Ocean Engineering 266 (2022) 112242

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

A comprehensive stepped planing hull systematic series: Part 1 - Resistance test

Luigi Vitiello [a,*], Simone Mancini [b], Rasul Niazmand Bilandi [c], Abbas Dashtimanesh [d], Fabio De Luca [a], Vincenzo Nappo [e]

[a] Department of Industrial Engineering, University of Napoli" Federico II", 80125, Napoli, Italy
[b] Department of Hydro and Aerodynamics, FORCE Technology, 2800, Kgs. Lyngby, Denmark
[c] Estonian Maritime Academy, Tallinn University of Technology, 11712, Tallinn, Estonia
[d] Department of Engineering Mechanics, School of Engineering Science, KTH Royal Institute of Technology, 114 28, Stockholm, Sweden
[e] MV Marine S.r.l, Italy

ARTICLE INFO

Keywords:
Stepped planing hull
Towing tank tests
Hull systematic series
CFD benchmark

ABSTRACT

This work addresses the experimental study of a new systematic series of stepped planing hulls. Indeed, the interest in the stepped planing hulls is constantly growing, both in the industrial/commercial and academic fields. Designers and boat builders have been orienting toward the multi-stepped hulls solution to ensure good dynamic stability, reliable seakeeping and operability at high speeds. However, there is a lack of a comprehensive stepped hull systematic series with various step configurations including a forward V-shaped step, as typically used on modern boats. For the abovementioned reasons, a systematic series of eight different models of stepped hulls have been developed and tested. The towing tank tests have been carried out at the naval basin of the *Università degli Studi di Napoli "Federico II" Dipartimento di Ingegneria Industriale (DII)* in calm water at different speeds ($Fr_\nabla = 1.077$–6.774) and for three different static trim conditions. All models are built with a transparent bottom to visualize the wetted surface and the eventual development of vortices generated behind the step. The eight models are defined by modifying three significant design parameters for stepped hulls (i.e. the number of steps, longitudinal step position, and step height).

1. Introduction

Nowadays, the design of high-speed craft is strongly conditioned by two anti-synergetic needs: the first is the reduction of fuel consumption and improvement of the speed, and the second is the improvement of comfort on-board (De Luca and Pensa, 2017). To reach a balance between these needs, it is necessary to study the effects of various parameters on hull resistance as well as seakeeping and manoeuvring motions. Several researchers have tried to develop a systematic series of planing hulls (Clement and Blount, 1963; Keuning and Gerritsma, 1982; Keuning et al., 1993; Kowalyshyn and Metcalf, 2006). However, these systematic series not only have not been developed for energy efficiency purposes but also their seakeeping and maneuvering behaviour have not been analysed in most of the cases. Just two systematic series report some considerations related to energy efficiency, specifically the Naples systematic series (De Luca and Pensa, 2017) and Southampton systematic series (Taunton et al., 2010). However, Naples systematic series is mainly suitable for the low range of speeds in the planing regime. The Southampton systematic series, instead, based on the stepped hull form, was tested at a wide range of speeds.

Stepped planing hulls have sparked up a tremendous interest in recent years, and few researchers have tried to provide an understanding of their performance in smooth/rough water (Niazmand Bilandi et al., 2020a&2021). These vessels are used for a wide range of purposes (e.g. military & patrol, fishing, and leisure). However, due to the lack of available data about systematic studies of the stepped hulls, there still is a non-trivial question for the designers to define the height, the position, and the shape of the step(s). Indeed, there are only a few studies that have tried to measure the performance of stepped planing hulls in calm water and in waves.

From 1960 to 1990, a few authors (Clement and Pope, 1961; Moore, 1967; Clement and Desty, 1980) had some contributions in the performance prediction of stepped hulls. Clement and Koelbel (1991) studied the effects of the step design on the performance of planing boats. Clement and Koelbel (1992) and Clement (2003) published two reports

* Corresponding author.
E-mail address: luigi.vitiello@unina.it (L. Vitiello).

https://doi.org/10.1016/j.oceaneng.2022.112242
Received 16 February 2022; Received in revised form 28 July 2022; Accepted 7 August 2022
Available online 30 October 2022

Nomenclature

A_T	Area of transom (m^2)
A_X	Area of maximum transvers section (m^2)
B	Breadth (m)
B_C	Maximum chine breadth (m)
B_r	Bias systematic uncertainty
B_{TC}	Chine breadth at transom (m)
c_j	Basis constant
Fr_∇	Volumetric Froude number
Fr_L	Froude number based on L_{WL}
Hs	Height of the step (mm)
K	Constant value
LSP	Longitudinal Step Position (mm)
L_{WL}	Waterline Length (m)
L_{OA}	Length overall (m)
Ns	Number of steps
P_r	Precision uncertainty
RT_M	Total model resistance (N)
S	Wetted surface (m^2)
$SDev_j$	Standard deviation of jth run
U	Uncertainty
U_r	Total uncertainty
U_k	k-input parameter uncertainty
V	Hull speed (m/s)
Z_G	Sinkage (m)
Z_O	Sinkage referred to the O of the coordinate system (m)
∇	Displacement volume (m^3)

Greek symbols

A	Constant value
Δ	Displacement weight (N)
ρ	Density (kg/m^3)
Λ	Expansion coefficient
$\Delta\tau$	Time step (s)
τ	Dynamic trim angle (deg)

Acronyms

CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
DAQ	Data acquisition device
DT	Down Thrust
EFD	Experimental Fluid Dynamics
FRP	Fibre Reinforced Plastic
ITTC	International Towing Tank Conference
LCB	Longitudinal Centre of Buoyancy
LCG	Longitudinal Centre of Gravity
PVC	Polyvinyl Chloride
RIB	Rigid Inflatable Boat
RSS	Root Sum Square
UA	Uncertainty Analysis

in which an efficient configuration of one-stepped hulls has been suggested.

