

Article

Seakeeping Performance of a New Coastal Patrol Ship for the Croatian Navy

Andrija Ljulj¹ and Vedran Slapničar^{2,*} ¹ Ministry of Defence of the Republic of Croatia, 10000 Zagreb, Croatia; andrija.ljulj@morh.hr² Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, 10000 Zagreb, Croatia

* Correspondence: vedran.slapnicar@fsb.hr

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Abstract: This paper presents seakeeping test results for a coastal patrol ship (CPS) in the Croatian Navy (CN). The full-scale tests were conducted on a CPS prototype that was accepted by the CN. The seakeeping numerical prediction and model tests were done during preliminary project design. However, these results are not fully comparable with the prototype tests since the ship was lengthened in the last phases of the project. Key numerical calculations are presented. The CPS project aims to renew a part of the Croatian Coast Guard with five ships. After successful prototype acceptance trials, the Croatian Ministry of Defence (MoD) will continue building the first ship in the series in early 2020. Full-scale prototype seakeeping test results could be valuable in the design of similar CPS projects. The main aim of this paper is to publish parts of the sea trial results related to the seakeeping performance of the CPS. Coast guards around the world have numerous challenges related to peacetime tasks such as preventing human and drug trafficking, fighting terrorism, controlling immigration, and protecting the marine environmental. They must have reliable platforms with good seakeeping characteristics that are important for overall ship operations. The scientific purpose of this paper is to contribute to the design process of similar CPS projects in terms of the development of seakeeping requirements and their level of fulfillment on an actual ship.

Keywords: coastal patrol ship (CPS); full-scale seakeeping trials; ship design

1. Introduction

1.1. Literature Review

Full-scale ship sea trials are the most important test of a ship's structure, equipment, and crew in order to prove its security, reliability, and operational capability. In principle, a ship's trials should provide the final check of the adequacy of theoretical and experimental predictions of ship behavior [1]. Ship trials are carried out for a variety of reasons, including to:

1. Confirm that the ship meets her design intention as regards performance;
2. Predict performance during service;
3. Prove that equipment can function properly in the shipboard environment;
4. Provide data on which future ship designs can be based; and
5. Determine the effect on human performance.

Ship seakeeping design predictions are based on numerical analyses and model tests that are conducted in model tanks. Validation, using full-scale experimental data, is essential to the development of a ship's motion prediction code [2]. Reference [2] presents validations of ship motion predictions using model tank tests and full-scale sea trials for a Canadian naval destroyer. Full-scale trials are

considered crucial because they include physical phenomena lacking in model tests due to oversight or scaling effects.

The results of full-scale seakeeping trials on several ships, including the Dutch naval destroyer “HM Groningen” are described in [3]. The main goal of these tests was to compare full-scale test results with numerical predictions that had been developed. It was noted that suitable conditions at sea are hard to find, or that the measuring or analyzing methods were not sufficient for correlation purposes.

A new experimental methodology to accurately predict wave-induced motions and load responses of ships was proposed in [4]. It is based on self-propelled large-scale model measurements that were conducted in natural environmental conditions. Onboard systems, operated by the crew, were used to measure and record sea waves and the responses of a model. A post-voyage analysis of the measurements, both of the sea waves and the model’s responses, was conducted to predict the ship’s motion and short term load responses to a corresponding sea state.

The results of extensive full-scale seakeeping trials of an all-weather lifeboat, conducted by the Royal National Lifeboat Institution in collaboration with Newcastle University and Lloyd’s Register, are shown in Reference [5]. The trials investigated the seakeeping behavior of the craft in real operational conditions.

Patrol vessels must have good performance criteria for seaworthiness, and an analysis of the hydrodynamic aspects of a ship’s design is one of the designer’s primary tasks [6]. This analysis describes ship motion and ship resistance. The seakeeping tests conducted two variations of a ship loading condition and involved two sea states, namely the World Meteorological Organization (WMO) sea states 3 and 4.

In [7], the stern boat deployment system was investigated to evaluate the capability of launching and recovering a rigid hull inflatable boat (RHIB) via the stern ramp. The seakeeping characteristics required for the successful operation of a mother ship and inflatable boat were analyzed.

