0.048	-7.82%	0.047	-8.57%	0.050	-4.50%	<b>0.054</b>	<b>3.66%</b>	<b>0.059</b>	<b>13.45%</b>		
		5%	0.039	-24.72%	0.039	-25.81%	0.040	-23.46%	0.043	-18.18%	0.047	-10.72%		
		10%	0.034	-35.43%	0.033	-36.49%	0.034	-35.39%	0.036	-31.72%	0.039	-26.22%		
<b><i>RMS</i><sub>heave acc</sub> (m/s<sup>2</sup>)</b>		0.981	-	-	0.699	-28.71%	0.713	-27.30%	0.751	-23.44%	0.828	-15.62%	0.951	-3.04%
<b><i>RMS</i><sub>pitch acc</sub> (rad/s<sup>2</sup>)</b>		0.065	-	-	0.042	-35.65%	0.051	-22.33%	0.062	-4.50%	<b>0.074</b>	<b>14.02%</b>	<b>0.085</b>	<b>30.95%</b>
<b><i>RMS</i><sub>roll acc</sub> (rad/s<sup>2</sup>)</b>		0.218	2.80	0%	0.071	-67.27%	0.071	-67.64%	0.070	-68.01%	0.069	-68.37%	0.068	-68.73%
	5%			0.062	-71.71%	0.061	-71.96%	0.061	-72.22%	0.060	-72.47%	0.059	-72.73%	
	10%			0.055	-74.71%	0.055	-74.89%	0.054	-75.07%	0.054	-75.25%	0.054	-75.43%	
	3.10		0%	0.061	-71.90%	0.060	-72.23%	0.060	-72.55%	0.059	-72.86%	0.058	-73.17%	
			5%	0.054	-75.08%	0.054	-75.29%	0.053	-75.51%	0.053	-75.72%	0.052	-75.93%	
			10%	0.050	-77.24%	0.049	-77.38%	0.049	-77.53%	0.049	-77.67%	0.048	-77.82%	
	3.40	0%	0.052	-76.04%	0.052	-76.26%	0.051	-76.49%	0.051	-76.70%	0.050	-76.91%		
		5%	0.048	-77.97%	0.048	-78.11%	0.047	-78.25%	0.047	-78.39%	0.047	-78.52%		
		10%	0.045	-79.35%	0.045	-79.43%	0.045	-79.52%	0.044	-79.60%	0.044	-79.69%		

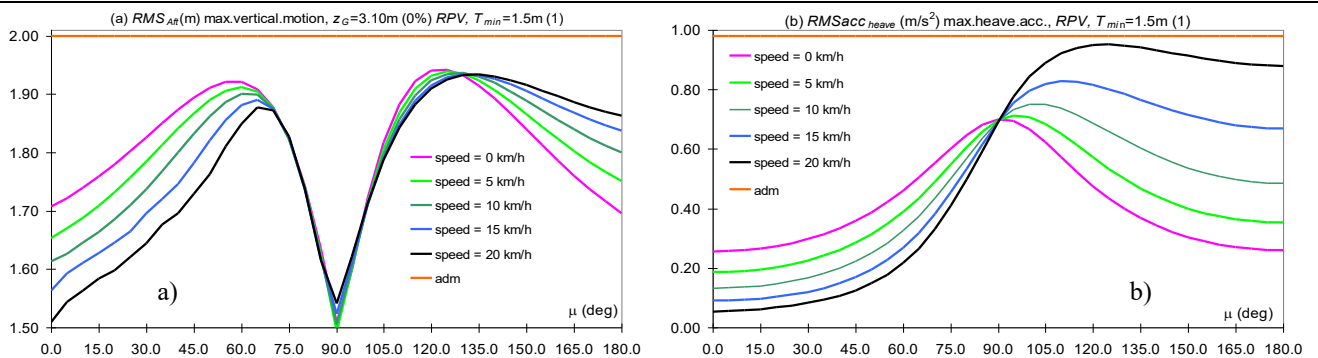


Fig. 12. The *RPV* vessel,  $T_{min}=1.5$  m (1), maximum *RMS*, (a) aft vertical combined motion and (b) heave acceleration.

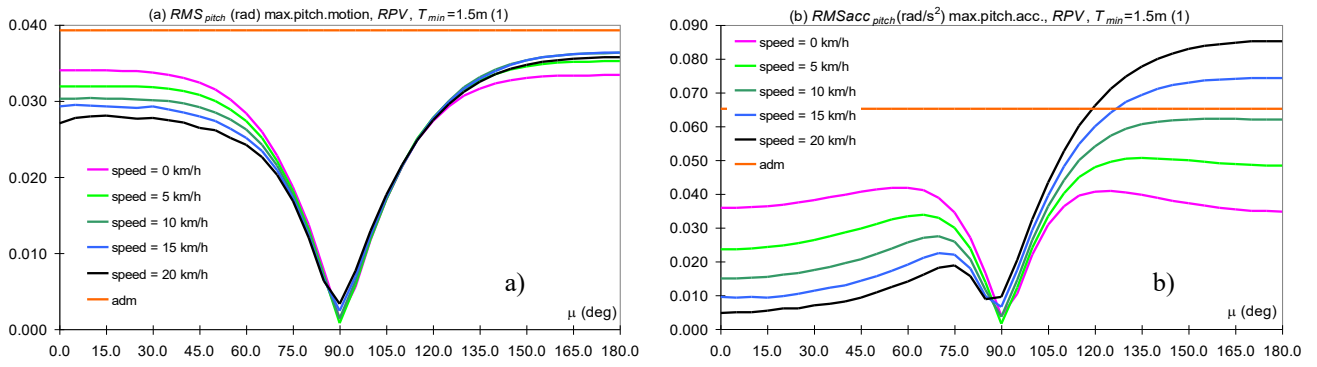


Fig. 13. The *RPV* vessel,  $T_{min}=1.5$  m (1), maximum *RMS*, (a) pitch motion and (b) pitch acceleration.

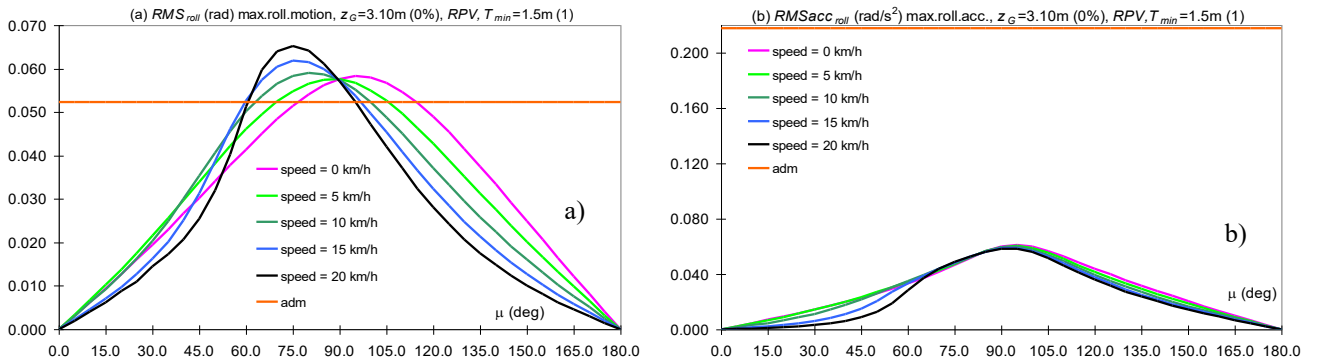


Fig. 14. The *RPV* vessel,  $T_{min}=1.5$  m (1),  $z_G=3.10$  m,  $BK(0\%)$ , maximum *RMS*, (a) roll motion and (b) roll acceleration.

Figures 12-14, and Table 5, present the maximum most probable amplitudes *RMS* for the dynamic response of the *RPV* ( $T_{min}$ ) minimum draught vessel in irregular *ISSC* averaged waves (Figure 5), including the evaluation of the seakeeping criteria (Table 4).

The combined vertical motion (heave-pitch-roll) criteria at aft-mid-fore, on both sides of the vessel (Figure 12.a, Table 5) lead to no restrictions for any of the navigation parameters, due to the freeboard vessel reserve in the case of  $T_{min}=1.5$  m, due to the parapet heights (Table 1), keeping the main deck dry. The safety limits on combined vertical motions, for  $H_s=2.5$  m reference, are at aft 1.65%÷7.34%, and fore 9.73%÷14.87%, increasing as the vessel speed decreases, and at mid 11.09%÷20.02%, increasing as the vessel speed increases, noticing an overall improvement as the  $z_G$  gravity centre is increased and the bilge keels  $k_{BK}$  are extended.

The vertical heave acceleration (Figure 12.b, Table 5) complies with the seakeeping admissible value, with safety limits 3.04%÷28.71%, for  $H_s=2.5$  m reference, improving as the vessel speed decreases.

The pitch motion criterion (Figure 13.a, Table 5) leads to no navigation restrictions, with safety limits 8.97%÷13.34%, for  $H_s=2.5$  m reference, improving as the vessel speed decreases.

The pitch acceleration criterion (Figure 13.b, Table 5) is satisfied only for vessel speed up to 10 km/h, with safety limits 4.50%÷35.65%, for  $H_s=2.5$  m reference, as the vessel speed decreases. Above speed 15 km/h, oblique-fore and head waves (110÷180 deg), the pitch acceleration criterion leads to navigation restrictions as the speed increases, the admissible value is exceeded up to 30.95%.

The roll criterion (Figure 14.a, Table 5) in the case without bilge keels ( $k_{BK}=0\%$ ), leads to navigation restrictions at oblique-beam sea wave (60÷120 deg), exceeding up to 33.00% the admissible roll angle, except for  $z_G=3.40$  m and vessel speed below 10 km/h, being necessary to consider by design the bilge keels as antiroll system for safety onboard operations. In the case of standard bilge keels ( $k_{BK}=5\%$ ), the roll angle criterion is not satisfied for  $z_G=2.80$  m; no restrictions occur for  $z_G \geq 2.95$  m, with safety limits 0.43%÷24.72%, improving as the vessel speed decreases. In the case of extended bilge keels ( $k_{BK}=10\%$ ) the roll criterion complies with the seakeeping admissible value, with safety limits 9.55%÷36.49%, for  $H_s=2.5$  m, improving as the vessel speed decreases.

