Design of a Self-Righting Pilot Boat of 9 m Length

Diseño de una lancha piloto autoadrizable de 9 m de eslora

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Abstract

Pilot service is the logistic activity provided to ships to facilitate the entry and exit in a specific port, which are knowledgeable about the area and the maneuvers to be performed. Currently the port of Cartagena de Indias is a strategic being in the Caribbean Sea, being located near the Panama Canal and in front of the crossroads of the main maritime routes of global trade. Where there is a high maritime traffic of merchant ships, which require a pilot service for entry and exit to the port, this service must be accompanied by a means to mobilize the pilot to the point of boarding the ship, serving as a logistical transport necessary to fulfill a role of comprehensive maritime security for the assistance of these ships that require the service to enter the port of Cartagena. Therefore, COTECMAR corporation has seen the need to have its own design for this type of vessel complying with all national and international regulations established, based on the classification society Bureau Veritas, and allowing self-righting in case of capsizing with the high speed of 27 knots for its approach to the authorized point to perform the maneuvers. This work presents numerical regressions, structural calculations, stability calculations, propulsion and generation design, general layout, seakeeping, and cost analysis.

Key words: Naval Engineering, Design, Pilotage, Self-righting, stability, seakeeping, regressions.

Resumen

El practicaje es la actividad logística que se brinda a los buques para facilitar el ingreso y salida en un puerto especifico, que son conocedores de la zona y las maniobras a realizar. Actualmente el puerto de Cartagena de Indias es estratégico en el mar Caribe, al estar ubicado cerca al canal de Panamá y frente al cruce de las principales rutas marítimas del comercio global. Donde hay un tráfico marítimo alto de buques mercantes, los cuales requieren un servicio de piloto práctico para la entrada y la salida al puerto, este servicio debe estar acompañado de un transporte para movilizar al piloto hacia el punto de embarque en el buque, sirviendo como transporte logístico necesario para cumplir un rol de seguridad integral marítima para la asistencia de estos buques que requieran el servicio para ingresar al puerto de Cartagena. Por eso, COTECMAR ha visto la necesidad de tener un diseño propio de este tipo de buques cumpliendo con todas las normativas nacionales e internacionales establecidas, basándose en la sociedad de clasificación Bureau Veritas y que permita autodrizarse por sí solo en caso de volcamiento con la alta velocidad que maneja de 27 nudos para su aproximación al punto autorizado para realizar las maniobras. Este trabajo presenta regresiones numéricas, cálculos estructurales, cálculos estabilidad, diseño de propulsión y generación, disposición general, comportamiento en la mar y análisis de costos.

Palabras claves: Ingeniería Naval, Diseño, Practico, Autoadrizable, estabilidad, Comportamiento en la mar, regresiones.

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Introduction

This work focuses on designing a vessel to transport pilots in the port of Cartagena de Indias [1]. It emphasizes the crucial role of transportation in enabling pilots to move efficiently from the dock [2] [3], where they board, to merchant ships (see Fig. 1). Such vessels play a vital role in maritime security by assisting ships entering the port [4]. Designing these vessels [5] involves analyzing variables to match the mission and required functions.

The study specifically examines the design of a self-righting pilot boat, 9 meters in length, capable of reaching speeds of 27 knots (85% MCR). Data from similar vessels were analyzed to determine the main dimensions through statistical regression. These dimensions informed the hull shapes, ensuring they meet all operational requirements for the vessel's mission.

Fig. 1. Practical pilot boarding.

Source: AMURA.

Once the hull shapes were generated, the hydrostatic characteristics were determined using the Maxsurf Modeller program [6]. Resistance values were calculated using Maxsurf Resistance to predict power requirements and select the optimal propulsion and generation systems, as well as a suitable steering system. A structural analysis was conducted to ensure the vessel could withstand anticipated loading conditions, and stability analysis included assessing the vessel's self-righting capability and behavior at sea. Additionally, an economic feasibility analysis of the project was carried out based on classification society guidelines [7] [8] and relevant international and national standards.

Parent vessel

The dimensions of the preliminary parent vessel design were based on the KRVE 58 (see Fig. 2), which shares characteristics similar to those proposed at the outset of the design process. The KRVE 58 is a proven aluminum crewtender designed for transporting crew, pilots, and personnel. It features a Deep-V hull with reinforced sides, an enclosed main deck, and an enclosed wheelhouse. This established crew concept has been in reliable service for years in the port of Rotterdam, which, like Cartagena, is among Europe's most significant ports. These vessels are utilized extensively for transporting pilots and personnel, averaging 4,000 operational hours per year per boat. The design of the KRVE 58 is specifically tailored for the demanding conditions of Rotterdam harbors and is noted for its robustness [9].