1.2. Paper Content and Main Particulars of the Coastal Patrol Ship

This paper presents the seakeeping requirements for a coastal patrol ship (CPS) for the Croatian Navy (CN) and the results of the full-scale seakeeping performance of the ship. The seakeeping requirements are based on Reference [8], which presents the seakeeping criteria for the reference ship, a frigate-size vessel. Because the CPS is a significantly smaller ship, the requirements are downsized accordingly, and presented in Section 2. The seakeeping requirements are composed of: the motion criteria of the ship (roll, pitch); vertical and lateral accelerations at significant positions on the ship; propeller emergence; deck wetness; slamming; and relative vertical motions of the edge of the ship stern. Full-scale trials were conducted during the acceptance of the ship, and the corresponding above-mentioned criteria were applied. After the ship was accepted by the CN, the prototype sea trials were conducted. The purpose of these tests was to check the utmost capabilities of the ship on higher sea states and see how those conditions affect the ship’s hull, machinery, other equipment, and the crew. The results of full-scale trials are presented in Section 4. The main CPS particulars are shown in Table 1.

The seakeeping numerical prediction and model tests were done during preliminary project design, but these results are not comparable with the full-scale tests since the ship was significantly changed in the last phases of the project (e.g., lengthened).

The general arrangement and body plan of the CPS are shown in Figures 1 and 2. The main tasks for the new coastal patrol ship are to conduct:

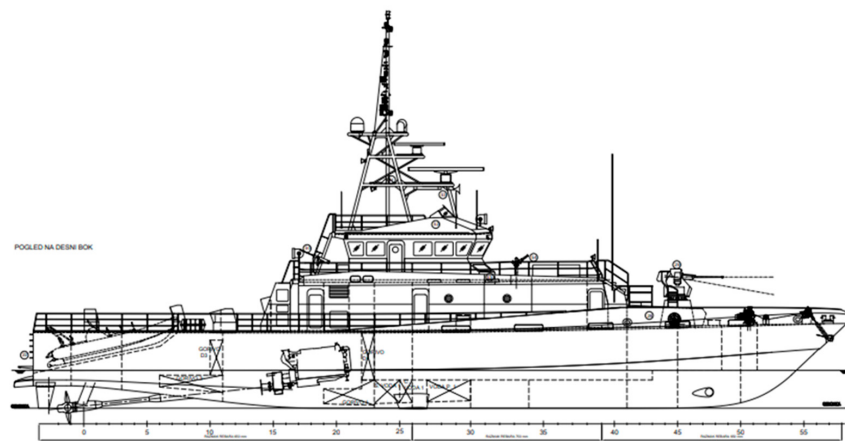
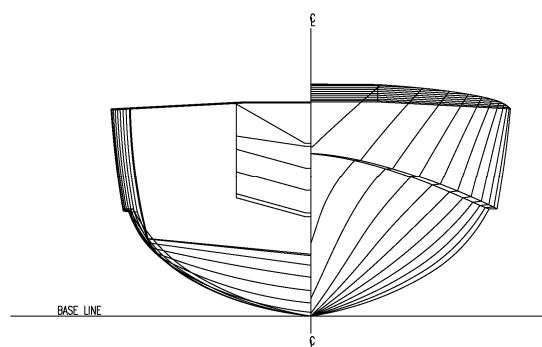
1. Peacetime tasks:

- Low enforcement at sea;
- Protection of fishing;
- Control and prevention of possible ecology incidents;
- Combat against terrorism;
- Trafficking of people and narcotics;

2. Miscellaneous tasks such as search and rescue and support of the local population in crises;
3. Tasks during wartime [9].

Table 1. The main coastal patrol ship (CPS) particulars.