The roll acceleration criterion (Figure 14.b, Table 5) has no navigation restriction, with very reduced acceleration amplitudes, due to the natural roll periods in the range of 7÷9 s representing a slow rotation motion around the vessel's longitudinal axis, with safety limits 67.27%÷79.69%.

Figures 15, 16, and Table 6 present the safety limits in terms of waves' significant height  $H_{slimit}$  for the dynamic response of the *RPV* ( $T_{min}$ ) minimum draught vessel in irregular *ISSC* averaged waves (Figure 5), applying the combined seakeeping criteria on vessel motions and accelerations relevant components (Table 4).

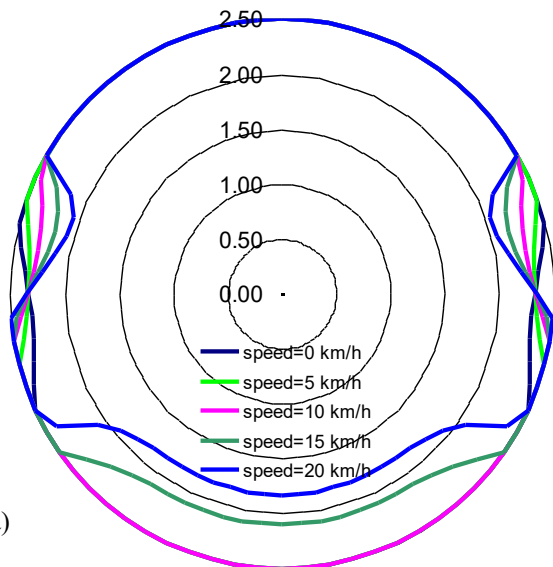
In the case of inland Danube navigation (Table 6, Figures 15, 16) no restrictions occur by seakeeping criteria, *IN*(2.0), for the *RPV* ( $T_{min}$ ) vessel with speed below 15 km/h, exception for  $z_G=2.80$  m, without bilge keels ( $k_{BK}=0\%$ ), due to the roll criterion at beam sea, with safety limit *IN*(1.98)  $\approx$  *IN*(2.0). For *RPV* ( $T_{min}$ ) vessel top

speed 20 km/h, without and with bilge keels, the roll criterion at beam sea (70÷85 deg,  $k_{BK}=0\%$ ,  $z_G=2.80, 2.95\text{m}$ ) and mainly the pitch acceleration criterion at oblique-head waves (115÷180 deg) reduces the inland safety limit to IN(1.8). In the case of coastal Black Sea navigation (Table 6, Figures 15, 16), no restrictions occur by seakeeping criteria, C(2.5), for the *RPV* ( $T_{min}$ ) vessel with speed bellow 10 km/h, with bilge keels ( $k_{BK}=5\%, 10\%$ ), exception for  $z_G=2.80\text{m}$ , with standard bilge keels ( $k_{BK}=5\%$ ), due to roll criterion at beam sea, with safety limit reduced to C(2.4).

Table 6. The *RPV* research-passenger design concept,  $T_{min}=1.5\text{ m}$  (1), safety seakeeping limits, river-coastal area.

$z_G(\text{m})$	$k_{BK}(\%)$		$v=0\text{ km/h}$		$v=5\text{ km/h}$		$v=10\text{ km/h}$		$v=15\text{ km/h}$		$v=20\text{ km/h}$
Safety limit		$H_s(\text{m})$	Criteria	$H_s(\text{m})$	Criteria	$H_s(\text{m})$	Criteria	$H_s(\text{m})$	Criteria	$H_s(\text{m})$	Criteria
2.80	0%	IN	no restr.	2.059	no restr.	2.053	no restr.	1.975	roll	1.817	pitch.acc
		C	roll		roll		roll		pitch.acc		roll
	5%	IN	no restr.	2.455	no restr.	2.468	no restr.	2.091	no restr.	1.817	pitch.acc
		C	roll		roll		roll		pitch.acc		roll
	10%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		
2.95	0%	IN	no restr.	2.174	no restr.	2.155	no restr.	2.060	no restr.	1.817	pitch.acc
		C	roll		roll		roll		pitch.acc		roll
	5%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		pitch.acc
	10%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		pitch.acc
3.10	0%	IN	no restr.	2.307	no restr.	2.274	no restr.	2.091	no restr.	1.817	pitch.acc
		C	roll		roll		roll		pitch.acc		roll
	5%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		pitch.acc
	10%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		pitch.acc
3.25	0%	IN	no restr.	2.460	no restr.	2.416	no restr.	2.091	no restr.	1.817	pitch.acc
		C	roll		roll		roll		pitch.acc		roll
	5%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		pitch.acc
	10%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		pitch.acc
3.40	0%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		roll
	5%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		pitch.acc
	10%	IN	no restr.	2.500	no restr.	2.500	no restr.	2.091	no restr.	1.817	pitch.acc
		C	restrictions		restrictions		restrictions		pitch.acc		pitch.acc
max. wave height	river	IN		2.000		2.000		≈2.000		1.817	
	coastal	C		2.059 ÷ 2.500		2.085 ÷ 2.500		2.053 ÷ 2.500		≈2.000 ÷ 2.091	restricted

(a)  $H_{slimit}(\text{m}), z_G=3.10\text{m}(0\%), RPV, T_{min}=1.5\text{ m}$  (1)



(b)  $H_{slimit}(\text{m}), z_G=3.10\text{m}(5\%), RPV, T_{min}=1.5\text{ m}$  (1)

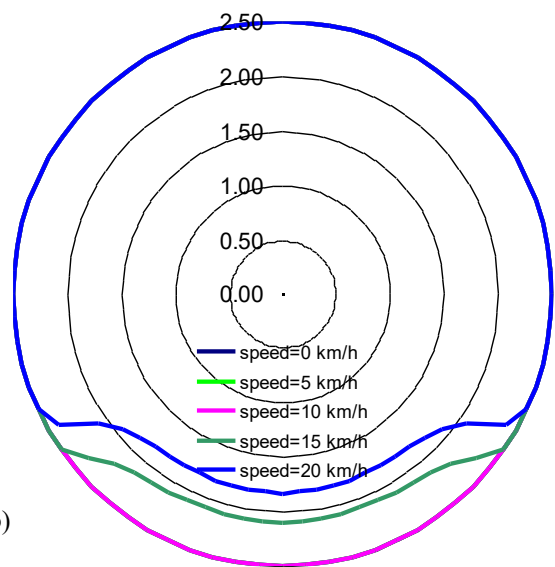


Fig.15. The *RPV* research-passenger design concept,  $T_{min}=1.5\text{ m}$  (1), safety limits (a)  $z_G=3.10\text{ m}$  (0%) and (b)  $z_G=3.10\text{ m}$  (5%).

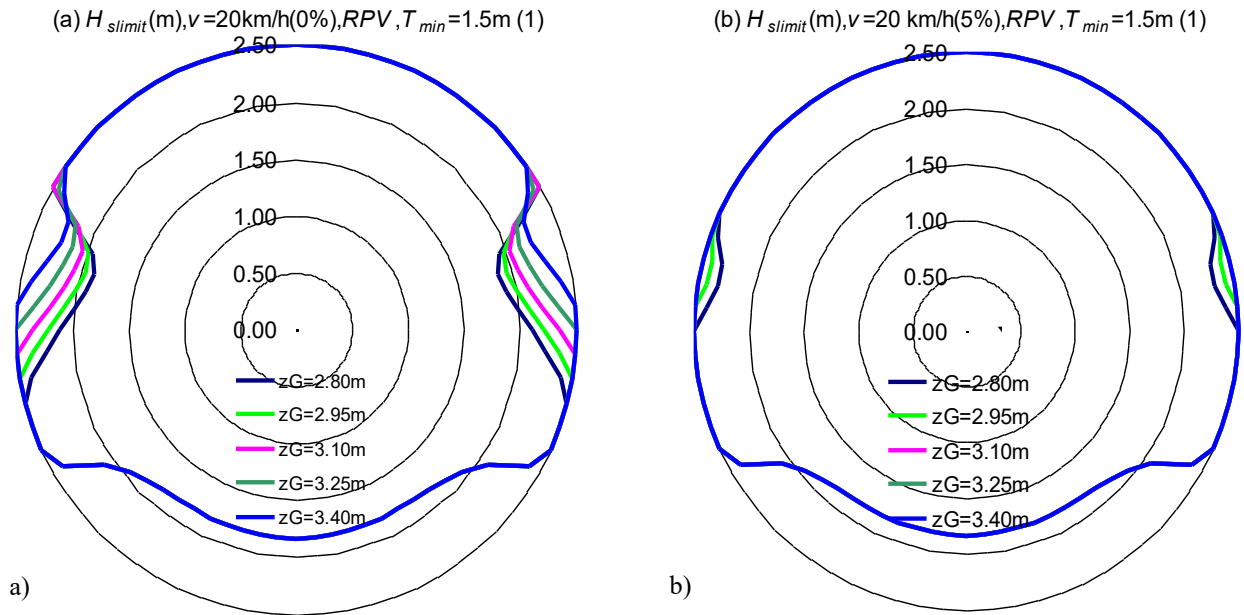


Fig.16. The *RPV* research-passenger design concept,  $T_{min}=1.5$  m (1), safety limits (a)  $v=20$ km/h (0%) and (b)  $v=20$ km/h (5%).

In the case of *RPV* ( $T_{min}$ ) vessel with speed below 10 km/h, without bilge keels ( $k_{BK}=0\%$ ), restrictions occur due to roll criterion at beam sea (60÷105 deg) for  $z_G=2.80\div 3.25$  m, with the coastal safety limits C(2.1)–C(2.4), and no restrictions for  $z_G=3.40$  m, C(2.5). For *RPV* ( $T_{min}$ ) vessel with speed around 15 km/h, with or without bilge keels, due to roll criterion at beam sea, but mainly to the pitch acceleration criterion at oblique-head (125÷180 deg), the coastal safety limit is reduced to C(2.1), except  $z_G=2.80$ m with coastal navigation restricted. For *RPV* ( $T_{min}$ ) vessel top speed 20 km/h the coastal navigation is totally restricted due mainly to pitch acceleration criterion at oblique-head waves (115÷180deg), for any design condition. The extended bilge keels design ( $k_{BK}=10\%$ ) reduces the maximum influence of roll motion criterion for the *RPV* ( $T_{min}$ ) vessel, but for speed above 15km/h the pitch acceleration criterion becomes dominant and restrictive for coastal navigation.