Fig. 2. KRVE 58, Preliminary Crewtender Characteristics.

v	32	kn
L_T	8,95	*m*
L_{FL}	7,8	*m*
B	3,1	*m*
T	0,7	*m*
Δ	9,5	*ton*
P	455	*kW*
C_{FL}	0,78	*N/A*

Source: KRVE & Habbeke, 2008.

Additionally, various pilot boats worldwide were selected from the Significant Small Ships journal (2020) [10], which share similar characteristics with the base vessel. Main dimensional characteristics were derived through regression analysis to establish the foundational values upon which the project is based. This approach ensured that the final parameters of the boat were verified to fall within established ranges.

Dimensions

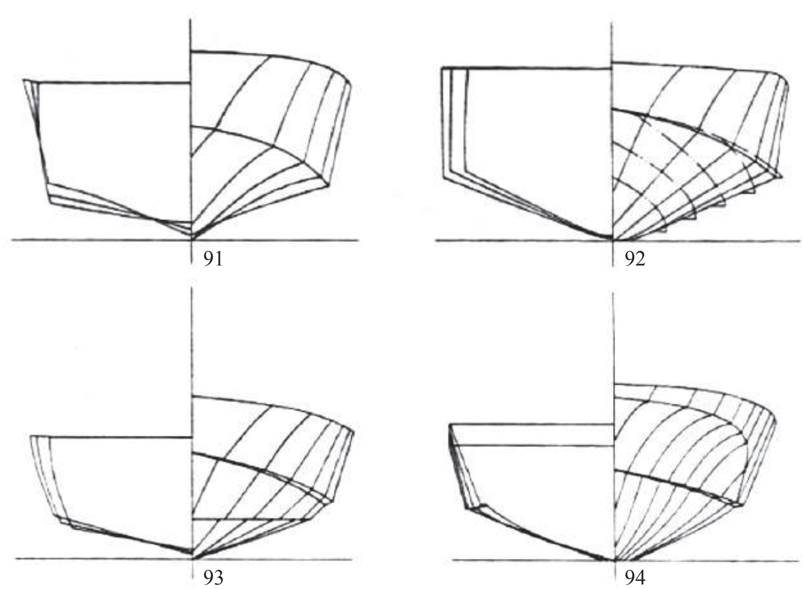
To achieve appropriate hull shapes [11], the design considered the operational specifications and requirements, focusing on facilitating planing [12]. Planing vessels utilize hulls that enable them to rise above the water's surface, generating dynamic lift and reducing resistance caused by wave formation. This effect requires a hull design with V-shaped frames, straight longitudinal lines, minimal bow inclination, and a transom stern that avoids excessive convex shapes to promote smooth water flow separation. This design increases stern volume, counteracting suction effects from water flow.

These characteristics are crucial for overcoming initial resistance caused by wave formation crests. As the vessel transitions into a planing state, frictional resistance becomes predominant, underscoring the importance of minimizing wetted surface area through structural features such as chines, anti-spray measures, and bottom strakes [13]. These elements collectively optimize flow separation and reduce frictional resistance during operation.

To determine the beam of the project, a scatter plot with smoothed lines was generated using the overall length (LT) and beam (B) values from the vessel database. This plot identifies the line that best fits the LT/B ratio. The R-squared (R^2) value indicates how well the data points fit this line, with higher values indicating a better fit. To ensure greater precision, the R^2 value was adjusted by excluding vessels that deviated significantly from the trend line, minimizing discrepancies in the index..

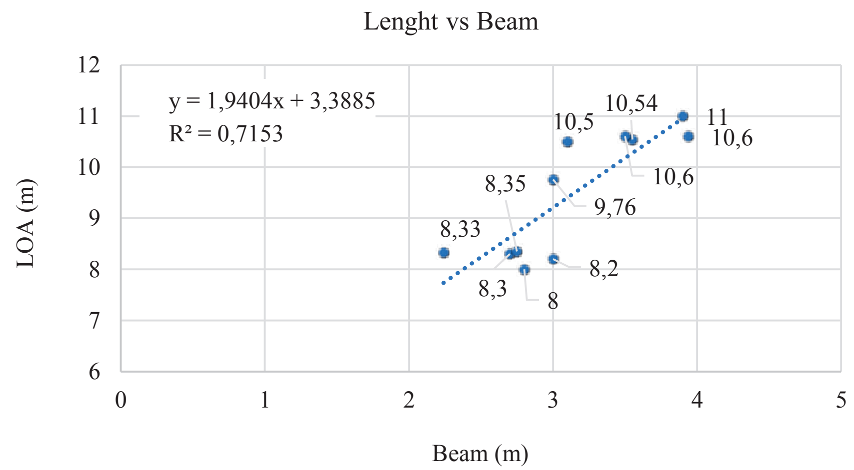
Following the same methodology and using a beam value of 2.89 meters, Equation (1) was employed to calculate the various dimensions.