Item	Specification
Length overall	43.5 m
Breadth overall	8.0 m
Breadth of hull at waterline	7.5 m
Draft over propellers	2.9 m
Maximum continuous speed	28 kn
Economy speed	15 kn
Block coefficient	0.45
Type of ship form	semi-displacement
Hull material	high strength steel
Superstructure material	Al alloy
Ship range	1000 nm
Armament	30 mm Aselsan bow gun 2x Browning machine guns 12.9 mm MANPADs
Propulsion	2x Caterpillar 16V, 3516C, 2525 kW
Main equipment	RHIB LoA 7.5 m

**Figure 1.** General arrangement of the CPS.**Figure 2.** Body plan of the CPS.

2. Seakeeping Requirements

Seakeeping requirements are based on Reference [8], and are reduced to suit the CPS size. Following Reference [9], the CPS should be fully operational at mid sea state 4 ($H_{1/3} = 1.8$ m) following the WMO scale, but not including the launch and recovery of the RHIB. Launch and recovery of the RHIB should be feasible at sea state 3 ($H_{1/3} = 1.25$ m–WMO) and with the CPS sailing at least 5 knots with heading waves. The CPS should be partially operational up to sea state 5 ($H_{1/3} = 3.1$ m–WMO) including sailing in a manner suitable for surveillance, monitoring the operational situation, and reporting. The requirements also include survivability of the CPS on the highest sea state observed on the Adriatic Sea. Other specific seakeeping requirements are shown in Table 2.

Table 2. Specific seakeeping requirements for the CPS.

Requirement		Criteria
1.	Rolling	$<4^\circ$ RMS at sea state 4 ($H_{1/3} = 1.8$ m) and speed of 15 knots, at sea state 3 ($H_{1/3} = 1.25$ m) and speed of 5 knots, as well as in conditions of the sea trials, and at the maximum continuous speed.
2.	Rolling	$<5^\circ$ RMS at sea state 3 ($H_{1/3} = 1.25$ m) speed of 0 knots, and beam waves.
3.	Pitching	$<1.5^\circ$ RMS at sea state 4 ($H_{1/3} = 1.8$ m) and speed of 15 knots, at sea state 3 ($H_{1/3} = 1.25$ m), and speed of 5 knots.
4.	Vertical accelerations at accommodation spaces	<0.2 g at sea state 4 ($H_{1/3} = 1.8$ m) and speed of 15 knots, at sea state 3 ($H_{1/3} = 1.25$ m) and speed of 5 knots, as well as in conditions of the sea trials, and at the maximum continuous speed.
5.	Lateral accelerations at accommodation spaces	<0.1 g at sea state 4 ($H_{1/3} = 1.8$ m) and speed of 15 knots, at sea state 3 ($H_{1/3} = 1.25$ m) and speed of 5 knots, as well as in conditions of the sea trials, and at the maximum continuous speed.
6.	Vertical displacement at the transom	<0.78 m at sea state 3 ($H_{1/3} = 1.25$ m) and speed of 5 knots.
7.	Deck wetness	<30 /h at sea state 4 ($H_{1/3} = 1.8$ m) and speed of 15 knots.
8.	Slamming	<20 /h at sea state 4 ($H_{1/3} = 1.8$ m) and speed of 15 knots.
9.	Propeller emergence	<90 /h at sea state 4 ($H_{1/3} = 1.8$ m) and speed of 15 knots.

3. Test Conditions and Measuring Equipment

The trials were conducted with half-full fuel and water tanks, in addition to stocked supplies, at departure. A record sheet captured additional information: sea state; wind speed; wind direction; ship's heading; GPS coordinates; engine RPM; speed over ground; speed through water; draft and displacement of ship at departure; and trial times and duration. The sea states were estimated by three crew members with extensive nautical experience. They were based on sea state descriptions of the Adriatic Sea set by Prof. Tonko Tabain according to experiments conducted during the 1970s [10]. Prof. Tabain also set the relationship between the Adriatic sea state scale and the WMO scale. Sea state estimates were also compared with the sea states provided by the Croatian Meteorological Institute (CMI) to validate the estimates provided by the crew members. The CMI uses a network of buoys for wave measurement and providing related waves statistics. It was difficult to find the required sea state conditions and the trials therefore lasted longer than expected. To record parameters for all seakeeping criteria described in Section 2, the CPS sailed for 20 minutes for each set of criteria. For measuring rolling and pitching angles, a fibro optic gyro (FOG) onboard the CPS was used. The FOG provided raw motion data that were recorded on a laptop and processed later. A typical sequence of maritime courses for seakeeping tests was used as shown in Figure 3. Following Reference [11], root mean square (rms) values of signals were calculated using the expression:

$$\sqrt{(1/N) \sum_{i=1}^N (\delta - \bar{\delta})^2} \quad (1)$$

where N represents the number of samples, δ is the measured signal value, and $\bar{\delta}$ is the mean value of the signal. The highest expected measured frequency was less than 0.5 Hz and the frequency of FOG data was 4.0 Hz, which assured consistent and well-sampled data. Accelerometers were used to measure vertical and lateral accelerations of specific points on the ship (i.e., the wheelhouse, the control cabin near the engine room, and the stern of the ship). Vertical displacement of the stern was measured using a liquid level sensor that was attached to the stern of the ship. Deck wetness, slamming, and propeller emergence were determined by counting their occurrences during one sailing course of 20 min, and then recalculating at the number of occurrences per hour.

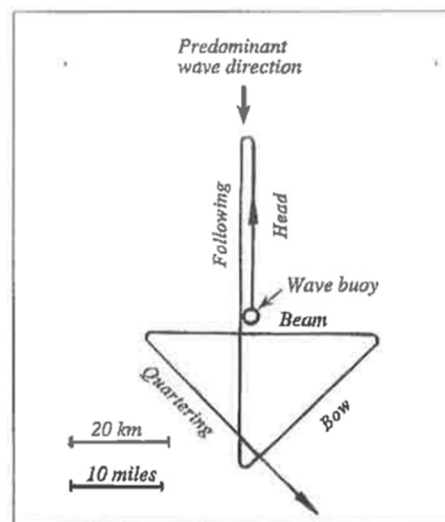


Figure 3. Sequence of maritime courses for seakeeping tests [12].

4. Seakeeping Performance Results

Seakeeping performance results are presented in Tables 3–5, and were taken from the report by the company hired by the Croatian Ministry of Defence (MoD) to conduct the trials [13].

Table 3 presents the results of the trial at sea state 3–4 (WMO), and at speeds of 0 and 5 knots. The speed of 5 knots was one of the required operational speeds designed for launch and recovery of the RHIB. One of the main goals, in addition to measuring all seakeeping parameters, was to check vertical displacement at the aft perpendicular (AP). This parameter is important for assessing the safe launch and recovery of the RHIB. For the operational sea state 3–4 (WMO), this parameter was 0.6 m, a result below the required limits and signaling the success of this crucial operation. This was born out in practice, with the RHIB successfully being launched and recovered during sea trials. Later on, when the crew had become more experienced, they launched and recovered the RHIB even at sea state 4–5 (WMO). All other parameters were within the required limits.

Table 4 presents the results of the trial at sea state 3–4 (WMO), and at a speed of 15 knots, representing the cruising speed of the CPS. As can be seen, all parameters were within required limits, except the angle of pitch (1.9° rms) at the heading angle of 90°, and the number of slammings that were slightly above the allowable limits.

Table 5 shows the results of the trial at sea state 3–4 (WMO), and at a speed of 27 knots (i.e., maximum continuous speed). The parameters that exceeded the required thresholds were the angle of pitching at the heading of 45° and 135°, deck wetness (33), and slamming (70). It was expected that the parameters for maximum continuous speed would be exceeded, although there were no requirements to measure these parameters at this speed.

Table 3. Results for the trial at sea state 3–4 (WMO), and speed of 0 and 5 knots.