In addition to those initial studies, Taunton et al. (2010, 2011) were one of the pioneers who carried out experimental work on two-stepped hulls. They provided a set of towing tank data that were suitable for the validation of numerical and mathematical models. Vitiello et al. (2012) also performed model experiments and sea trial tests on a two-stepped hull in the towing tank of the *Università degli Studi di Napoli "Federico II"*. White et al. (2012) have performed some experiments on two-stepped hulls and concluded that stepped hulls may improve the powering performance of planing boats only under certain conditions. Lee et al. (2014) have studied two-stepped hulls by various transverse step configurations and displacements. They observed that in all cases, two-stepped hulls led to a resistance reduction. Some researchers have also tried to develop numerical methods for calm water performance prediction of stepped hulls. Brizzolara and Federici (2013) used Computational Fluid Dynamics (CFD) to investigate the resistance reduction in stepped planing hulls. Sheingart (2014) investigated the influence of a cambered-shaped step on the performance of V-stepped planing hulls using a numerical method. Dashtimanesh et al. (2018) tried to develop a numerical setup based on the morphing mesh approach in CD-Adapco StarCCM+ in which the two-stepped planing hull was free to heave and pitch.

Moreover, some researchers have developed mathematical models to evaluate the stepped hulls performance. Svahn (2009) used the existing wake formulas (Savitsky and Morabito, 2010) and extended Savitsky's (1964) method for performance prediction of one-stepped hulls. Danielsson and Strųmquist (2012) tried to develop Svahn's model for two-stepped hulls. However, they failed in the implementation of the wake formula for the two-stepped hull because of its range of applicability and other issues. Accordingly, Dashtimanesh et al. (2017) assumed a Linear Wake Pattern and presented a simplified mathematical model for performance prediction of double-stepped planing hulls based on Savitsky's formulas. Then, Niazmand et al. (2019 and 2020b) developed a mathematical model based on the 2D + T method for the performance prediction of two-stepped hulls.

It is worth mentioning although there are many studies about calm water performance of stepped hulls, the effects of step height and position, the number of steps and step shape are still unknown. The focus of most of the previous studies has been on transverse steps while transverse steps are not the case suitable for industrial/commercial applications where forward or backward V-shaped steps, instead, are largely implemented. To tackle this challenge, towing tank measurements can be used to provide an early understanding of the performance of boats with various step shapes, numbers, heights and positions.

Therefore, in the current work, an experimental campaign, conducted on a new systematic series of stepped hulls with various step configurations, has been designed at the naval section of *Dipartimento di Ingegneria Industriale (DII)* of the *Università degli Studi di Napoli "Federico II.* This study aims to measure resistance, trim, sinkage and wetted surface for eight stepped hull models with a systematic variation of relevant design parameters, i.e. step numbers, step height, and longitudinal step position in three different starting trim conditions. All models are built with a transparent bottom hull to visualize the complicated fluid flows underneath the stepped hulls. All experimental tests have been performed in calm water and it has been tried to capture the wetted surface during the towing tank tests. All the 3D CAD models are available on Github (Vitiello, 2022).

The remaining part of this work has been organized as follows: the Rigid Inflatable Boats (RIB) state of the art has been reported in section 2 where there is a market analysis of the boats similar to the parent's hull. A comparison based on the Gabrielli-von Karman efficiency transport diagram has been provided in addition to a review of available systematic series with and without steps. The description of the models' characteristics, as well as their building details, have been presented in Section 3. In section 4, the facilities with laboratory instrumentation and measurements devices have been described. Moreover, the test procedure has been discussed in Section 5. Results and Discussions along with uncertainty analysis have been reported in Section 6 and the paper has been finalized by a conclusion in Section 7. The towing tank test results are presented in Appendix A, the experimental uncertainty analysis is shown in Appendix B, and the wetted surface photos at all speeds for all the models are available in Appendix C.

2. State-of-the-art

In this section, a market analysis of boats similar to parent's hull has been reported to have a better understanding of stepped hulls background. It is a comparison based on Gabrielli-Von Karman efficiency transport diagram by considering all available planing hulls systematic series (with and without steps). At the end of this section, a comparison between Taunton's Systematic Series (Taunton et al., 2010) and the present series has been shown.