Fig. 3. Hull shapes of high-speed craft.



Source: Gonzalez, 1991.

Fig. 4. Length vs Beam.



$$B = \frac{L_T - 3.3885}{1.9404} = 2.89m \quad (1)$$

To determine the draft, the same method was applied using regressions of beam (B) against draft (T), as shown in Fig. 5. Additionally, to validate this result, a second regression was conducted using overall length (LT) and beam (B), yielding a draft value of 0.66 meters.

To estimate the block coefficient, an arithmetic mean was calculated using all values from Equation (1).

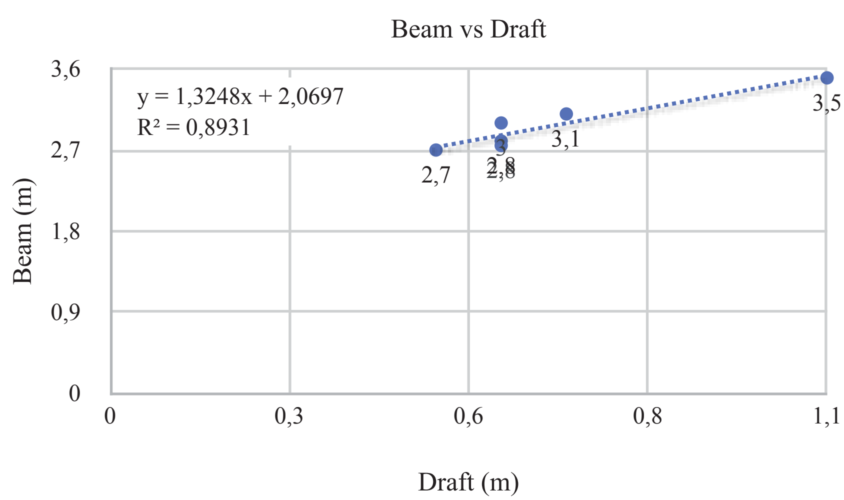
$$X = \frac{\sum_{i=1}^{N} C_{Bi}}{N} = 0.5075 \approx 0.51 \quad (2)$$

Once the displacement of the vessel was obtained.

$$\Delta = Lwl \cdot B \cdot T \cdot \rho \cdot C_B = 7.8 \cdot 2.89 \cdot 0.66 \cdot 1.025 \cdot 0.51 = 7.725\ ton \quad (3)$$

The calculation was performed to determine the deadweight and lightship (LS). The lightship refers to the total weight of the vessel once construction is complete and it is ready to sail, excluding cargo, passengers, stores, consumables, and crew; but including fluids in equipment and piping. The remaining weight constitutes the deadweight, which is the difference between the displacement at a specific load line or draft and the displacement of the vessel in lightship condition [14].

Fig. 5. Beam vs Draft.



Within the deadweight, Marine Diesel Oil (MDO) fuel weight and volume are estimated using equations (2) and (3), along with lubricant weight from equation (4), and crew weight. This collective sum yields the deadweight in equation (5), which subsequently determines the displacement at a specific draft in equation (6).

$$\text{Fuel weight } (P_{DO}) = \frac{\text{Hours of use} \cdot C_e \cdot BHP \cdot MCR \cdot 1{,}1}{1000} = 0{,}55 \text{ ton} \quad (4)$$

$$\text{Fuel volumen } (V_{DO}) = \frac{P_{DO}}{\rho_{DO}} = 0{,}62\ m^3 \quad (5)$$

$$\textit{Lubricant weight}(P_{LO}) = 0.04 \cdot P_{DO} = 22{,}1\,Kg \quad (6)$$

$$LS = P_{Consumption} + P_{pas.trip} = 1{,}18\,ton \quad (7)$$

$$PR = \Delta - PM = 7{,}725 - 1{,}18 = 6{,}54\,ton \quad (8)$$

To calculate the fuel weight, we use data from the parent vessel where the main engine power is *BHP* = 455 *kW* and specific fuel consumption: *Ce* = 175.63 *g/kW-h*, with an autonomy of 200 nautical miles operating at 85% of Maximum Continuous Rating (MCR), as specified in the project parameters, plus a 15% margin.

The calculation for fresh water for the cooling system of onboard equipment is initially set at 100 liters. For provisions, a daily consumption rate of 5 kg per person is chosen. Given that the vessel will not operate more than one day away from port, a total weight of 80 kg per person is estimated for the 6 crew members, resulting in a total crew weight of 480 kg.

Forms

The shape generation defined the geometric model, adhering to form coefficients and shapes derived from the sizing process. The Maxsurf Modeller program was utilized to adjust the shapes for a planing boat. A parametric transformation was employed to achieve the specified and defined dimensions, based on selecting a hull that meets the required criteria. This process involved modifying and adapting the outcome of the parametric transformation. The resulting dimensions are presented in Table 1.