Parameter	Symbol	Units	Trial I	Trial II	Trial III	Trial IV	Trial V	Trial VI
Initial ship speed	V_0	kn	0	5	5	5	5	5
Ship draft at AP	TKA	m	2.0	2.0	2.0	2.0	2.0	2.0
Ship draft at FP	TKF	m	1.98	1.98	1.98	1.98	1.98	1.98
Ship heading	COG	°	030	205	075	030	345	300
Sea state	WMO	-	3–4	3–4	3–4	3–4	3–4	3–4
Waves heading	-	°	90	0	45	90	135	180
Average speed (SOG)	v	kn	1.7	5.3	4.7	4.5	4.8	5.1
Roll	Φ	°	2.5	1.7	3.3	2.3	2.7	2.6
Pitch	θ	°	0.7	0.9	0.7	0.7	0.6	1.1
Vertical accel. at wheelhouse	w'	m/s^2	0.3	0.3	0.3	0.3	0.3	0.2
Lateral accel. at wheelhouse	v'	m/s^2	0.5	0.7	0.6	0.7	0.7	0.7
Vertical displ. at the transom	h_{2Pk-Pk}	m	N/A	0.60	N/A	N/A	N/A	N/A

Table 4. Results for the trial at sea state 3–4 (WMO), at 15 knots.

Parameter	Symbol	Units	Trial I	Trial II	Trial III	Trial IV	Trial V
Initial ship speed	V_0	kn	15	15	15	15	15
Ship draft at AP	TKA	m	2.0	2.0	2.0	2.0	2.0
Ship draft at FP	TKF	m	1.98	1.98	1.98	1.98	1.98
Ship heading	COG	°	205	130	270	310	345
Sea state	WMO	-	3–4	3–4	3–4	3–4	3–4
Waves heading	-	°	0	45	90	135	180
Average speed (SOG)	v	kn	14.9	15.5	15.9	15.8	15.7
Roll	Φ	°	1.0	2.2	2.7	2.7	1.8
Pitch	θ	°	0.9	1.5	1.9	1.3	0.8
Vertical accel. at wheelhouse	w'	m/s^2	0.4	0.9	0.5	0.4	0.3
Lateral accel. at wheelhouse	v'	m/s^2	0.2	0.6	0.7	0.6	0.4
Deck wetness	-	No. of occur./h	0	0	0	0	0
Slamming	-	No. of occur./h	24	20	0	0	0
Propeller emergence	-	No. of occur./h	0	0	0	0	0

Table 5. Results for the trial at sea state 3–4 (WMO), and speed of 27 knots.

Parameter	Symbol	Units	Trial I	Trial II	Trial III	Trial IV	Trial V
Initial ship speed	V_0	kn	27	27	27	27	27
Ship draft at AP	TKA	m	2.0	2.0	2.0	2.0	2.0
Ship draft at FP	TKF	m	1.98	1.98	1.98	1.98	1.98
Heading	COG	°	165	125	085	310	345
Sea state	WMO	-	3–4	3–4	3–4	3–4	3–4
Waves heading	-	°	0	45	90	135	180
Average speed (SOG)	v	kn	26.7	26.9	26.7	27.3	26.0
Roll	Φ	°	2.0	2.6	3.2	2.9	3.6
Pitch	θ	°	2.5	2.2	1.5	2.2	2.1
Vertical accel. (at wheelhouse)	w'	m/s ²	1.3	1.2	0.7	0.4	0.5
Lateral accel. (at wheelhouse)	v'	m/s ²	0.6	0.7	0.7	0.6	0.7
Deck wetness	-	No. of occur./h	33	0	0	0	0
Slamming	-	No. of occur./h	70	0	0	0	0
Propeller emergence	-	No. of occur./h	0	0	0	0	0

Tables 6 and 7 show the results of numerical calculations, based on strip theory and Jonswap spectra, conducted during the preliminary phase of ship design.

Measuring signal examples for the angles of pitching and rolling at $v = 15$ kn and wave heading = 45° are given on Figures 4 and 5 respectively.