Table 7. The *RPV* research-passenger design concept,  $T_{min}=1.5$  m (1), safety limits, combined seakeeping and strength criteria.

Strength criteria [3]		Navigation restrictions		$v=0$ km/h		$v=5$ km/h		$v=10$ km/h		$v=15$ km/h		$v=20$ km/h							
$H_{slimit}$ (m)		$H_{slimit}$ (m)		DYN Combined		DYN Combined		DYN Combined		DYN Combined		DYN Combined							
$RPV$ $T_1$	$RPV$ $T_2$	$z_G$ (m)	$k_{BK}$	Zone	$H_{slimit}$ (m)	T1	T2	$H_{slimit}$ (m)	T1	T2	$H_{slimit}$ (m)	T1	T2	$H_{slimit}$ (m)	T1	T2			
2.185	2.500	2.80	0%	IN	2.059	IN(2.0)	IN(2.0)	2.085	IN(2.0)	IN(2.0)	2.053	IN(2.0)	IN(2.0)	1.975	≈IN(2.0)	IN(1.8)	restricted		
				C		C(2.1)	C(2.1)		C(2.1)	C(2.1)		C(2.1)	C(2.1)		restricted				
				IN	2.455	IN(2.0)	IN(2.0)	2.488	IN(2.0)	IN(2.0)	2.468	IN(2.0)	IN(2.0)	2.091	IN(2.0)	IN(1.8)	restricted		
				C		C(2.2)	C(2.4)	C(2.4)		C(2.2)	C(2.4)		C(2.1)						
				IN	2.500	IN(2.0)	IN(2.0)	IN(2.0)	2.500	IN(2.0)	IN(2.0)	2.500	IN(2.0)	IN(2.0)	2.091	IN(2.0)	IN(1.8)	restricted	
				C		C(2.2)	C(2.5)	C(2.5)		C(2.2)	C(2.5)		C(2.1)	C(2.1)		restricted			
				2.95	0%	IN	2.174	IN(2.0)	IN(2.0)	2.198	IN(2.0)	IN(2.0)	2.155	IN(2.0)	IN(2.0)	2.060	IN(2.0)	IN(1.8)	restricted
						C		C(2.2)	C(2.2)		C(2.2)	C(2.2)		C(2.1)					
						IN	2.500	IN(2.0)	IN(2.0)	IN(2.0)	2.500	IN(2.0)	IN(2.0)	2.091	IN(2.0)	IN(1.8)	restricted		
						C		C(2.2)	C(2.5)	C(2.5)		C(2.2)	C(2.5)		C(2.1)				
				3.10	0%	IN	2.307	IN(2.0)	IN(2.0)	2.329	IN(2.0)	IN(2.0)	2.274	IN(2.0)	IN(2.0)	2.091	IN(2.0)	IN(1.8)	restricted
						C		C(2.2)	C(2.3)	C(2.3)		C(2.2)	C(2.3)		C(2.1)				
						IN	2.500	IN(2.0)	IN(2.0)	IN(2.0)	2.500	IN(2.0)	IN(2.0)	2.091	IN(2.0)	IN(1.8)	restricted		
						C		C(2.2)	C(2.5)	C(2.5)		C(2.2)	C(2.5)		C(2.1)				
				3.25	0%	IN	2.460	IN(2.0)	IN(2.0)	2.479	IN(2.0)	IN(2.0)	2.416	IN(2.0)	IN(2.0)	2.091	IN(2.0)	IN(1.8)	restricted
						C		C(2.2)	C(2.4)	C(2.4)		C(2.2)	C(2.4)		C(2.1)				
						IN	2.500	IN(2.0)	IN(2.0)	IN(2.0)	2.500	IN(2.0)	IN(2.0)	2.091	IN(2.0)	IN(1.8)	restricted		
						C		C(2.2)	C(2.5)	C(2.5)		C(2.2)	C(2.5)		C(2.1)				
				3.40	0%-10%	IN	2.500	IN(2.0)	IN(2.0)	2.500	IN(2.0)	IN(2.0)	2.500	IN(2.0)	IN(2.0)	2.091	IN(2.0)	IN(1.8)	restricted
						C		C(2.2)	C(2.5)	C(2.5)		C(2.2)	C(2.5)		C(2.1)				

For the completed navigation operational assessment of the *RPV* ( $T_{min}$ ) vessel, Table 7 combines the seakeeping criteria with the strength criteria [3] for the two structural vessel design concept versions,  $T_1$  (standard) and  $T_2$  (enhanced). For the inland Danube navigation case, no restrictions occur by strength criteria on both structural versions; for speed below 15 km/h, the seakeeping criteria are satisfied, with safety limit IN(2.0), and for speed 20 km/h, the safety limit is reduced to IN(1.8). For the coastal Black Sea navigation case, the standard structural

version ( $T_1$ ) has restrictions by strength criteria, so that for speed below 10 km/h the combined safety limit is mainly C(2.2), being reduced to C(2.1) for 15 km/h, and coastal restricted for 20 km/h. For coastal navigation, the enhanced structural version ( $T_2$ ) has restrictions only by seakeeping criteria, so that for speed below 15 km/h the safety limit is C(2.1)÷C(2.5), with coastal restricted to the top speed of 20 km/h.

#### 4.2. THE RESEARCH-PASSENGER VESSEL DESIGN CONCEPT NAVIGATION SAFETY LIMITS FOR LOADING CASE 2 ( $T_{max}=1.7$ m)

For the maximum draught loading case of the vessel design concept, with full onboard masses, the dynamic regular waves' analyses compute the main oscillation amplitude response  $RAO$  operators. Figures 17, 18 present the selected  $RAO_{33}$  heave response functions for the  $RPV$  ( $T_{max}$ ) maximum draught vessel. The natural heave frequency is 1.559 rad/s (4.030 s) (Table 3), with heave motion relevant for the frequency domain 0.5÷2.5 rad/s. The heave motion characteristics are similar to the first loading case. The heave response is much influenced by the increased vessel speed at oblique-head (120÷180 deg) waves, and less at oblique-follow (0÷60 deg) waves, keeping the resulting amplitudes below the maximum at beam sea (90 deg) condition.

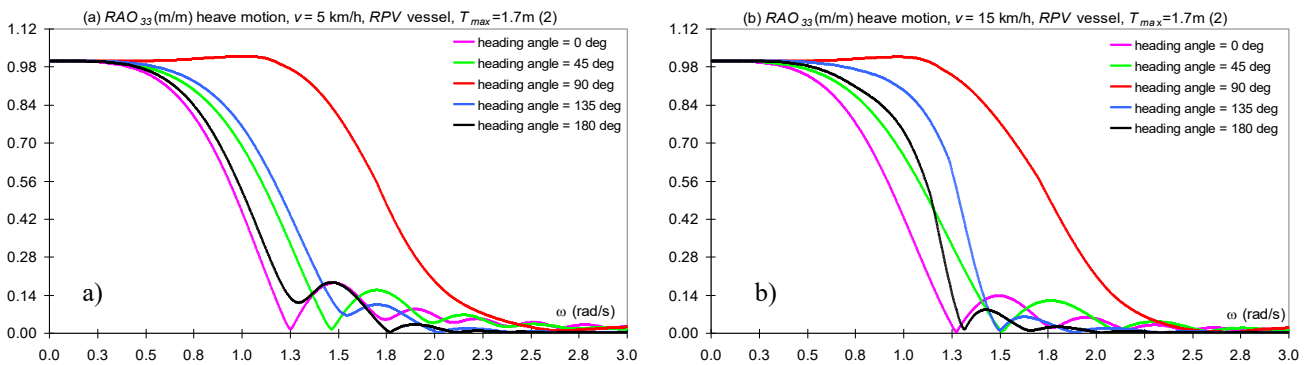


Fig. 17. The  $RPV$  research-passenger design concept heave  $RAO_{33}$ (m/m),  $T_{max}=1.7$  m (2), (a)  $v=5$  km/h and (b)  $v=15$  km/h.

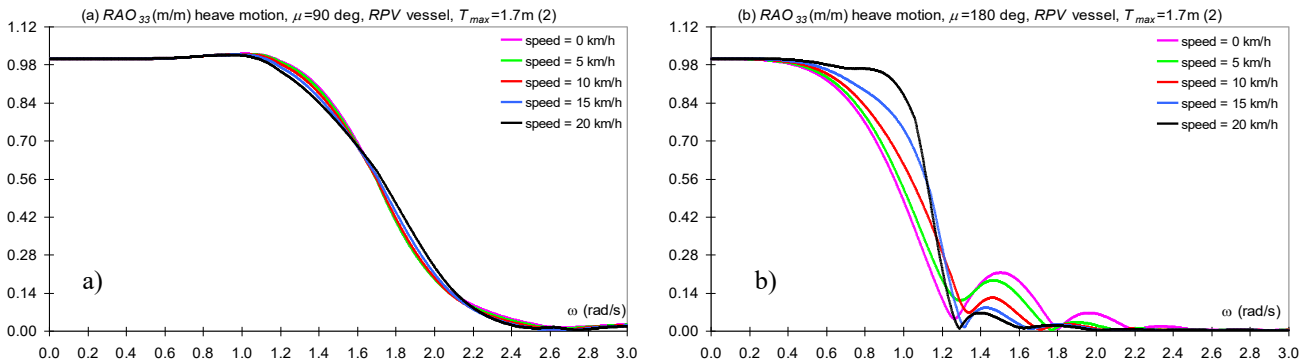


Fig. 18. The  $RPV$  research-passenger design concept heave  $RAO_{33}$ (m/m),  $T_{max}=1.7$  m (2), (a)  $\mu=90$  deg and (b)  $\mu=180$  deg.

Figures 19 and 20 present the selected  $RAO_{55}$  pitch response functions for the  $RPV$  ( $T_{max}$ ) maximum draught vessel. The natural pitch frequency is 1.714 rad/s (3.666 s) (Table 3), with pitch motion relevant for the frequency domain 0.2÷2.5 rad/s, and similar characteristics to the first loading case.