Table 1. Hydrostatic parameters obtained by Maxsurf Modeller.

Parameters	Pilotboat	Units
Δ	6,295	Ton
V	6,142	m^3
T	0,66	M
LT	9	M
LWL	8,234	M
B	2,89	M
BWL	2,238	M
CP	0,741	
CB	0,505	
Cwl	0,802	
CM	0,682	
LCB	3,222	m (from forward)
LCF	3,458	m (from aft)

The area curve depicts the distribution of frame areas along the length, thereby determining the displacement throughout the vessel's length. Additionally, it facilitates the identification of the hull's center of gravity, which is pivotal for the vessel's stability and performance.

Fig. 6 illustrates the boat's area curve, showcasing a characteristic shape typical of fast vessels known for their favorable seakeeping qualities [15]. This includes a mirrored stern and a forward body that occupies more than half of the vessel's length, with minimal aft body presence.

Fig. 6. Area curve of pilot boat. By Maxsurf Modeller, 2022.

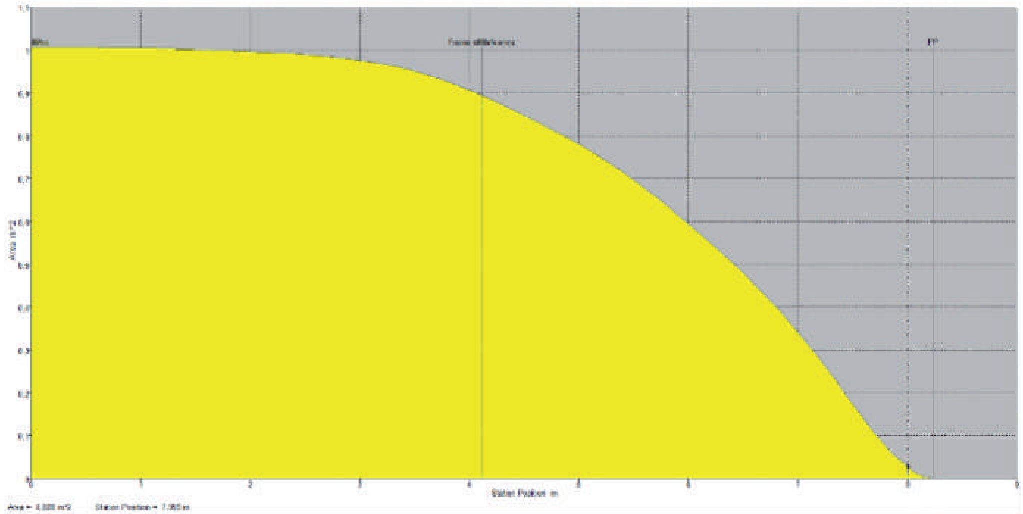
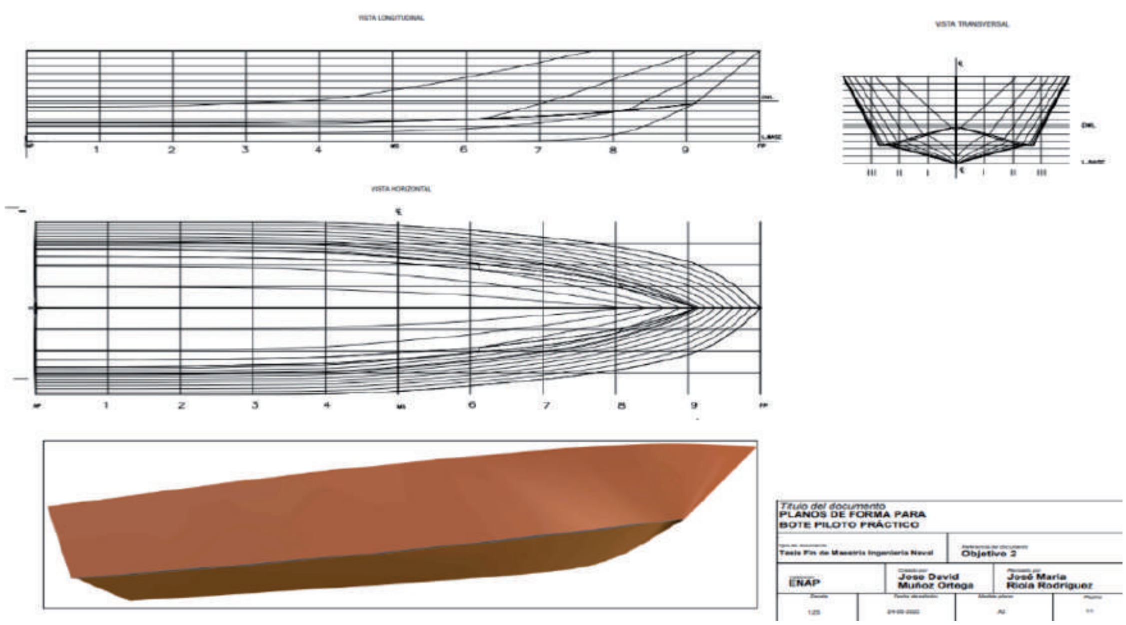


Fig. 7. Plane of forms.