2.1. Stepped hulls RIB

Table 1 has collected the state of the art of RIB available on the market. In this table have been listed the main boat data, in specific: length overall (L_{OA}), beam max (B), L/B ratio, sea trial power installed, weight/Sea trial power ratio, maximum speed during the sea trial test, Ⓜ, S/L, K-value, volumetric Froude number, and Transport efficiency (E_T), that according to Gabrielli and von Kàrmàn (1950), is defined as:

$$E_T = \frac{W \cdot V}{0.102 P_d} \tag{1}$$

where V is the speed in m/s, W is the displacement in metric tonnes and the Pd is the propeller delivered power in kW. E_T is the weight/power ratio and represents the quality of the whole means of transport. The Gabrielli-von Karman transport efficiency index can be assumed as a sort of "efficiency" ranking based on the maximum speeds of the type of the hull available.

As reported on Gabrielli-von Karman graph in Fig. 1, on abscissa axis there is the volumetric Froude number and on the ordinate axis there is the Transport Efficiency. The hard chine hulls show the best efficiency index at very low Fr_∇ numbers up to 0.8. At Fr_∇ between 0.8 and 1.5, the round bilge hulls are the most efficient hulls, and at Fr_∇ number between 1.5 and 6.0, the Surface Effect Ship (SES) shows the best efficiency index. Finally, for speeds growing up to Fr_∇ 6.0, the stepped hulls have undisputed supremacy. Specifically, for volumetric Fr higher than 6, there are several stepped planning hulls above the threshold trend line of the hard chine hull, showing the best efficiency of the stepped hull at these extremely high speeds. The following stepped RIBs, in ascending order of Fr_∇, have a better Gabrielli-von Karman efficiency index comparing with hard chine hulls: Anvera 48, Technohull Omega 45, Magazzu MX 12 and MX 11, Buzzi 42, MV Marine Mito 31 (Fig. 2), Technohull 38 Grand Sport.

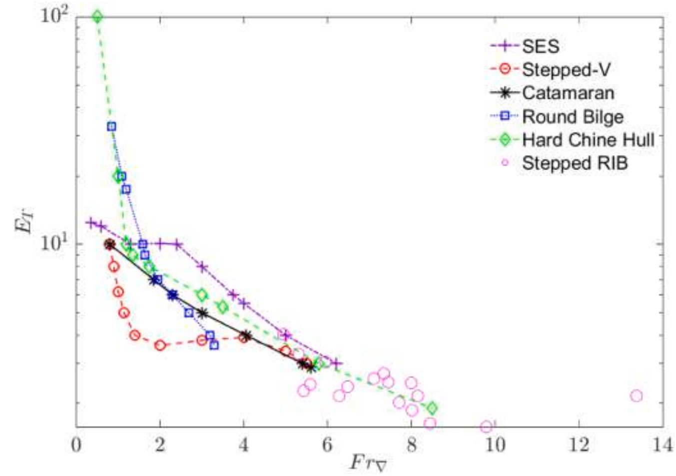

Fig. 1. Gabrielli-von Karman – transport efficiency index.

2.2. Systematic series overview

The state-of-the-art planing hull systematic series has been shown in Table 2 where there are 7 hard chine hull series and 2 stepped hull series.

Warped hard chine hulls (Naples Systematic Series - *NSS*) reported in De Luca and Pensa (2017) were designed at the naval section of the *Dipartimento di Ingegneria Industriale* (*DII*) of the *Università degli Studi di Napoli "Federico II"* as the VMV Stepped Hull series shown in this paper. The NSS series was designed with a deadrise angle constantly growing from astern to forward and by an A_T/A_X close to 1.0.

The other systematic series with a single chine (Hubble, 1974; Keuning and Gerritsma, 1982; Keuning et al., 1993; Taunton et al., 2010) have a constant deadrise angle along one-third of the hull.

Taunton's systematic series (Taunton et al., 2010) and the present VMV Series have the same B_{TC}/B_C ratio but with a different section geometry. In Taunton et al. (2010) a monohedric hull bottom with a constant deadrise angle of 22.5° is considered, on the contrary, in VMV Series there is warped bottom with a transom deadrise angle of 23.0° and an angle of 31.0° at the midship section. The following Table 2 summarizes the main hull data of the referenced series.

A detailed comparison between the Taunton's systematic series (Taunton et al., 2010) and VMV Series has been presented in Table 3. The main differences are related to, the hulls' dimensions, the

Table 1
The state of the art of RIBs.