The pitch motion is minimum around beam sea (80÷100 deg) waves' conditions. The vessel speed has a noticeable influence at any wave angle, but is most relevant for oblique-head (120÷180 deg) waves, where the pitch motion has the maximum amplitudes, and is also linked to the small pitch period (fast motion), the pitch acceleration increase becomes most probable.

Figures 21, 22 present the selected  $RAO_{44}$  roll response functions for the  $RPV$  ( $T_{max}$ ) maximum draught vessel. The natural roll frequencies are 0.620÷0.811 rad/s (7.747÷10.134 s) (Table 3), related to the design selection of the vessel gravity centre vertical position  $z_G$ , and the bilge keels system, and is also linked to the high roll period (slow motion), the roll acceleration is expected to be low. Although at the natural frequency the roll response is of a narrow band type ( $\pm 0.3$  rad/s), for the extended spectral roll response becomes of a wide frequency band, so that roll is relevant in the frequency domain 0.2÷2.8 rad/s. Around the beam sea (70÷110 deg) waves, the maximum roll response is recorded, where the vessel speed has a noticeable effect. Zero roll response is on head

and follow sea conditions. The bilge keel system has a positive effect by reducing the roll amplitude, and as the  $z_G$  gravity center position increases, the roll response also decreases.

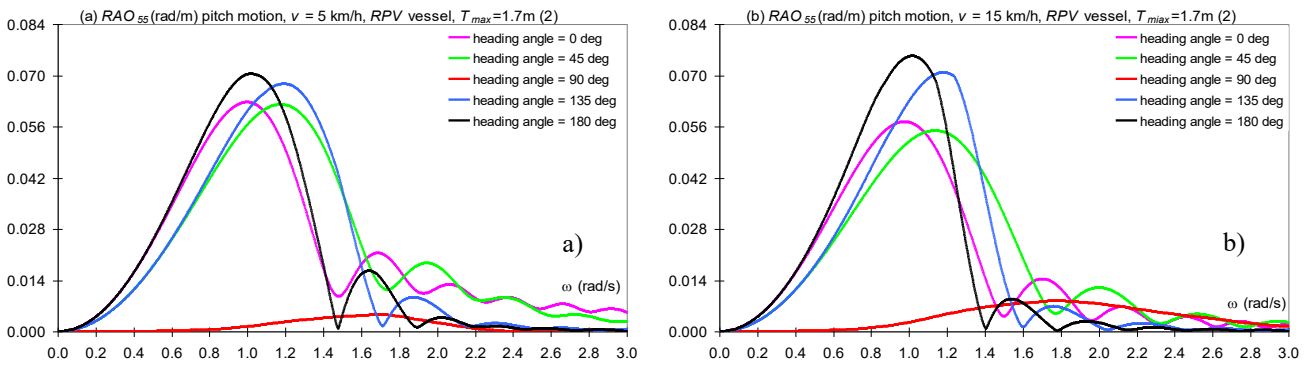


Fig. 19. The *RPV* research-passenger design concept pitch  $RAO_{55}$ (rad/m),  $T_{max}=1.7$  m (2), (a)  $v=5$  km/h and (b)  $v=15$  km/h.

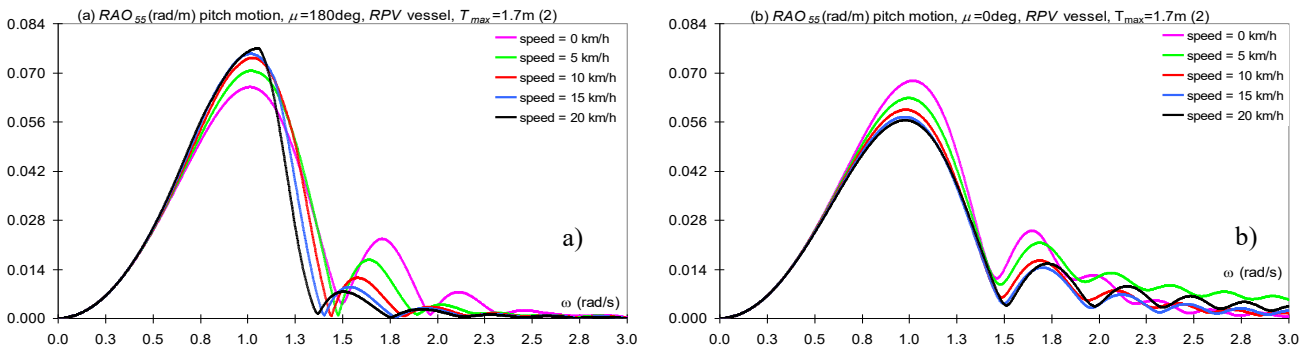


Fig. 20. The *RPV* research-passenger design concept pitch  $RAO_{55}$ (rad/m),  $T_{max}=1.7$  m (2), (a)  $\mu=180$  deg and (b)  $\mu=0$  deg.

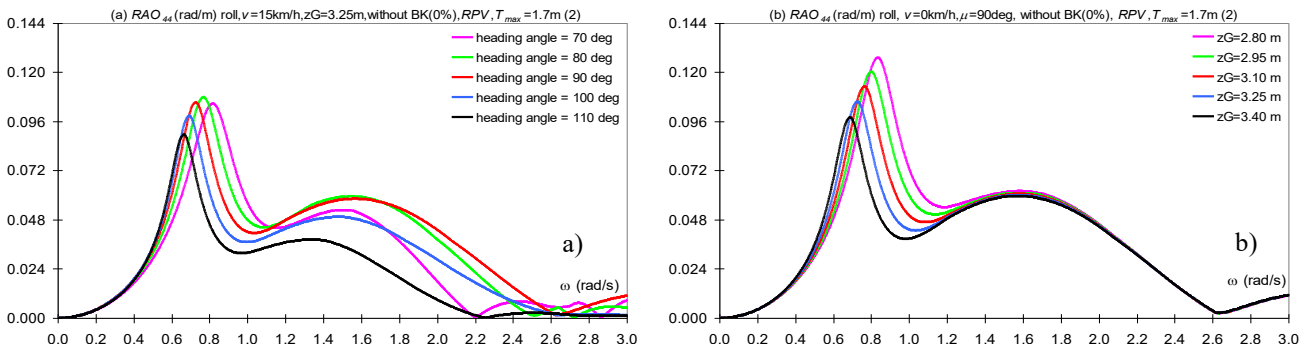


Fig. 21. The *RPV* vessel roll  $RAO_{44}$ (rad/m),  $T_{max}=1.7$  m (2), (a)  $z_G=3.25$  m,  $v=15$  km/h (0%) and (b)  $\mu=90$  deg,  $v=0$  km/h (0%).

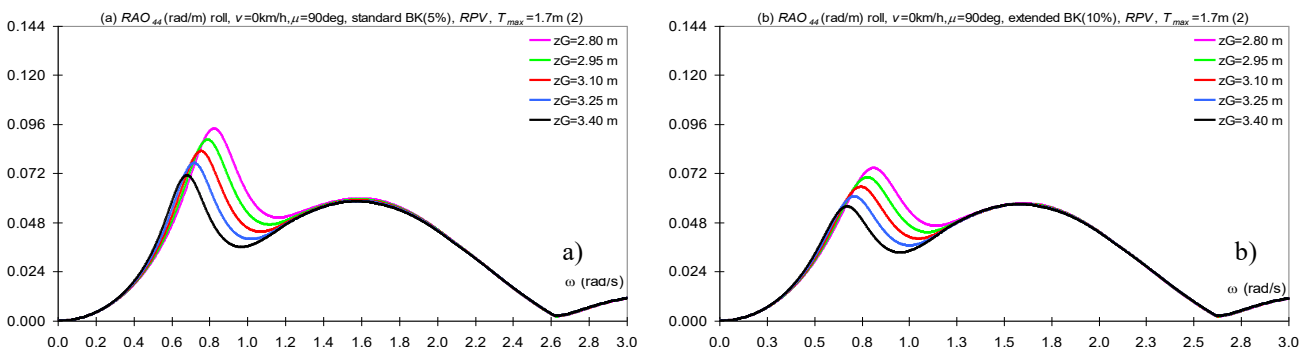


Fig. 22. The *RPV* vessel roll  $RAO_{44}$ (rad/m),  $T_{max}=1.7$  m (2), (a)  $\mu=90$  deg,  $v=0$  km/h (5%) and (b)  $\mu=90$  deg,  $v=0$  km/h (10%).

For the maximum draught loading case of the vessel design concept, the dynamic irregular waves' analyses are computed the short-term *RMS* statistical vessel response, for the *ISSC* wave spectrum averaged power density distribution (Figure 5,  $H_{smax}=2.5$  m), on Danube River and Black Sea Coast navigation conditions. The *RPV* ( $T_{max}$ ) maximum draught vessel safety navigation limits are obtained by seakeeping criteria (Table 4).

Figures 23-25, and Table 8, present the maximum most probable amplitudes *RMS* for the dynamic response of the *RPV* ( $T_{max}$ ) vessel in irregular *ISSC* averaged waves (Figure 5), including the seakeeping criteria (Table 4).

The combined aft vertical motion criterion (Figure 23.a, Table 8) leads to significant restrictions for any of the navigation parameters, due to reduction of the aft freeboard vessel reserve in the case of  $T_{max}=1.7\text{m}$ , so that the admissible values are exceeded 0.17%÷6.24%, improving as the  $z_G$  gravity centre increases, vessel speed decreases, and the keel bilge system is added. The combined mid-fore vertical motion criteria (Table 8) lead to no restrictions for any of the navigation parameters, with safety limits, for  $H_s=2.5\text{m}$  reference, at mid 2.99%÷11.32%, increasing as the vessel speed increases, and at fore 1.93%÷7.65%, increasing as the vessel speed decreases; the  $z_G$  gravity centre increase and the bilge keels system added improve those criteria.

The heave acceleration criterion (Figure 23.b, Table 8) is satisfied, with safety limits 2.87%÷29.33%, for  $H_s=2.5\text{m}$  reference, improving the criterion as the vessel speed decreases.

The pitch motion criterion (Figure 24a, Table 8) is satisfied, with safety limits 10.45%÷15.42%, for  $H_s=2.5\text{m}$  reference, improving the criterion as the vessel speed decreases.