Design of propulsion system

Using the Maxsurf Resistance program, resistance prediction was conducted employing two methods: the Compton method, suitable for displacement or semi-displacement vessels like motorboats or pleasure craft, and the Savitsky method, commonly used for planning boats operating in planing conditions [16]. These predictions covered speeds ranging from 0 to 27 knots.

The results were obtained for the bare hull, excluding appendages or equipment weights, and assumed free-water navigation conditions. Fig. 8 illustrates the resistance as a function of speed. Through this analysis, the hump speed, approximately 10 kn, was determined.

Using equation (9), the brake power (BHP) can be calculated, incorporating a mechanical efficiency ranging from 0.94 to 0.96, with an average of 0.95.

Fig. 8. Resistance vs speed.

Fig. 9. Power vs speed.

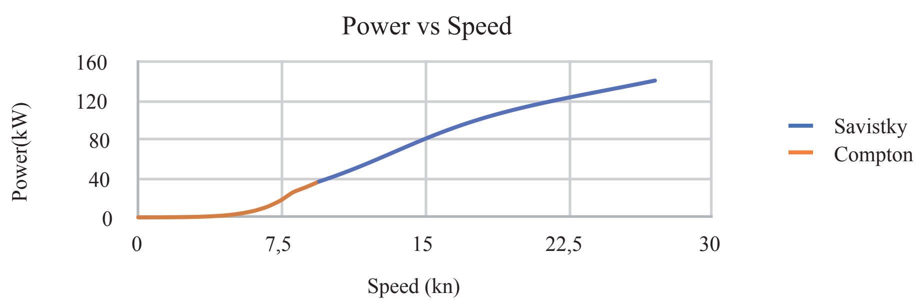


Table 2. Results obtained by Maxsurf Resistance.

RT	11 kN
EHP	140,42 kW

The propulsive efficiency, derived from waterjet specifications, is set at 0.9.

$$BHP = \frac{140{,}42}{0{,}9 \cdot 0{,}95} = 164{,}23\ kW \tag{9}$$

As previously mentioned, the vessel is designed to achieve a maximum speed of 27 knots at 85% of its Maximum Continuous Rating (MCR), with an additional 15% service margin. Therefore, the power is defined as follows:

$$BHP_T = \frac{164{,}23 \cdot 1{,}15}{0{,}85} = 222{,}2\ kW \tag{10}$$

As the analysis was made with the bare hull, the engine power is 111.1 kW for each shaft line, it is estimated that the power to be developed for each shaft line will increase to approximately 200 kW.

Choice of propulsion system

The chosen steering system for the practical boat will be a waterjet [17], which will be coupled with an electric motor. This choice is advantageous for improved maneuverability, high-speed navigation, and reduced noise and vibrations. With an effective power requirement of 140.42 kW, and considering the boat will have two thrusters, each waterjet must deliver a minimum of 120.21 kW of power.

Upon analysis, both the HJ241 and HJ212/213 models meet the minimum power requirement of 260 kW, as indicated in Figure 10. The HJ241 model is selected due to its lower operational revolutions per minute (rpm), ensuring compatibility with the electric motor coupling.

When selecting an electric motor for marine propulsion, it is essential to consider that electric motors typically operate at lower rpm ranges compared to waterjets. Among the available types, 2-pole motors offer the widest range of rpm capabilities, making them the most suitable for integration with the chosen waterjet system.

Fig. 10. HamiltonJet Catalog Series 80 to 900 kW.