Shipyard	Model (Commercial name)	L_{OA} [m]	B [m]	L/B	Δ [t]	P [HP]	Δ/P	V_{max} [Kn]	Ⓜ	S/L	Fr_∇	E_T
Anvera	48	14.50	4.91	2.95	10.00	740	13.51	44	6.79	6.38	4.94	4.01
BSK Marine Skipper	NC 100C	9.85	2.90	3.40	2.68	800	3.35	70	7.15	12.31	9.80	1.58
BSK Marine Skipper	Desire 120S	12.40	3.50	3.54	6.50	1880	3.46	70	6.70	10.97	8.45	1.63
Buzzi	42 RIB sport	13.20	3.60	3.67	9.02	1730	5.21	70	6.39	10.64	8.00	2.46
Joker Boat	Clubman 30	9.50	3.28	2.90	4.00	600	6.67	48	6.03	8.60	6.28	2.16
Magazzù	MX-11 coupè	11.00	3.80	2.89	5.50	900	6.11	60	6.28	9.99	7.45	2.47
Magazzù	MX-12 gransport	12.00	4.80	2.50	6.00	900	6.67	60	6.66	9.56	7.34	2.70
MV Marine	Mito 29	8.65	3.30	2.62	2.87	600	4.78	58	6.14	10.89	8.02	1.87
MV Marine	Mito 31	9.35	3.30	2.83	3.20	600	5.33	60	6.40	10.83	8.15	2.16
MV Marine	Mito 40	12.14	3.86	3.15	5.98	900	6.64	53	6.74	8.40	6.49	2.38
MV Marine	Mito 45	13.50	4.18	3.23	5.65	740	7.64	44	7.64	6.61	5.44	2.27
Pirelli	1400	13.70	3.64	3.76	7.95	900	8.83	51	6.92	7.61	5.95	3.04
Pirelli	42	13.10	4.10	3.20	8.50	800	10.63	46	6.47	7.02	5.31	3.30
Tecnohull	seaDNA999	10.30	2.80	3.68	2.70	300	9.00	40	7.46	6.88	5.59	2.43
Tecnohull	38 Grand Sport	11.10	3.20	3.47	4.20	1350	3.11	103	6.94	17.07	13.37	2.16
Tecnohull	Explorer 40	12.10	3.50	3.46	4.50	900	5.00	60	7.39	9.52	7.70	2.02
Tecnohull	Omega 45	13.80	3.50	3.94	5.93	900	6.59	58	7.69	8.62	7.11	2.58

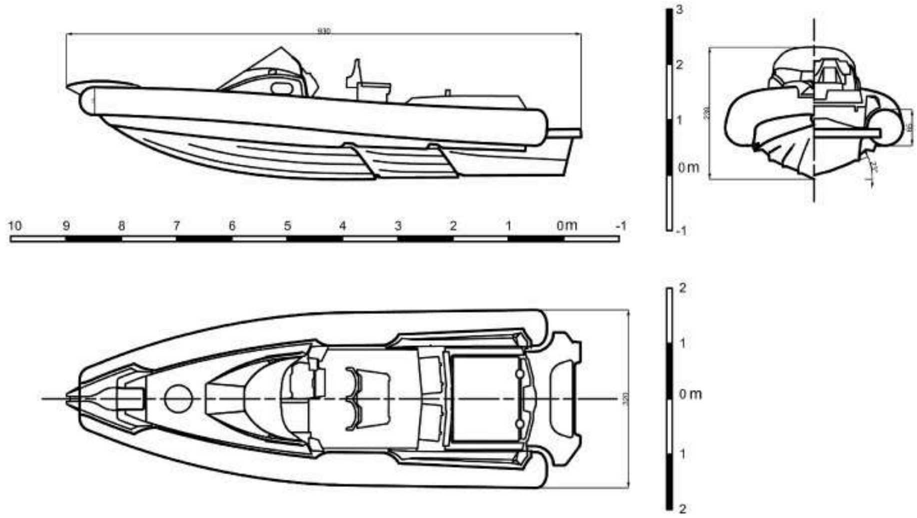

Fig. 2. Mito 31 body plan and profile.

Table 2
Planing hull systematic series – state-of-the-art.

Series	L/B range	Ⓜ range	B_{TC}/B_C
Clement and Blount (1963)	2.00	2.97	0.66
	7.00	8.46	
Keuning and Gerritsma (1982)	1.95	2.99	0.66
	6.82	8.36	
Keuning et al. (1993)	3.41	3.29	0.66
	7.00	8.25	
Hubble – A (1974)	3.20	4.0	0.35
	9.26	10.0	
Hubble – B (1974)	2.32	4.0	1.00
	9.28	10.0	
Kowalyshyn and Metcalf (2006)	3.24	4.98	0.96
	4.50	0.87	
Taunton et al. (2010)	3.77	6.25	1.00
	6.25	8.70	
Grigoropoulos and Loukakis (2002)	4.00	6.18	–
	7.00	10.00	
NSS De Luca and Pensa (2017)	3.24	4.83	0.95
	5.86	7.49	
VMV Stepped Series (present study)	3.41	6.24	1.00

Table 3
Comparison of main characteristics of two stepped hull series, Taunton et al. (2010) and VMV stepped Series (present study).

Model	Unit	Taunton model A	Taunton Model B	Taunton model C	Taunton model D	VMV Stepped Series (present study)
L	[m]	2.00	2.00	2.00	2.00	0.91
B	[m]	0.32	0.39	0.46	0.53	0.268
Δ	[N]	119.25	175.83	243.4	321.95	30.71
$L/\nabla^{1/3}$	[-]	8.7	7.64	6.86	6.25	6.24
L/B	[-]	6.25	5.13	4.35	3.77	3.41
β	[deg]	22.5	22.5	22.5	22.5	23
LCG	[%L]	0.33	0.33	0.33	0.33	from 0.30 to 0.34

displacements, and the design criteria of the hulls.