The pitch acceleration criterion (Figure 24.b, Table 8) is satisfied for vessel speeds below 10 km/h, with safety limits 7.21%÷37.20%, being affected as the vessel speed increases. For speeds above 15 km/h, in oblique-head (115÷180 deg) waves, as the speed increases, the pitch acceleration criterion has restrictions, so that the admissible value is exceeded 10.85%÷27.35%.

Table 8. The *RPV* research-passenger design concept,  $T_{max}=1.7\text{ m}$  (2), maximum most probable amplitudes, seakeeping response.

Criteria	Adm.	$z_G(\text{m})$	$k_{BK}(\%)$	$v=0\text{ km/h}$		$v=5\text{ km/h}$		$v=10\text{ km/h}$		$v=15\text{ km/h}$		$v=20\text{ km/h}$		
<b>Comb. Vertical Aft <math>RMS_{aft}</math> (m)</b>	1.800	2.80	0%	1.901	5.63%	1.902	5.65%	1.903	5.71%	1.907	5.92%	1.912	6.24%	
			5%	1.866	3.64%	1.872	4.00%	1.881	4.51%	1.891	5.03%	1.901	5.63%	
			10%	1.842	2.32%	1.853	2.92%	1.867	3.71%	1.881	4.49%	1.894	5.22%	
		3.10	0%	1.870	3.89%	1.871	3.95%	1.877	4.26%	1.884	4.69%	1.894	5.25%	
			5%	1.842	2.32%	1.850	2.75%	1.862	3.43%	1.875	4.19%	1.889	4.94%	
			10%	1.823	1.28%	1.836	2.02%	1.852	2.88%	1.869	3.83%	1.885	4.73%	
	3.40	0%	1.833	1.82%	1.840	2.20%	1.852	2.86%	1.867	3.71%	1.882	4.58%		
		5%	1.815	0.84%	1.828	1.57%	1.845	2.48%	1.862	3.47%	1.880	4.46%		
		10%	1.803	0.17%	1.820	1.13%	1.840	2.21%	1.860	3.31%	1.878	4.36%		
	<b>Comb. Vertical Mid <math>RMS_{mid}</math> (m)</b>	1.500	2.80	0%	1.455	-2.99%	1.451	-3.27%	1.448	-3.44%	1.445	-3.65%	1.444	-3.76%
				5%	1.413	-5.81%	1.409	-6.07%	1.407	-6.23%	1.403	-6.44%	1.400	-6.68%
				10%	1.385	-7.68%	1.381	-7.92%	1.379	-8.08%	1.376	-8.28%	1.372	-8.52%
3.10			0%	1.416	-5.59%	1.413	-5.81%	1.410	-5.97%	1.407	-6.18%	1.407	-6.17%	
			5%	1.384	-7.76%	1.381	-7.96%	1.378	-8.12%	1.375	-8.33%	1.372	-8.56%	
			10%	1.362	-9.18%	1.359	-9.37%	1.357	-9.53%	1.354	-9.73%	1.350	-9.97%	
3.40		0%	1.374	-8.41%	1.372	-8.56%	1.369	-8.72%	1.366	-8.92%	1.365	-9.00%		
		5%	1.354	-9.72%	1.352	-9.86%	1.350	-10.02%	1.347	-10.22%	1.343	-10.45%		
		10%	1.341	-10.60%	1.339	-10.73%	1.337	-10.89%	1.334	-11.09%	1.330	-11.32%		
<b>Comb. Vertical Fore <math>RMS_{fore}</math> (m)</b>		2.000	2.80	0%	1.945	-2.74%	1.947	-2.67%	1.951	-2.47%	1.955	-2.26%	1.961	-1.93%
				5%	1.909	-4.53%	1.918	-4.11%	1.929	-3.56%	1.940	-2.99%	1.951	-2.47%
				10%	1.886	-5.72%	1.900	-5.01%	1.915	-4.26%	1.930	-3.49%	1.944	-2.78%
	3.10		0%	1.914	-4.31%	1.917	-4.16%	1.924	-3.78%	1.934	-3.30%	1.945	-2.77%	
			5%	1.886	-5.72%	1.897	-5.16%	1.910	-4.49%	1.925	-3.76%	1.939	-3.03%	
			10%	1.867	-6.65%	1.884	-5.82%	1.901	-4.93%	1.919	-4.04%	1.936	-3.22%	
	3.40	0%	1.877	-6.17%	1.887	-5.66%	1.901	-4.96%	1.917	-4.16%	1.933	-3.35%		
		5%	1.859	-7.05%	1.875	-6.23%	1.894	-5.29%	1.913	-4.33%	1.931	-3.46%		
		10%	1.847	-7.65%	1.868	-6.62%	1.889	-5.53%	1.911	-4.47%	1.929	-3.55%		
	<b><math>RMS_{pitch}</math> (rad)</b>	0.039	-	-	0.033	-15.42%	0.034	-12.47%	0.036	-9.45%	0.036	-9.09%	0.035	-10.45%
	<b><math>RMS_{roll}</math> (rad)</b>	0.052	2.80	0%	0.053	1.57%	0.052	-0.95%	0.052	-0.19%	0.054	3.15%	0.056	7.43%
				5%	0.044	-16.39%	0.043	-18.73%	0.043	-18.51%	0.044	-16.20%	0.046	-12.80%
10%				0.038	-28.32%	0.036	-30.50%	0.036	-30.65%	0.037	-29.08%	0.039	-26.43%	
3.10			0%	0.044	-15.12%	0.043	-17.07%	0.044	-15.36%	0.047	-10.19%	0.050	-3.81%	
			5%	0.037	-28.93%	0.036	-30.77%	0.037	-30.20%	0.038	-27.17%	0.041	-22.25%	
			10%	0.032	-38.03%	0.032	-39.75%	0.032	-39.68%	0.033	-37.82%	0.034	-34.39%	
3.40		0%	0.035	-33.16%	0.034	-34.60%	0.035	-32.71%	0.038	-26.72%	0.043	-17.30%		
		5%	0.031	-41.49%	0.030	-42.87%	0.030	-42.32%	0.032	-39.30%	0.035	-33.69%		
		10%	0.028	-47.10%	0.027	-48.41%	0.027	-48.31%	0.028	-46.73%	0.030	-43.52%		
<b><math>RMS_{heave}</math> acc(m/s<sup>2</sup>)</b>		0.981	-	-	0.693	-29.33%	0.708	-27.80%	0.748	-23.73%	0.825	-15.89%	0.953	-2.87%
<b><math>RMS_{pitch}</math> acc(rad/s<sup>2</sup>)</b>		0.065	-	-	0.041	-37.20%	0.049	-24.71%	0.060	-7.24%	0.072	10.85%	0.083	27.35%
<b><math>RMS_{roll}</math> acc (rad/s<sup>2</sup>)</b>		0.218	2.80	0%	0.060	-72.55%	0.059	-72.90%	0.058	-73.25%	0.058	-73.58%	0.057	-73.91%
	5%			0.054	-75.24%	0.053	-75.49%	0.053	-75.74%	0.052	-75.99%	0.052	-76.23%	
	10%			0.050	-77.18%	0.049	-77.37%	0.049	-77.56%	0.049	-77.74%	0.048	-77.93%	
	3.10		0%	0.053	-75.82%	0.052	-76.06%	0.052	-76.31%	0.051	-76.54%	0.051	-76.77%	
			5%	0.049	-77.47%	0.049	-77.65%	0.048	-77.82%	0.048	-77.99%	0.048	-78.16%	
			10%	0.046	-78.75%	0.046	-78.88%	0.046	-79.00%	0.046	-79.12%	0.045	-79.25%	
	3.40	0%	0.048	-78.19%	0.047	-78.31%	0.047	-78.44%	0.047	-78.55%	0.047	-78.67%		
		5%	0.046	-79.06%	0.045	-79.15%	0.045	-79.23%	0.045	-79.31%	0.045	-79.39%		
		10%	0.044	-79.82%	0.044	-79.88%	0.044	-79.93%	0.044	-79.98%	0.044	-80.04%		

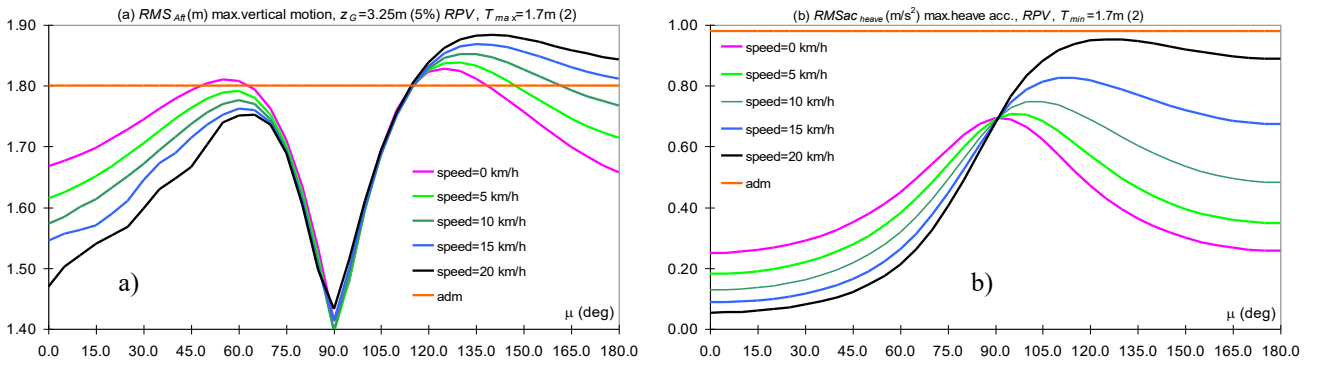


Fig. 23. The *RPV* vessel,  $T_{max}=1.7\text{ m}$  (2), maximum RMS, (a) aft vertical combined motion and (b) heave acceleration.