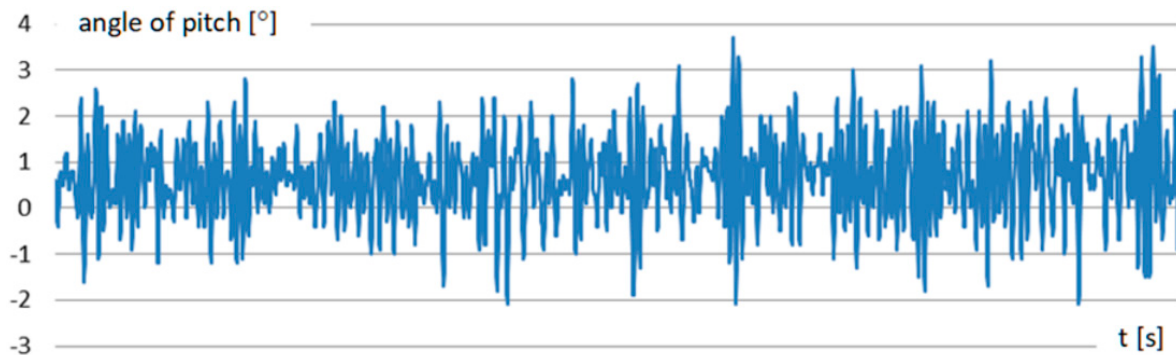
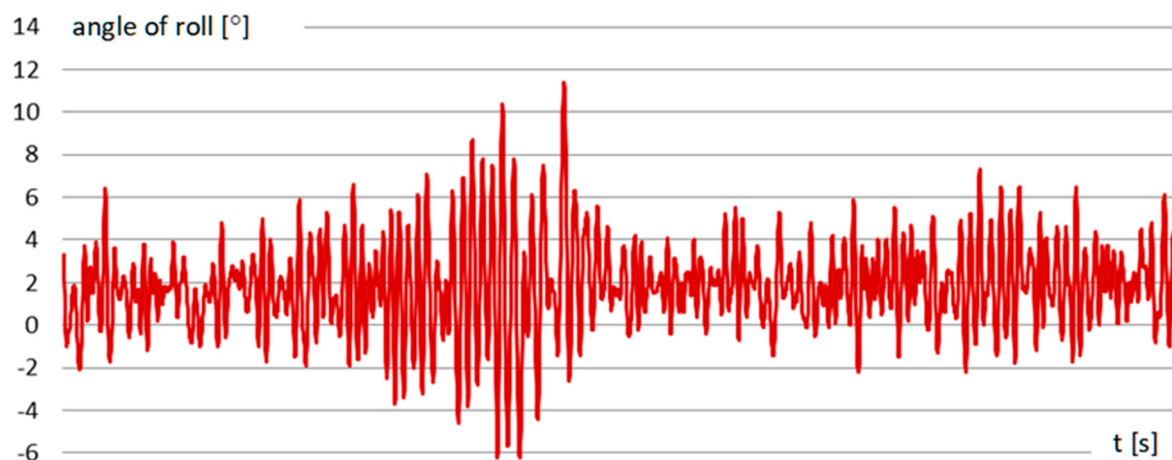
In further trials, the prototype of the vessel was tested at the higher sea states 4–5 (WMO), and the results obtained were more than satisfactory. Even in these sea state conditions, the RHIB could be successfully launched and recovered, and there was negligible loss of speed. Generally, the vessel demonstrated very good seakeeping characteristics.

Table 6. Results of numerical calculations for sea state 3–4 (WMO), and ship speed of 5 knots.

Parameter	Symbol	Units	Trial I	Trial II	Trial III	Trial IV	Trial V	Trial VI	Trial VII
Waves heading			0°	30°	60°	90°	120°	150°	180°
Average speed	v	kn	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Roll	Φ_{RMS}	°	0.0	3.52	7.15	9.01	12.60	4.59	0.0
Pitch	θ	°	1.21	1.29	1.31	0.57	1.18	1.28	1.2
Vertical accel. (at wheelhouse)	w'	m/s ²	0.348	0.435	0.675	0.788	0.451	0.106	0.063
Lateral accel. (at wheelhouse)	v'	m/s ²	0.0	0.866	1.633	2.004	2.609	0.508	0.0
Vertical displ. at the transom	h_{2Pk-Pk}	m	0.406	N/A	N/A	N/A	N/A	N/A	N/A

Table 7. Results of numerical calculation for sea state 3–4 (WMO), and ship speed of 15 knots.