In Taunton et al. (2010), the length of the hulls has been kept constant and the L/B ratio, B, and step number (with the same step shape) have been varied. Instead, in the present study (VMV Series), L/B ratio has been kept constant and the main focus has been on the effects of various design parameters on the hull performance (resistance and running attitude). The considered design parameters are including the Number of steps (Ns), Height of steps (Hs) and Longitudinal Step Position (LSP) explained in detail in the next sections.

3. Description of the hull models

3.1. Parent hull

The parent hull used in this study represents an example of a modern high-speed hull for Rigid Inflatable Boats (RIB). This hull can be a representative hull for typical pleasure or military high-speed craft. The parent hull comes from a RIB built by MV-Marine S.r.l., type Mito 31 (Fig. 2) powered with two outboard engines.

The assumed parent hull is a traditional stepped hull with longitudinal spray rails and without an artificial bottom cavity or artificially inflated air in the cavity and without the bracket for engines. The parent hull is a hard chine hull with two transverse steps with a forward V shape, with the Center of Gravity (CG) located in the center of the surface between the first and second steps. This step shape is different from the arrow-like and transverse bottom step is as reported in Sverchkov (2010). The parent hull performance data are available in Miranda and Vitiello (2014).

All models have the same main geometric dimensions (keel line, chine line, deadrise angle, displacement, LCG, step shape, step angle) of RIB Mito 31, with a 1:10 scale ratio.

Starting from the parent hull, the design parameters have been defined based on a critical review of the literature related to the stepped hull design. The specific design parameters, which have been selected to cover a wide domain of investigation, have been described as follows:

- Step Number (Ns): Following Peters (2010) and Akers (2003), the single or double-step choice depends on the length-to-beam ratio and speed. For instance, a low aspect-ratio lifting surface of a boat with a narrow beam requires two steps for lift.
- Step Height (Hs): Peters (2010) defines a minimum and maximum value for step height (31.8 mm–65.5 mm in full scale). Akers (2003) in accordance with Norman Skene (1938), specifies that high steps are not necessary and that experience shows steps as lower as 16 mm could be effective. Sailing at high speed, a high height of steps could affect the angle of attack of the flow on the eventual successive steps conditioning the buttock lines behind the first step.
- About Longitudinal Step Position (LSP), there are different approaches in the literature. The first one, in accordance with

Acampora and Racer (1995), Akers (2003) and Peters (2010), is based on the idea that it is necessary to have the LCG close to the forebody stagnation line to have a correct distribution of the vertical forces between forebody and after body (Savitsky and Morabito, 2010). The second one, according to Clement and Pope (1961), derives the LSP as a function of the main hull geometric parameters. However, the step is always further forward than the LCG. The third one, based on Clement (1964), defines a design approach for a stepped hull similar to hydrofoil boats or aeroplanes. This approach tries to find the optimum configuration of a lifting surface to obtain a maximum lift-drag ratio. The CG position, as well as the centre of pressure, are not negligible points since they could trigger dynamic instabilities phenomena.

Based on the abovementioned design parameters, the hull models of the present series have been generated by varying the number of steps (1 or 2), the Hs (20 mm and 60 mm, full scale), and the LSP, as summarized in Table 4.

3.2. Models identifications

All the models in the present study are identified with an Identification Number (ID). This ID is composed of six alphanumeric characters (i.e. C02_1_20_0), in particular:

- C02 – indicated the hull progressive number, from 2 to 9.
- 1 – Indicate the step number (1 or 2).
- 20 – Indicate the step height in mm (20 or 60 mm in full scale, the scale factor is 10).
- 0 – Indicate the Longitudinal Step Position: 0 for LSP = LCG; 1 for LSP 140 mm forward of LCG.

In Table 4, all models are reported with their geometric characteristics. O-XYZ is located at the intersection between keel line and transom with X-axis positive forward, Y-axis positive right hand, and Z-axis positive up.

3.3. Models building

The hull models for towing tank tests were designed with commercially available 3D CAD software. The 3D CAD files are available on the Github platform (Vitiello, 2022). To provide a full view of the water flow under the hull, the models have a full transparent bottom built only with high-gloss neopentylic gelcoat transparent surface and isophthalic transparent resin. The side of the model was built in Fibre Reinforced Plastic (FRP) with a surface of high-gloss neopentylic gelcoat transparent, isophthalic transparent resin and two layers of glass fibre Chopped Strand Mat (CSM) of 450 gr/m^2, to ensure the necessary structural strength.

The hull models are built with female moulds realized with a hand-made layup with composite materials. In order to build the female mould, in a hand-made layup, was manufactured a model for the mould. The model for the mould was designed in 3D CAD/CAM and the female mould was built in FRP, the two parts are built through the following step:

- milling of high-density PVC foam with CNC five-axis machine with a rough finish to build a *model for mould*;
- covered with a spray polyester paste;
- milling the foam covered with the polyester pastes with CNC machine five-axis with a good finish;
- spraying the polyester gelcoat;
- tooling in hand-made and after applying the polish and wax;
- spraying the polyester gelcoat for mould;
- laminating the FRP with glass CSM and isophthalic resin in hand-made layup;

CAD/CAM building process ensures that the model hull tolerances (for breadth, draught, and length) are in the range of ±0.5 mm, as requested by the ITTC procedures (7.5-01-01-01, 2002). In particular, the length manufacturing tolerance is less than 0.05%, and very special attention was paid to the shaping of chines and steps to ensure very hard edges.