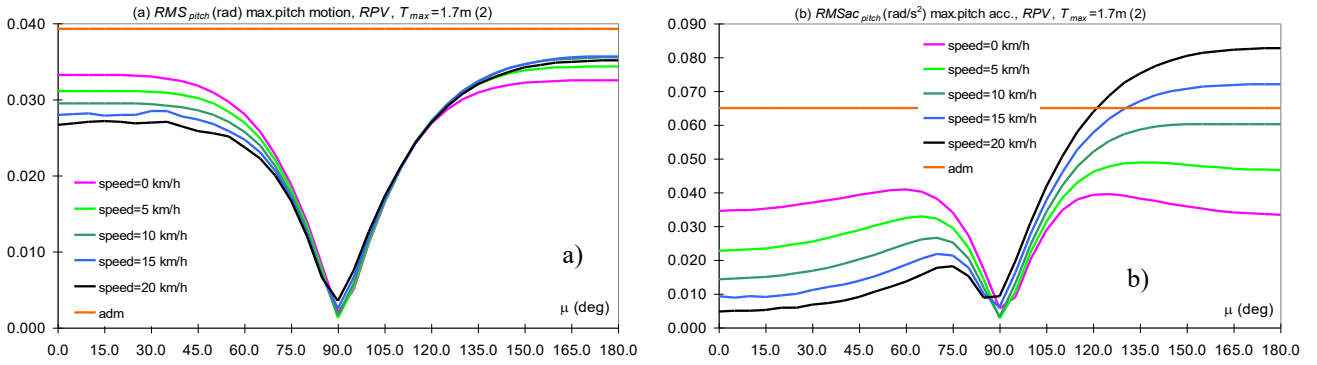


Fig. 24. The *RPV* vessel,  $T_{max}=1.7\text{ m}$  (2), maximum RMS, (a) pitch motion and (b) pitch acceleration.

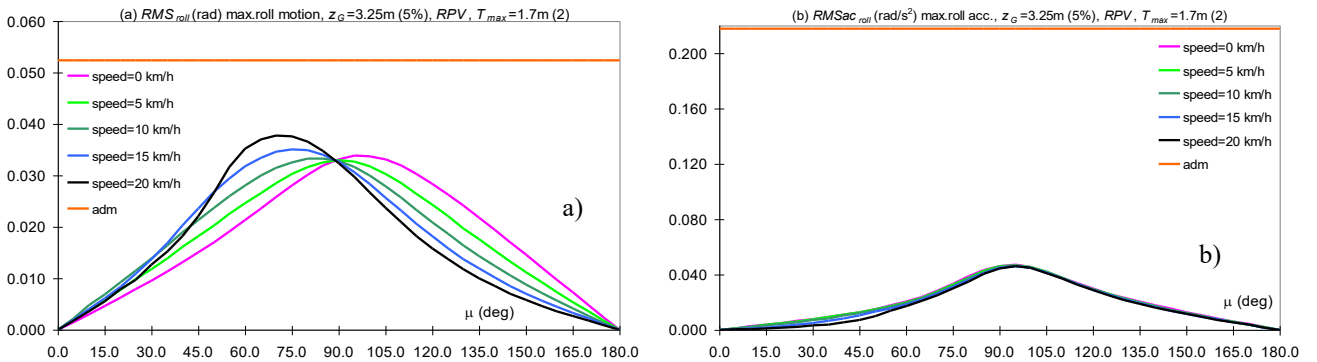


Fig. 25. The *RPV* vessel,  $T_{max}=1.7\text{ m}$  (2),  $z_G=3.25\text{ m}$ ,  $k_{BK}(5\%)$ , maximum RMS, (a) roll motion and (b) roll acceleration.

The roll criterion (Table 8) in the case of  $z_G=2.80\text{ m}$ , without bilge keels ( $k_{BK}=0\%$ ), and speeds  $0\text{ km/h}$  ( $\mu=90\div 105\text{ deg}$ ),  $15, 20\text{ km/h}$  ( $\mu=70\div 90\text{ deg}$ ), has navigation restrictions around the beam sea state, exceeding with  $1.57\%\div 7.43\%$  the admissible value. For the other navigation cases and design concept versions, the roll motion criterion (Figure 25.a, Table 8) is satisfied, with safety limits  $0.19\%\div 48.41\%$ , for  $H_s=2.5\text{ m}$  reference, improving as the bilge keels are added and the vessel speed decreases. Compared to the first load case, the roll motion criterion is better satisfied due to the increase of inertial and damping vessel characteristics, related to the increase of the vessel draught from  $1.5\text{ m}$  to  $1.7\text{ m}$ . The roll acceleration criterion (Figure 25.b, Table 8) is satisfied for any navigation case, with much reduced values in comparison to the admissible limit. This is related to the slow roll motion with safety limits of  $72.55\%\div 80.04\%$ ; the natural roll periods are  $8\div 10\text{ s}$ . Figures 26, 27, and Table 9 present the safety navigation limits for the dynamic response of the *RPV* ( $T_{max}$ ) maximum draught vessel, for irregular *ISSC* averaged river Danube and coastal Black Sea waves (Figure 5), combining the vessel motions and accelerations seakeeping criteria (Table 4).

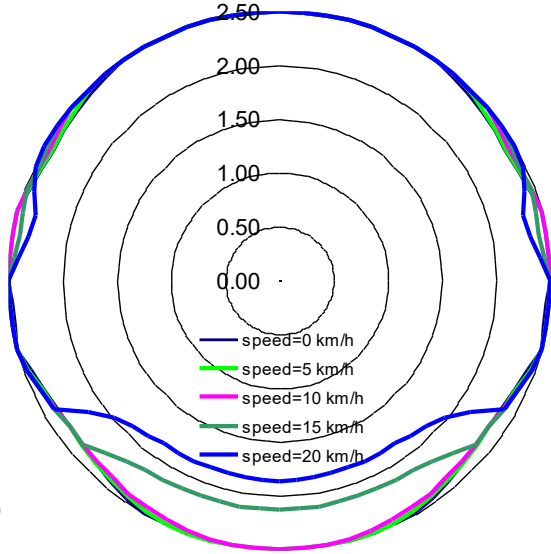
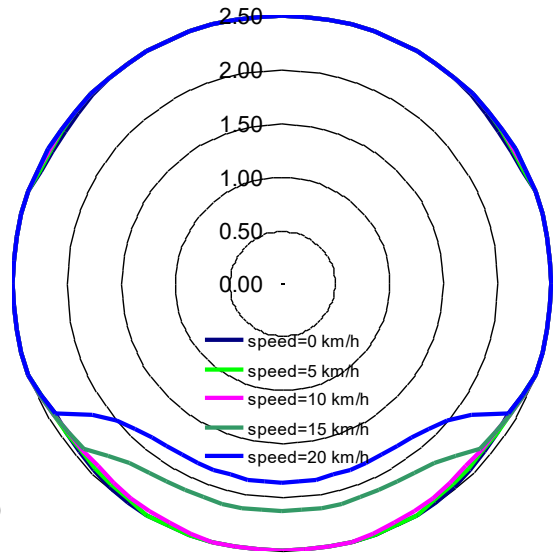
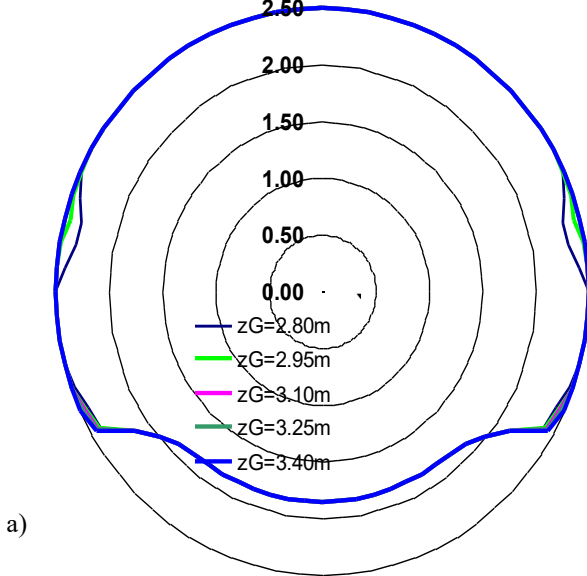
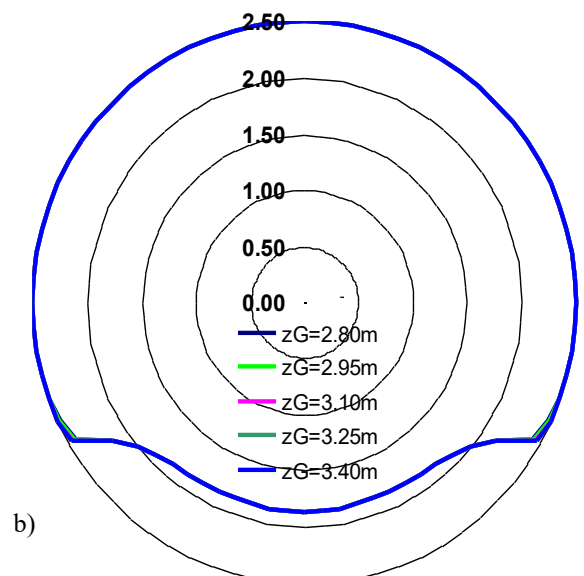
In the case of inland Danube navigation (Table 9, Figures 26, 27), no restrictions occur by seakeeping criteria, *IN*(2.0), for the *RPV* ( $T_{max}$ ) vessel with speeds up to  $15\text{ km/h}$ . For *RPV* ( $T_{max}$ ) vessel speed  $20\text{ km/h}$ , the pitch acceleration criterion at oblique-head waves ( $130\div 180\text{ deg}$ ) reduces the inland safety limit to *IN*(1.8).

In the case of coastal Black Sea navigation (Table 9, Figures 26, 27), for the *RPV* ( $T_{max}$ ) vessel with speeds up to  $10\text{ km/h}$ , due to combined aft vertical criterion at oblique-fore waves ( $115\div 160\text{ deg}$ ), the coastal safety limit is reduced to *C*(2.4), with exceptions for  $z_G=2.80\text{ m}$ ,  $k_{BK}=0\%$ , with safety limit *C*(2.3), and  $z_G=3.40\text{ m}$ ,  $k_{BK}=0\%$  ( $v=0$ ), with safety limit *C*(2.5).

Table 9. The *RPV* research-passenger design concept,  $T_{max}=1.7$  m (2), safety seakeeping limits, river-coastal area.