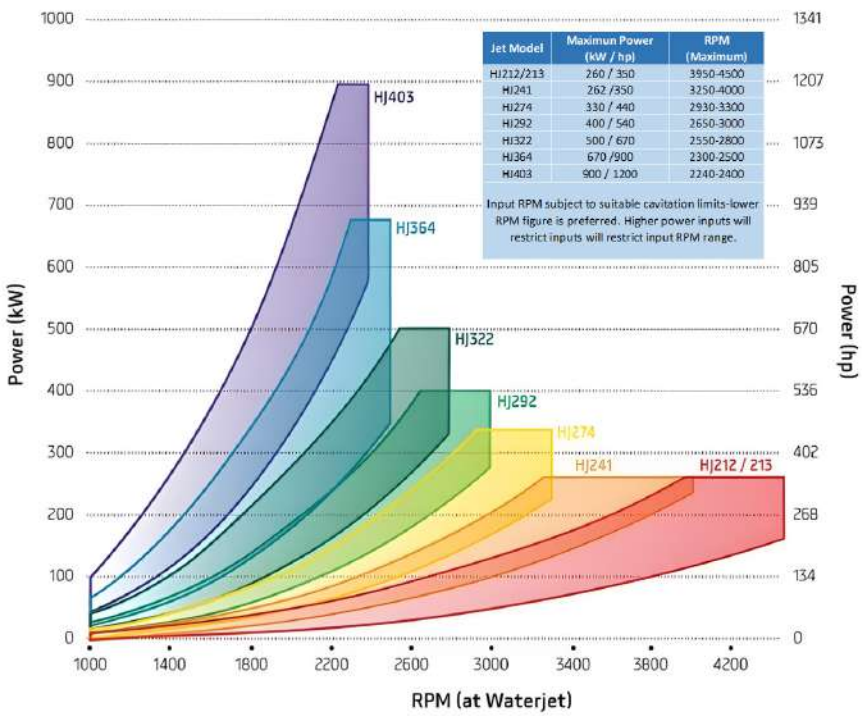
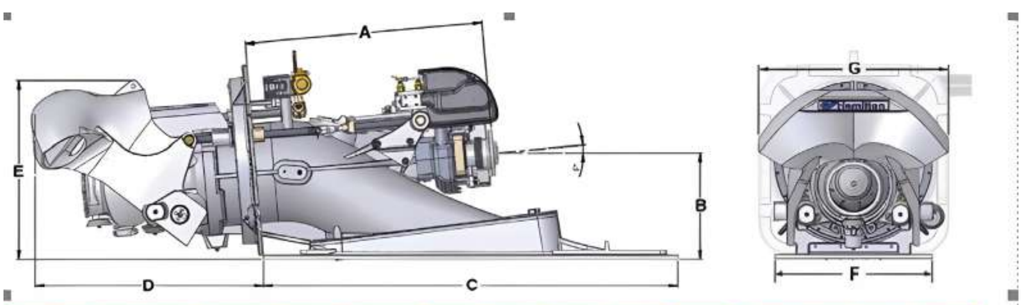


Fig. 11. HamiltonJet Catalog Series 80 to 900 kW.



Jet Model	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)	F (mm)	G (mm)	Intake Block (kg / lbs)	Dry Weight (kg / lbs)	Entrained Water (kg / lbs)
HJ212	450.3[a]	252	762	609	440	386	450	7 / 15.4	75 / 165	17 / 37
HJ213	413	249	762	609	420	386	450	7 / 15.4	84 / 185	17 / 37
HJ241	424	284	829	705	491	451	502	10 / 22	104 / 229	26 / 57
HJ274	570	302	1100	710	548	470	608	22 / 48.5	152 / 335	35 / 77
HJ292	681	330	1180	750	550	495	608	26.4 / 58	187 / 412	45 / 99
HJ322	866	371	1380	835	637	550	680	37 / 82	260 / 573	62 / 137
HJ364	937	420	1634	901	709	621	747	62 / 137	408 / 899	79 / 174
HJ403	1053	474	1723	1080	752	690	904	72 / 159	641 / 1407	110 / 243

Source: Hamilton, 2022.

Fig. 12. W22 IE3 Premium efficiency engine.

Source: NEMA, 2022

Power generation and distribution

For the selection of the generator set, the initial electrical balance must take into account the estimated electrical power demand (kW) required by various auxiliary systems. This preliminary assessment is crucial and will be based on information provided by the project manager, data from similar vessels, and research from the "Universidad Politécnica de Madrid."

To proceed, a table should be created listing the planned consumers and analyzing the varying load demand scenarios corresponding to each operation mode established for the vessel. This table will help outline the comprehensive electrical requirements necessary for effective generator set selection and integration into the vessel's electrical system.

The apparent power calculation is essential for selecting the appropriate generator set for each consumer onboard. The preliminary electrical balance will provide estimated values for active power (kW), apparent power (kVA), and reactive power (kVAR) under various electrical load conditions.

In this calculation, an additional margin of 20% has been factored in to account for losses and equipment not initially considered. This ensures that the generator set chosen can reliably meet the vessel's electrical demands, including unexpected loads and operational contingencies.