Table 4
Geometric characteristics of the hull models.

ID number	Steps Number; (N_S)	Step Height (H_S) [mm]	Longitudinal Step Position (LSP) [mm]	Longitudinal Center of Buoyancy (LCB) [mm]
C02_1_20_0	1	2	0: step 1 = 300 mm	277
C03_1_60_0	1	6	0: step 1 = 301 mm	291
C04_1_20_1	1	2	+1.4: step 1 = 440 mm	276
C05_1_60_1	1	6	+1.4: step 1 = 441 mm	286
C06_2_20_0	2	2	0: step 1 = 147 mm step 2 = 300 mm	283
C07_2_60_0	2	6	0: step 1 = 149 mm step 2 = 302 mm	307
C08_2_20_1	2	2	+1.4: step 1 = 288 mm step 2 = 441 mm	282
C09_2_60_1	2	6	+1.4: step 1 = 290 mm step 2 = 443 mm	310

4. Facility and equipment

The calm water tests were conducted in the towing tank of the naval section of the *Dipartimento di Ingegneria Industriale (DII)* of the *Università degli Studi di Napoli "Federico II"*. Details of the towing tank are outlined in Table 5. The front view of the tank carriage is shown in Fig. 3.

The details of the laboratory instrumentation implemented in the experimental tests and the measurement techniques are reported in Appendix A and also available in De Marco et al. (2017).

The dynamometer carriage is equipped with a Programmable Logic Controller, a sensor network and a Data-AcQuisition (DAQ) device. The sensors necessary for these tests are an encoder for measuring the speed carriage, the load cell for resistance measurement, the balance for models and ballast weights, a digital thermometer for acquiring the water temperature, an accelerometer for trim measurement, two lasers (one located at the stern and another located at the bow of the model) for sinkage measurement, two photo cameras and one video camera for sinkage measurement, wetted surface and the vortex phenomena recording.

The digital thermometer used during the tests allows a range from −5 °C to 40 °C, with an accuracy of 0.1 °C and a resolution of 0.1 °C as reported on the datasheet.

The dynamometer carriage speed was measured by a high-quality

Table 5
Main particulars of the towing tank of *Università di Napoli "Federico II"*.

Parameter	Value	Unit
Length of the tank	137.0	m
Width of the tank	9.0	m
Depth of the tank	4.25	m
Maximum carriage speed	10.0	m/s
Max acceleration/deceleration	±1.0	m/s^2

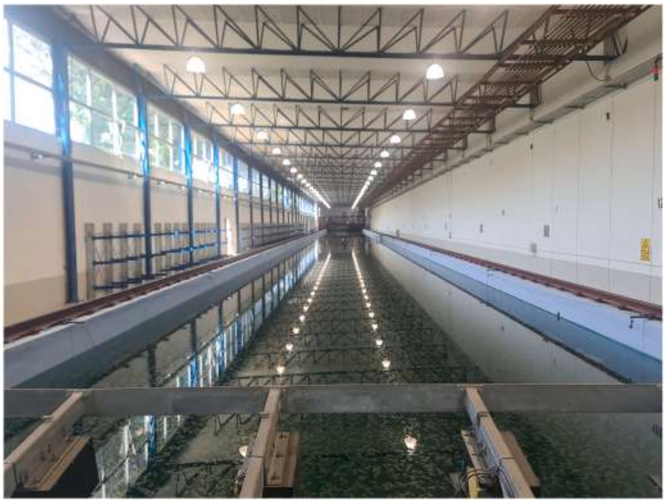

Fig. 3. A front view of the carriage of the *Università di Napoli "Federico II"* towing tank.

encoder and a counter/timing card. The high-quality encoder was not fixed to any wheel drive of carriage and rolls without rolling resistance driven by the carriage (it gives 1000 pulses per one round, 1 pulse for each mm). The encoder sensor has an accuracy of 1 mm/m and a resolution of 1 mm. The period between two pulses was measured by a counter/timing card at 32 bits with a clock of 80 MHz. The card has a range from 1.25×10^{-8} s to 53.69 s; the clock at 80 MHz has an accuracy of $\pm 4 \times 10^{-3}$ MHz and a resolution of 1.25×10^{-8} s.

The resistance measurements were acquired by a high-quality load cell (precision class 0.003) with a conditioning-acquisition card. The specific load cell used in this test has a range up to 50 N, an accuracy of 0.003%, and a resolution of 0.005 N. The conditioning-acquisition card has a software programmed range of 50 N, an accuracy of 0.08%, 16-bit resolution, and a sampling rate up to 200 kSamples/s. For these measurements, the row data were oversampled at a rate of 10 kSamples/s and compressed at a rate of 500 Samples/s for ulterior reduction of the noise.

Running trim measurements were performed by an accelerometer and a conditioning-acquisition card. The accelerometer sensor has a range of 40 m/s^2, accuracy of ±0.1%, and resolution virtually infinite. The conditioning-acquisition card has a software programmed range of 40 m/s^2, an accuracy of 0.1%, and a 16-bit resolution.