$z_G$ (m)	$k_{BK}$ (%)		$v=0$ km/h		$v=5$ km/h		$v=10$ km/h		$v=15$ km/h		$v=20$ km/h	
<i>Safety limit</i>			$H_s$ (m)	<i>Criteria</i>	$H_s$ (m)	<i>Criteria</i>	$H_s$ (m)	<i>Criteria</i>	$H_s$ (m)	<i>Criteria</i>	$H_s$ (m)	<i>Criteria</i>
2.80	0%	IN	2.372	no restr.	2.373	no restr.	2.374	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		aft.vert./roll		aft.vert.
	5%	IN	2.415	no restr.	2.408	no restr.	2.399	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
	10%	IN	2.445	no restr.	2.432	no restr.	2.415	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
2.95	0%	IN	2.391	no restr.	2.391	no restr.	2.390	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
	5%	IN	2.430	no restr.	2.422	no restr.	2.410	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
	10%	IN	2.457	no restr.	2.443	no restr.	2.424	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
3.10	0%	IN	2.412	no restr.	2.410	no restr.	2.405	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
	5%	IN	2.446	no restr.	2.436	no restr.	2.422	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
	10%	IN	2.469	no restr.	2.453	no restr.	2.433	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
3.25	0%	IN	2.434	no restr.	2.431	no restr.	2.420	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
	5%	IN	2.463	no restr.	2.450	no restr.	2.433	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
	10%	IN	2.483	no restr.	2.463	no restr.	2.442	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
3.40	0%	IN	2.458	no restr.	2.450	no restr.	2.434	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
	5%	IN	2.480	no restr.	2.463	no restr.	2.443	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
	10%	IN	2.496	no restr.	2.473	no restr.	2.449	no restr.	2.130	no restr.	1.852	pitch.acc
		C		aft.vert.		aft.vert.		aft.vert.		pitch.acc		aft.vert.
<i>max. wave height</i>	<i>river IN coastal C</i>		2.000		2.000		2.000		2.000		1.852	
			2.372 ÷ 2.496		2.373 ÷ 2.473		2.374 ÷ 2.449		2.130			restricted

For *RPV* ( $T_{max}$ ) vessel with speed around 15 km/h, due to the combined aft vertical criterion at oblique-head waves (115÷180 deg), and mainly to pitch acceleration criterion at oblique-head waves (125÷180 deg), the coastal safety limit is reduced to C(2.1). For *RPV* ( $T_{max}$ ) vessel speed 20 km/h, the coastal navigation is totally restricted in any design version, due to the combined aft vertical criterion at oblique-head waves (110÷180 deg), and mainly to the pitch acceleration criterion at oblique-head waves (125÷180 deg). For the *RPV* ( $T_{max}$ ) vessel, the influence of the roll motion criterion is reduced, the combined aft vertical criterion induces coastal restrictions for any cases, and the pitch acceleration criterion becomes dominant for speeds above 15 km/h, being very restrictive for coastal navigation.

(a)  $H_{slimit}(m), z_G=2.80\text{ m}(0\%), RPV, T_{max}=1.7\text{ m}(2)$ (b)  $H_{slimit}(m), z_G=3.25\text{ m}(0\%), RPV, T_{max}=1.7\text{ m}(2)$ Fig.26. The *RPV* research-passenger design concept,  $T_{max}=1.7\text{ m}(2)$ , safety limits (a)  $z_G=2.80\text{ m}(0\%)$  and (b)  $z_G=3.25\text{ m}(0\%)$ .(a)  $H_{slimit}(m), v=20\text{ km/h}(0\%), RPV, T_{max}=1.7\text{ m}(2)$ (b)  $H_{slimit}(m), v=20\text{ km/h}(10\%), RPV, T_{max}=1.7\text{ m}(2)$ Fig.27. The *RPV* research-passenger design concept,  $T_{max}=1.7\text{ m}(2)$ , safety limits (a)  $v=20\text{ km/h}(0\%)$  and (b)  $v=20\text{ km/h}(10\%)$ .Table 10. The *RPV* research-passenger design concept,  $T_{max}=1.7\text{ m}(2)$ , safety limits, combined seakeeping and strength criteria.

Strength criteria [3] $H_{slimit}(m)$		Navigation restrictions $H_{slimit}(m)$		v=0 km/h		v=5 km/h		v=10 km/h		v=15 km/h		v=20 km/h				
				DYN	Combined	DYN	Combined	DYN	Combined	DYN	Combined	DYN	Combined			
$RPV_{T1}$	$RPV_{T2}$	$z_G(m)$	$k_{BK}$	Zone	$H_{slimit}(m)$	T1	T2	$H_{slimit}(m)$	T1	T2	$H_{slimit}(m)$	T1	T2	$H_{slimit}(m)$	T1	T2
1.980 $\approx 2.0$	2.500	0%	IN	C	2.372	IN(2.0)	2.373	IN(2.0)	2.374	IN(2.0)	2.130	IN(2.0)	1.852	IN(1.8)		
						restr. C(2.3)	restr. C(2.3)	restr. C(2.3)	restr. C(2.1)	restricted						
		2.80	5%	IN	C	2.415	IN(2.0)	2.408	IN(2.0)	2.399	IN(2.0)	2.130	IN(2.0)	1.852	IN(1.8)	
							restr. C(2.4)	restr. C(2.4)	restr. C(2.4)	restr. C(2.1)	restricted					
		10%	IN	C	2.445	IN(2.0)	2.432	IN(2.0)	2.415	IN(2.0)	2.130	IN(2.0)	1.852	IN(1.8)		
						restr. C(2.4)	restr. C(2.4)	restr. C(2.4)	restr. C(2.1)	restricted						
	2.500	0%	IN	C	2.391	IN(2.0)	2.391	IN(2.0)	2.390	IN(2.0)	2.130	IN(2.0)	1.852	IN(1.8)		
						restr. C(2.4)	restr. C(2.4)	restr. C(2.4)	restr. C(2.1)	restricted						
		2.95	5%	IN	C	2.430	IN(2.0)	2.422	IN(2.0)	2.410	IN(2.0)	2.130	IN(2.0)	1.852	IN(1.8)	
							restr. C(2.4)	restr. C(2.4)	restr. C(2.4)	restr. C(2.1)	restricted					
		10%	IN	C	2.457	IN(2.0)	2.443	IN(2.0)	2.424	IN(2.0)	2.130	IN(2.0)	1.852	IN(1.8)		
						restr. C(2.4)	restr. C(2.4)	restr. C(2.4)	restr. C(2.1)	restricted						
3.10	0%	IN	C	2.412	IN(2.0)	2.410	IN(2.0)	2.405	IN(2.0)	2.130	IN(2.0)	1.852	IN(1.8)			
					restr. C(2.4)	restr. C(2.4)	restr. C(2.4)	restr. C(2.1)	restricted							
	5%	IN	C	2.446	IN(2.0)	2.436	IN(2.0)	2.422	IN(2.0)	2.130	IN(2.0)	1.852	IN(1.8)			
				restr. C(2.4)	restr. C(2.4)	restr. C(2.4)	restr. C(2.1)	restricted								

10%	IN	2.469	<i>IN(2.0)</i>	2.453	<i>IN(2.0)</i>	2.433	<i>IN(2.0)</i>	2.130	<i>IN(2.0)</i>	1.852	<i>IN(1.8)</i>
	C		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.1)</i>		<i>restricted</i>
0%	IN	2.434	<i>IN(2.0)</i>	2.431	<i>IN(2.0)</i>	2.420	<i>IN(2.0)</i>	2.130	<i>IN(2.0)</i>	1.852	<i>IN(1.8)</i>
	C		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.1)</i>		<i>restricted</i>
3.25	5%	IN	<i>IN(2.0)</i>	2.450	<i>IN(2.0)</i>	2.433	<i>IN(2.0)</i>	2.130	<i>IN(2.0)</i>	1.852	<i>IN(1.8)</i>
		C	<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.1)</i>		<i>restricted</i>
10%	IN	2.483	<i>IN(2.0)</i>	2.463	<i>IN(2.0)</i>	2.442	<i>IN(2.0)</i>	2.130	<i>IN(2.0)</i>	1.852	<i>IN(1.8)</i>
	C		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.1)</i>		<i>restricted</i>
0%	IN	2.458	<i>IN(2.0)</i>	2.450	<i>IN(2.0)</i>	2.434	<i>IN(2.0)</i>	2.130	<i>IN(2.0)</i>	1.852	<i>IN(1.8)</i>
	C		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.1)</i>		<i>restricted</i>
3.40	5%	IN	<i>IN(2.0)</i>	2.463	<i>IN(2.0)</i>	2.443	<i>IN(2.0)</i>	2.130	<i>IN(2.0)</i>	1.852	<i>IN(1.8)</i>
		C	<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.1)</i>		<i>restricted</i>
10%	IN	2.496	<i>IN(2.0)</i>	2.473	<i>IN(2.0)</i>	2.449	<i>IN(2.0)</i>	2.130	<i>IN(2.0)</i>	1.852	<i>IN(1.8)</i>
	C		<i>restr. C(2.5)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.4)</i>		<i>restr. C(2.1)</i>		<i>restricted</i>

For the *RPV* ( $T_{max}$ ) vessel, the complete navigation operational assessment is done in Table 10, combining the strength and the seakeeping criteria, for the two structural design vessel concept versions  $T_1$  &  $T_2$  [3].

For the Danube inland navigation case, no restrictions occur by seakeeping and strength criteria for speeds up to 15 km/h, for both structural  $T1$  &  $T2$  versions, with safety limit  $IN(2.0)$ , and for top speed 20 km/h, the safety limit is reduced to  $IN(1.8)$ . For the Black Sea coastal navigation case, the standard structural version ( $T1$ ) has coastal navigation restricted due to the strength criteria limits for any condition. For coastal navigation, the enhanced version ( $T2$ ) has restrictions only due to seakeeping criteria, so that for speeds below 10 km/h the coastal safety limit is  $C(2.3)÷C(2.5)$ , for speeds around 15 km/h  $C(2.1)$ , and is coastal restricted for 20 km/h.

## 5. CONCLUSIONS

The dynamic capabilities of a research-passenger design-concept vessel (section 3) are evaluated by interlinked deterministic regular waves, and short-term statically irregular waves, with seakeeping criteria assessment, integrated methodology (section 2), for the river Danube ( $H_{smax}=2$  m) and coastal Black Sea ( $H_{smax}=2.5$  m) navigation conditions, with improved for mono-slender hull vessels eigen *DYN\_OSC* version 2025 program [15]. The design-concept vessel has two structural versions [3], standard ( $T1$ ) and enhanced ( $T2$ ), and by selection of the onboard masses (Figure 3), provisions, and research equipment, the parametric hydrodynamic analyses are developed for two extreme vessel loading cases, with relevant draughts of 1.5 m ( $T_{min}$ ) and 1.7 m ( $T_{max}$ ).