System	Consumer	#	Unit power (kW)	Total output	Power demanded (kW)	FP
Propulsion System	Starting Equipment	2	0,8	0,93	0,86	0,8
	Drive Motor	2	200	0,97	206,19	0,93
Steering System	Servomotor	2	10	0,98	10,20	0,92
Fuel System	Racking Pump	2	0,2	0,98	0,20	0,92
	Feed Pump	2	0,15	0,98	0,15	0,92
	Circulation Pump	2	0,15	0,98	0,15	0,92
Cooling System	Cooling Pump	1	8	0,98	8,16	0,92
Ventilation System	MR fan	2	0,2	0,98	0,20	0,92
	MR exhaust fan	2	0,15	0,98	0,15	0,92
Ballast System	Ballast Pump	1	0,29	0,98	0,30	0,93

Bilge and bilge system	Bilge Pump	3	0,72	0,98	0,73	0,93
	MR Bilge Pump	1	1,44	0,98	1,47	0,93
	Emergency Bilge Pump	1	0,72	0,98	0,73	0,93
Fresh Water System	FW pump	1	0,04	0,98	0,04	0,93
Grey and Black Water System	Black Water Pump	1	0,09	0,98	0,09	0,93
Fire Fighting System	Fire Fighting alarms	1	0,1	0,93	0,11	0,8
	Fire Fighting Systems	2	0,7	0,93	0,75	0,8
Lighting System	Navigation Lights	1	0,02	0,93	0,02	0,8
	Internal Lighting	1	0,73	0,98	0,74	0,8
	External Lighting	1	0,915	0,98	0,93	0,8
	Emergency Lighting	1	0,33	0,98	0,34	0,8
Enabling System	Hvac	1	0,31	0,98	0,32	0,8
Navigation and Communication System	Navigation Equipment	1	0,8	0,93	0,86	0,8
	Internal com.	1	0,4	0,93	0,43	0,8
	Outer com.	1	0,4	0,93	0,43	0,8
Mooring System	Winch	1	0,23	0,98	0,23	0,93

Table 3. The preliminary electrical balance.

	Navigation	Maneuvering to the Vessel	Maneuvering berthing and departure
Apparent (kVA)	460,78	396,79	323,49
Active (kW)	428,02	368,96	300,58
Reactive (kVAr)	170,65	145,98	119,56

For selecting the power plant, adherence to level 3 or TIER III emission standards is crucial due to regulations governing SOx and NOx emissions under the MARPOL Convention. Caterpillar has been chosen for its accessibility and reputation for providing top solutions in power generation. Specifically, the CAT C9.3 ACERT [19] model has been selected as it meets these stringent emission requirements and is well-established in studies for fast boats and vessels of similar class.

This decision ensures compliance with environmental regulations while also meeting the performance demands expected for the vessel.

Table 4. Calculated operating speeds for CAT 250 kW engine.

	Power (kW)	Navigation	Boarding and landing	Berthing and departure
Configuration	250	87%	75%	61%

Fig. 13. CAT 9.3 ACERT TM" Marine Generator Engine.

Source: CAT.

The operational regimes for the engine configuration 2x250 have been analyzed as shown in Table 4.

Structural design

Aluminum alloy AA5083 H321, chosen for the boat, is highly favored in marine applications for its excellent resistance to intergranular corrosion in seawater.

Table 5. Mechanical properties of alloy 5083 H321.

Yield stress	228 Mpa
Tensile stress	317 Mpa
Young's modulus	70,3 Gpa
Density	2,66 g/cm^3
Poisson's coefficient	0,3

According to Bureau Veritas [20], the heeling length is defined as the horizontal distance measured at the waterline of the heeling draft or summer float, extending from the bow to the stern perpendicular. This length must align with the length between perpendiculars, ideally falling between 96% to 97% of the waterline length for the specified draft.

For the pilot boat, where the waterline length is equivalent to the length between perpendiculars, measured at 8.234 meters, the scantling dimensions will be defined accordingly:

Table 6. Scantling dimensions.

Scantling length (Le)	7,9 m
Scantling beam (Be)	2,238 m
Scantling draft (Te)	0,66 m
Scantling depth (He)	1,5 m

It is necessary to calculate the bending moments and shear forces to which the vessel will be subjected.

Table 7. Bending moments and shear stresses..

		Sheer	Damage
Still water	Bending moment (kNm)	0	10,39
	Shear stress (kN)	0	5,05
Induced by waves	Bending moment (kNm)	-10,39	8,31
	Shear stress (kN)	-31,16	27
Load induced	Bending moment (kNm)	-133,45	133,45
	Shear stress (kN)	-51,86	51,86

The calculation of pressures used to verify the scantling of the vessel's plates and structural stresses aims to determine maximum parameters that adhere to the project's requirements. Bureau Veritas [20] specifies the following criteria for hull pressures:

- Hydrostatic pressures *(Ph)*: Generated by sea pressure in both swell and calm waters.
- Hydrodynamic pressures *(Pw)*: Resulting from ship movement, including functional side impacts for plate and secondary element calculations, bottom impacts for hull bottom structural elements, and pressures from pounding, crucial for planning hull structural elements.
- Internal local pressures *(Pi)*: Induced by internal loads within the vessel.