Sinkage was measured by two high-quality laser sensors and a conditioning-acquisition card. The two lasers have a range from 0.2 to 1 m, an accuracy of 0.5 mm, and a resolution of 0.05 mm. These laser devices were placed perpendicularly on the water surface, at two different positions (at the fore section and the aft section of the models). The conditioning-acquisition card has a software programmed range of up to 1 m, an accuracy of 0.1%, and a 16-bit resolution.

The weight of the model and ballast were measured with a scale with a range of 600 N, accuracy of ±0.1 N, and resolution of 0.1 N.

5. Test procedure

Calm water measurements are performed following the ITTC procedures (7.5-02-02-01, 2011) with a stop (over 10 min) between two consecutive runs to ensure calm water condition. The displacement condition for resistance tests is 30.705 N with three different trim conditions (+1°, −1°, and 0° trim) and eight speeds: 1.290, 2.357, 3.131, 4.631, 5.368, 6.340, 7.301, and 8.050 m/s (Appendix A).

Speed, resistance, sinkage, trim angle and photo/video recording are the data acquired. Digital photos and videos for each run were acquired by three cameras, one in the right-fore hand, the second in the right-aft hand and the third camera with a 50 mm lens placed on the towing carriage, in a perpendicular position to the model's centre of gravity. This third camera was set for the measurement of dynamic wetted surface and capturing the vortical flow under the hull.

The resistance dynamometer has been placed on the towing carriage and connected to the model through a quasi-inextensible rope Spectra™, which is a super fibre made by Honeywell©. The calm water resistance experiments are conducted with a "Down-Thrust" (DT) methodology according to Miranda and Vitiello (2014). The towed point is located in the intersection between the direction of thrust of engines and the keel line at the bow. In this way, the model tested has 4 degrees of freedom with only the yaw and drift motions restricted. To avoid any instability phenomena, the models have been built with two guide masts, realized in carbon fibre, located at the bow and at the stern, which engage two forks in stainless steel (Fig. 4). DT measurement solution ensures the high sensitivity of the hull model to the externally applied forces (*i.e.* the instrumentation weight). The DT procedures can be considered as a free running-like resistance test and this solution ensures reproducing the real system of forces exerted by the outboard engines and the same dynamics of the real boat.

The sinkage is calculated through the measurements of two lasers located in the fore and aft section of the model, acquired by a digital photo made with a 50 mm camera placed perpendicularly to the model's centre of gravity (CG) and elaborated with a 3D CAD model.

To estimate the dynamic wetted surface, as mentioned above, a hull with transparent bottom was built to ensure a full view of the water flow under the hull. The experimental wetted surface values are estimated through digital analysis of video frames acquired by a 50 mm camera put on CG. For each speed, the top view pictures (see Appendix C) acquired from the camera are post-processed with the 3D CAD software to measure the dynamic wetted surface.

6. Results and Discussions

The results of calm water resistance tests are presented in Appendix A. The experimental results are exposed in terms of non-dimensional total resistance (RT_M/Δ), dynamic trim angle (τ), non-dimensional dynamic sinkage ($Z_G/\nabla^{1/3}$), and non-dimensional dynamic wetted surface ($S/\nabla^{2/3}$). The results are raw data without a fairing post-process.

The uncertainty Analysis (UA) of the towing tank test results, reported in Appendix B, has been carried out following the ITTC procedures for uncertainty analysis in resistance towing tank tests (7.5-02-02-02, 2002). The UA shows a total uncertainty in an acceptable range for planing hull towing tank tests. The measures with the highest uncertainty are the sinkage and wetted surface. The wetted surface uncertainty is mainly related to the spray areas which are difficult to be estimated based on the recorded photos and videos.

An interesting finding of the present experimental campaign is the observation, thanks to the hulls' transparent bottom, of some vortices developing into the aft body region behind the step and partially continuing downstream in the wake. This vortex phenomenon has been detected only for hull models with a step height of 6 mm and appears at speeds greater than 2.36 m/s ($Fr_\nabla > 1.97$). This vortex phenomenon was already described in De Marco et al. (2017) and the towing tank video recording of the C03 hull was openly released on 2016 (Vitiello and Miranda, 2016). For more details, fluid flow and wetted surface pictures of present stepped hulls in trimmed forward condition at all speeds are reported in Appendix C.

Analyzing and comparing the resistance test results in the range of Fr_∇ between 5 and 6.7 (very-high-speed), the hull C04 trimmed aft has the best performance. In the range of Fr_∇ between 3.4 and 5 (high-speed), the best results are for the hull C05 trimmed aft. For the range of Fr_∇ between 2.6 and 3.4 (medium-speed range), the best hull is the C05 even keel, and in the range of Fr_∇ between 1.1 and 2.6 (low-speed range), the best results are for the hull C06 trimmed fore.