A preliminary dynamic characteristic evaluation is done by the natural oscillation periods for both loading cases, heave (3.900÷4.030 s), pitch (3.582÷3.666 s), and roll (7.020÷8.788 s; 7.767÷10.134 s) (Table 3). So, it can be stated that roll is the slowest vessel oscillation, resulting in reduced roll acceleration, and pitch is the fastest vessel oscillation, leading to increased vessel pitch acceleration. The regular waves *RAO* amplitude response functions (Figures 6-11, 17-22) (sections 4 and 5) are spectral wide range type for the main mono-slender vessel oscillation components,  $\omega=0.2÷2.8$  rad/s, so that the spectral transition of the wave energy on the vessel body is ensured for the whole irregular wave's spectra *ISSC* model (Figure 5). The heave *RAO* response (Figures 6, 7, 17, 18), for both draught cases, is maximum at beam waves (90 deg), and increases with speed at oblique-head (135÷180 deg) waves. The pitch *RAO* response (Figures 8, 9, 19, 20), for both draught cases, is maximum and increases with speed at oblique-head waves (135÷180 deg). The roll *RAO* response (Figures 10, 11, 21, 22) for both draught cases is maximum around beam waves (70÷120 deg), with speed influence also noticeable. The roll *RAO* response is significantly influenced by two design-concept variables:  $z_G$  gravity centre vertical position and bilge keels system, the roll amplitude getting reduced as  $z_G$  (2.80÷3.40 m) is increased, and the bilge keels are added (5%, 10%), involving changes in the inertial-damping and stability terms (Figure 4).

For the first loading case ( $T_{min}$ ) (Figures 12-16, Tables 5, 6) (section 4.1), the irregular waves response has no seakeeping restrictions on the river Danube navigation condition,  $H_{slimit}=2$  m, for vessel speeds below 15 km/h, and with restriction  $H_{slimit}=1.817$  m for vessel top speed 20 km/h. On the coastal Black Sea navigation condition, for vessel speed below 10 km/h, without bilge keels, due to the roll motion criterion around beam sea (60÷105 deg), restrictions occur  $H_{slimit}=2.053÷2.479$  m ( $z_G\leq 3.25$ m), and no restrictions  $H_{slimit}=2.5$  m ( $z_G\geq 2.95$  m) with bilge keels added. For vessel speed 15 km/h, the pitch acceleration criterion at oblique-head waves (125÷180 deg) leads to coastal navigation restrictions  $H_{slimit}=2.091$  m, and coastal restricted navigation for speed 20 km/h.

For the second loading case ( $T_{max}$ ) (Figures 23-27, Tables 8, 9) (section 4.2), the irregular waves response has no seakeeping restrictions on the river Danube navigation condition,  $H_{slimit}=2$  m, for vessel speeds below 15 km/h, and with restriction  $H_{slimit}=1.852$  m for vessel top speed 20 km/h. For the coastal Black Sea navigation condition, for vessel speeds below 10 km/h, due to the combined vertical aft motion criterion at oblique-fore waves (115÷160 deg), restrictions occur  $H_{slimit}=2.372÷2.496$  m, improving as the  $z_G$  gravity center increases and bilge keels are added. For vessel speed 15 km/h, the pitch acceleration criterion at oblique-head waves leads to coastal navigation

restrictions  $H_{slimit}=2.130$  m, and coastal restricted navigation for top speed 20 km/h.

Combined seakeeping and strength criteria [3] (Tables 7, 10) (sections 4.1 and 4.2) deliver the full assessment of the navigation safety limits for the research-passenger vessel design concept, on the two loading cases ( $T_{min}$ ,  $T_{max}$ ), for the two structural versions ( $T1$ ,  $T2$ ).

The standard vessel structure ( $T1$ ) [3], with combined criteria, on the inland Danube route, for both draught cases, has no navigation restrictions IN(2.0) if speed is up to 15 km/h, and restricted to IN(1.8) for a top speed of 20 km/h. On the coastal Black Sea route, for first draught ( $T_{min}$ ), the coastal navigation is restricted to C(2.1)÷C(2.2) for speeds below 15 km/h, and coastal navigation is restricted to a maximum speed of 20 km/h; for second draught ( $T_{max}$ ), the strength criteria lead to fully restricted coastal navigation.

The enhanced vessel structure ( $T2$ ) [3], has no restrictions by strength criteria, only from seakeeping criteria for both draughts, on inland Danube route, has no restriction IN(2.0) and speeds below 15 km/h, and IN(1.8) restriction for 20 km/h vessel speed; on coastal Black Sea route, the limits are C(2.1)÷C(2.5) for speeds up to 15 km/h, and coastal navigation restricted for 20 km/h vessel speed.

*In conclusion*, the parametric research-passenger design concept seakeeping study, combined with strength assessment [3], points out that both structural versions ( $T1$ ,  $T2$ ) are safe for inland Danube navigation, class IN(2.0), for speeds up to 15 km/h, and class IN(1.8) for 20 km/h speed. For coastal Black Sea navigation, the standard structure vessel ( $T1$ ) is not safe, due to structural restrictions, being safe only the enhanced structure vessel ( $T2$ ), with coastal class C(2.1)÷C(2.5), for speeds below 15 km/h, improved by  $v$ ,  $z_G$ ,  $k_{BK}$  parameters changes, but coastal navigation restricted for 20 km/h speed, due to pitch acceleration criterion. If only the Danube River route is foreseen in operations for the research-passenger vessel, it is recommended to select the standard structure ( $T1$ ) design, ensuring also the maximum onboard mass capacity [3]. The vessel speed shall be reduced from 20 km/h to 15 km/h to also cover the Sulina area, at the Danube River and Black Sea transition, with navigation class IN(2.0). For the other lower and higher Danube sectors, with class IN(1.2) and IN(0.6), the  $RPV$  vessel speed restrictions are only related to the international regulations [21].

*Further studies* of the combined seakeeping and structural analyses will address the catamaran and trimaran vessel types, requiring further enhancements of the own codes [3, 15], for river and coastal navigation cases.

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## REFERENCES

1. ISSC, (2025). *Design Principles and Criteria. Loads. Dynamic Response. Quasi-Static Response*, Proceeding of the 22<sup>th</sup> International Conference Ship and Offshore Structures, (Wenwei W. and Jun D. Eds.), ISSC, Wuxi.
2. BV, (2025). *NR217. Passenger vessel. Rules for Inland Navigation Vessels*, Bureau Veritas, Paris.
3. Domnisoru, L., (2025). *On the Structural Design Concept of a River-Coastal Research-Passenger Ship Assessment under Oblique Wave Scenarios*, International Journal of Modern Manufacturing Technologies, XVII (3), 36-52.
4. ITTC, (2024). *Seakeeping*. Proceedings of the 30<sup>th</sup> International Towing Tank Conference Association, (Gerhardt F. and Hermundstad O.A. Eds.), ITTC, Hobart.
5. ABS, (2018). *DLA-Vessels. Dynamic Loading Approach for Vessels (Safehull). Wave Spectrum. Response Amplitude Operators. Short-Term Response*, American Bureau of Shipping, Houston TX.
6. BV, (2019). *NI638. Environmental conditions. Short-term Statistics. Seakeeping*, Bureau Veritas, Paris.
7. DNV, (2025). *RPC205. Short-Term Wave Conditions. Seakeeping*, Det Norske Veritas, Novik.
8. Lothar, B., (2019). *Fundamentals of Ship Hydrodynamics*, John Wiley & Sons Inc., New Jersey.
9. Journée, J.M.J.; Pinkster, J., (2002). *Introduction in Ship Hydromechanics (MT519)*, DUT, Delft.
10. Bertram, V., (2012). *Practical Ship Hydrodynamics*, Butterworth Heinemann, Oxford.
11. Matusiak, J., (2021). *Dynamics of a Rigid Ship, with Applications*, Aalto University Publisher, Helsinki.
12. ITTC, (2011). *RPG 7.5-02-07-02. Seakeeping*, International Towing Tank Conference Association, Zurich.
13. DNV, (2018). *CG0130. Wave Loads. Seakeeping - Strip Theory. Statistics*, Det Norske Veritas, Novik.
14. DNV, (2025). *Seakeeping Analysis of Ships by Strip Theory (Waveship)*, Det Norske Veritas, Novik.
15. Domnisoru, L. (2025). *Seakeeping. DYN\_OSC Program User Guide*, UDJG Publishing House, Galati.
16. Domnisoru, L., (2023). *Preliminary Hydrodynamic Analyses for a River Research Ship. Comparative Study of Mono-Hull and Catamaran Ship Type*, Galati University Press, (XI), Shipbuilding, 46, 39-47.
17. Bidoae, R.; Ionas, O., (2004). *Ship Theory*, Didactic & Pedagogic Publishing House, Bucharest.
18. Obreja, D.; Nabergoj, R.; Crudu, L.; Domnisoru, L., (2017). *Seakeeping Performance of a Mediterranean*

- Fishing Vessel*, Proceedings of 17<sup>th</sup> International Congress of the International Maritime Association of the Mediterranean, 9-11 October 2017, Lisboa, Developments in Maritime Transportation and Harvesting of Sea Resources (C.G. Soares and A. Teixeira Eds.), CRC Press / A.A. Balkema Publishers, (IMAM 2017), 483-491.
19. Pacuraru, F.; Domnisoru, L.; Pacuraru, S., (2020). *On the Comparative Seakeeping Analysis of the Full-scale KCS by Several Hydrodynamic Approaches*, Journal of Marine Science and Engineering, Paper no. 962, 8(12), 1-32.
20. FEMAP, (2026). *Femap Program User Guide*. Siemens PLM Software (License Academic).
21. Via Donau, (2019). *Manual on Danube Navigation*, Via Donau (Hasenbichler H.P. and Gansterer S. Eds.), Oesterreichische Wasserstrassen-Gesellschaft mbH, Wien.