With the results obtained previously on the resistance that the ship's structure must have with respect to hydrostatic and hydrodynamic pressures, the scantling of the structure is defined.

Bureau Veritas [20] conducts calculations to determine the minimum thickness required for each structural component based on local loads. The scantling of plates, primary, and secondary reinforcements is defined in accordance with the NR600 R04 E standard:

- Bottom structure.
- Side structure.
- Deck structure.
- Transverse and longitudinal bulkhead structure.

Costs

One of the critical aspects for completing the project successfully is its feasibility, particularly in evaluating the acquisition costs for constructing and operating the vessel [21]. These costs must align with market conditions and facilities. It's essential to seek technical design solutions that do not increase costs yet still attract shipowners. The project's feasibility also depends on aligning construction costs at the shipyard [22], which benefits from the difference between construction costs and the agreed-upon client price. Thus, generating economic benefits for the shipowner is crucial for ensuring profitability.

To estimate the cost of materials and equipment, three procedures will be considered:

- Experimental formulations
- Data obtained from equipment and system manufacturers.
- Data obtained from projects of similar vessels.

Fig. 14 illustrates the percentage breakdown of costs associated with the project, providing an approximate analysis for materials and equipment expenses.

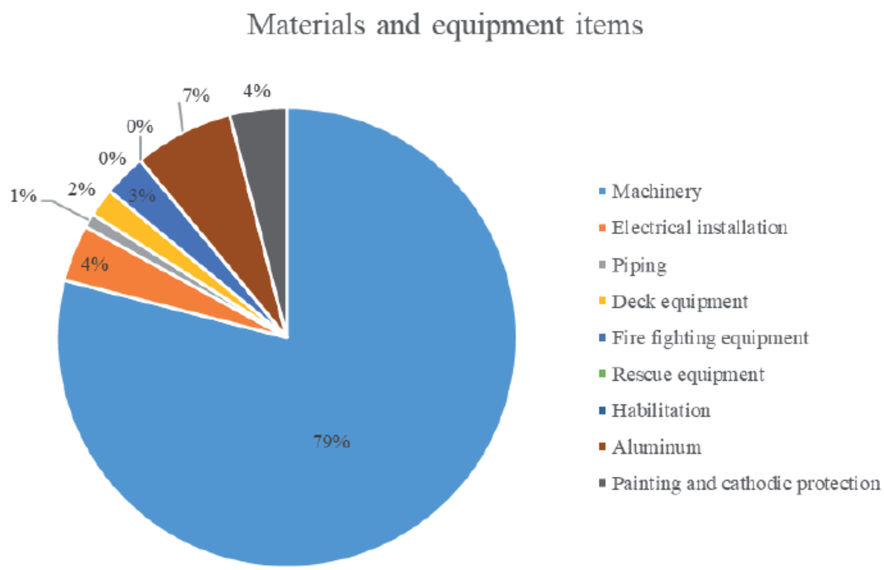
Table 9. Costs.

Equipment	Costs (€)
Materials and equipment	400.000 €
Labor	200.000 €
Overheads	100.000 €
Total cost	700.000 €

Table 8. Bending moments and shear stresses.

		Bottom	Side	Main Deck	Engine room deck	Watertight Bulkheads	Superstructure
Hydrostatic		11,46	5,88	5,88	-	-	-
Hydrodynamic		132,27	38,5	-	-	-	38,5
Internal	Displacement	-	-	-	24,1	5,52	-
	Planing	-	-	-	23,82	5,06	-

Fig. 14. Materials and equipment items.



Conclusions

- A boat has been designed for practical piloting to establish a domestic design for potential construction within the country, aiming to reduce reliance on imported vessels. The design includes its form, general layout, and structural analysis at the conceptual stage. Naval architecture calculations are now necessary to analyze stability in planing and semi-displacement conditions, as well as to assess self-righting parameters and sea behavior characteristics specific to its V-shaped hull.

Fig. 15. Pilot boat.

Source: DAMEN [23].

- For optimal hydrodynamics, the bow shapes are designed to enhance sea-keeping qualities, while the stern provides sufficient lift for navigation. Once the vessel transitions into planing, resistance primarily arises from friction. Therefore, incorporating a hard knuckle facilitates flow separation, significantly reducing wetted surface area and enhancing stability. Additionally, the hull bottom features strakes to separate flow, minimizing frictional resistance, reducing spray for a more comfortable sailing experience, and enhancing speed by decreasing pressure and viscosity components of forward resistance.

- When analyzing the operational regimes of the generator plant configuration, it is apparent that the maneuvering time for docking and launching is close to the lower allowable limit. However, this maneuvering time is considered insignificant. The use of two generators allows for better weight and load distribution to meet the boat's requirements, facilitating the configuration and layout in the engine room.

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