Parameter	Symbol	Units	Trial I	Trial II	Trial III	Trial IV	Trial V	Trial VI	Trial VII
Waves heading			0°	30°	60°	90°	120°	150°	180°
Average speed	v	kn	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Roll	Φ_{RMS}	°	0.0	2.6	6.99	10.41	6.5	3.37	0.0
Pitch	θ	°	1.73	1.72	1.53	0.64	1.01	1.07	1.05
Vertical accel. (at wheelhouse)	w'	m/s ²	1.360	1.362	1.291	0.83	0.205	0.15	0.232
Lateral accel. (at wheelhouse)	v'	m/s ²	0.0	0.786	1.636	2.225	0.934	0.609	0.0

**Figure 4.** Measuring signal example—the angle of pitching at v = 15 kn and wave heading = 45°.**Figure 5.** Measuring signal example—the angle of rolling at v = 15 kn and wave heading = 45°.

5. Discussion

The presented seakeeping results and performances of the CPS show very good seaworthiness capabilities of the ship. The ship is fully operational at the mid sea state 4 (WMO), which was one of the main seakeeping criteria. When the crew had enough experience manipulating the RHIB, the RHIB could be launched and recovered even at the upper limit of sea state 4. During tests on higher sea states 5 (WMO), the ship showed reasonable seakeeping characteristics, a high level of reliability of all ship subsystems, and a low level of speed loss on waves. Considering some specific criteria that were exceeded (e.g., slamming at maximum continuous speed in a head sea), this was expected and does not mean that ship has unsatisfactory seakeeping performance. There were also some deviations in the angle of pitching at a wave direction of 0 and 45 degrees that were unsurprising due to the size of the ship.

Upon increasing ship speed from 5 to 15 knots (cruising speed), the seakeeping parameters changed as follows:

- Roll angle became lower for the wave headings 0° and 180° due to the hydrodynamic stabilization of ship, but it became higher for beam seas (90°).
- Pitch angle was generally higher, except for a wave heading of 0° .
- Vertical accelerations were higher for all wave headings.
- Lateral accelerations had a similar pattern to the rolling of the ship.

Upon raising the ship speed to maximum continuous, it can be observed that all seakeeping parameters rose significantly, and the highest rising rate was related to the vertical acceleration, slamming, and deck wetness, which was expected especially from the heading seas.

Comparing numerical calculations and full-scale test results, the following conclusions can be drawn:

- Numerical calculations showed much higher roll and lateral acceleration responses because the numerical model could not take into account the influence of viscous forces on ship roll by ship appendages such as bilge keels, stern trim plate, etc.
- Numerical prediction of pitch angle and vertical accelerations showed reasonable agreement.

Seakeeping is one of the most important characteristics of a ship, and there is a need to continuously and rigorously consider it throughout all phases of ship design. This was the case with the CPS; seakeeping was tested through numerical analyses, model tests, and finally, full-scale tests on the ship. Setting seakeeping requirements at an early phase of the project is crucial for successful ship design, and the results presented herein indicate that it is reasonable and useful to set these seakeeping requirements for patrol ships of the CPS' size, as it helps designers to satisfy them.

Author Contributions: A.L. contributed to the paper by establishing the concept of paper and definitions of research goals and aims. He participated in conducting the research, control of experiments, and data collection and integration. He wrote an initial paper draft including data and graphics design and presentation. V.S. contributed to the paper through its review, validation, and its final preparation for publication. He participated in the analysis of references dealing with this research area. He also did management and coordination of the research planning. He is responsible for the presentation and interpretation of the work. All authors have read and agree to the published version of the manuscript.

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Nomenclature

AP	Aft perpendicular
CMI	Croatian Meteorological Institute
COG	Course over ground
CPS	Coastal Patrol Ship
FOG	Fiber Optic Gyro
FP	Fore perpendicular
g	Acceleration of gravity (9.80665 m/s^2)
GPS	Geographical Positioning System
$H_{1/3}$	Significant Wave Height
MANPAD	Man Portable Air Defense
MoD	Ministry of Defense
N	The number of measured samples
NATO	North Atlantic Treaty Organization
RHIB	Rigid Hull Inflatable Boat
RMS	Root Mean Square
RPM	Rotation per Minute
SOG	Speed over ground

STANAG	Standardization Agreement
δ	Measured signal value
$\bar{\delta}$	Average of measured signal value

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