Regarding the effect of static trim angle on the hull performance, the experimental results are according to the general principles that for low

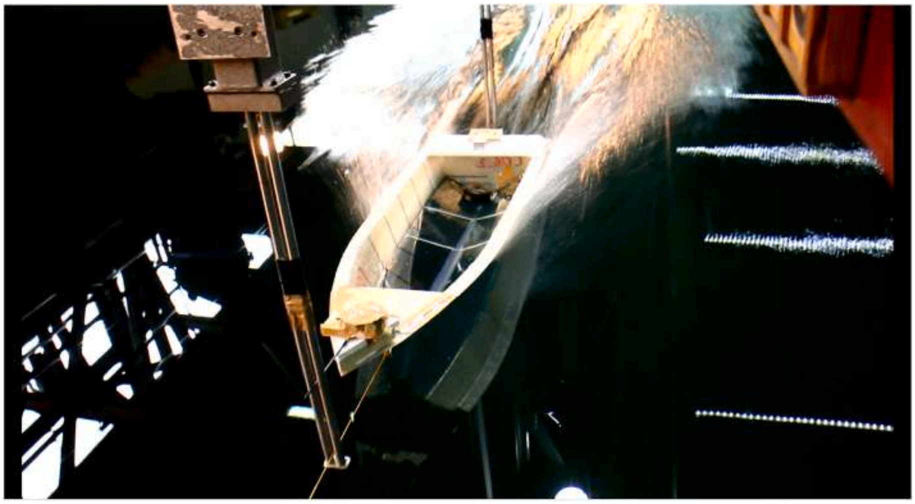

Fig. 4. Towing tank test with down-thrust methodology.

speeds a low resistance (compared with the even keel condition) is detected on the hull trimmed fore cases. On the contrary, at high speeds, low resistance (compared with the even keel condition) is detected on the hull trimmed aft cases.

Regarding the step geometric parameters, the results show that the single-step configuration is effective at almost all speed ranges (except at low speeds). Increasing the hull speeds, a decrement of step height allows a resistance reduction. Furthermore, moving forward the step (increasing LSP) at low speeds decrease the resistance.

7. Conclusions

Calm water resistance experiments have been conducted at towing tank of the naval section of the *Dipartimento di Ingegneria Industriale (DII) della Università degli Studi di Napoli "Federico II"*, on 8 models of a new stepped hull model series.

Towing tank tests are performed by implementing the "Down-Thrust" methodology since all the hull models are low-weighs and are sensitive to the externally applied forces, indeed the "Down-Thrust" methodology is able to keep free the model from the equipment and instrumentation weights. Furthermore, this testing methodology, developed exclusively for these towing tank tests, allows reproducing the real system of forces on the hull at full scale.

All models were built with a transparent bottom with the aim to quantify the wetted surface and observe the vortical flow phenomena on the area(s) behind the step(s). These vortex structures have been detected only in the hulls with a height step of 6 mm (model scale) and confirmed via CFD simulations, as reported in De Marco et al. (2017).

The results of calm water resistance tests are presented in Appendix A, where all values acquired are plotted against the volumetric Froude number (Fr_∇). In particular, the non-dimensional total resistance (RT_M/Δ), the dynamic trim angle (τ); the non-dimensional dynamic sinkage ($Z_G/\nabla^{1/3}$), and the non-dimensional dynamic wetted surface ($S/\nabla^{2/3}$) are shown for each hull in three different static equilibrium conditions: even keel, trimmed aft, and trimmed fore. The results for each model are shown in graphical and tabular ways. All the models' hull lines and the 3D CAD surface are openly available for research and investigation in the academic, technical, and practitioner communities.

The uncertainty analysis of the experimental results is performed in compliance with the ITTC guidelines and shows an acceptable level of accuracy.

The proposed VMV stepped hull planing series is intended to be a support to designers and boat builders that intend to design a stepped hull. In future works, the authors want to extensively apply the CFD tool on these hulls for both calm water and seakeeping tests with the idea to extend the present results for speed over $Fr_\nabla = 6.724$ (over 50 knots in boat speed).

CRediT authorship contribution statement

Luigi Vitiello: Conceptualization, Methodology, Towing Tank Test, Visualization, Writing – original draft. **Simone Mancini:** Resources, Investigation, Data curation, Writing – review & editing. **Rasul Niazmand Bilandi:** Data curation, Formal analysis, Visualization, Writing – original draft. **Abbas Dashtimanesh:** Supervision, Writing – review & editing. **Fabio De Luca:** Data curation, Writing – review & editing. **Vincenzo Nappo:** Data curation, Formal analysis, model building & data analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors are deeply grateful to Prof. Salvatore Miranda, Mr. Raffaele di Donna and to the towing tank staff as Mr. Andrea Bove, Antonio Alfano, Biagio D'Abbusco, Lucio Iadicicco, and Vitale Esposito. This work has been supported by: ECO-RIB project grant (D.M. 01/06/2016 - Horizon 2020 - PON 2014/2020), and PON AIM RTDA Ricerca e Innovazione.

Appendix A. Towing tank test results

Hull model C02_1_20_0

ID number	Steps Number; N_S	Step Height; H_S [mm]	Longitudinal Step Position; LSP [mm]	Longitudinal Center of Buoyancy; LCB [mm]
C02_1_20_0	**1**	**2**	**0:** **step 1 = 300 mm**	**277**

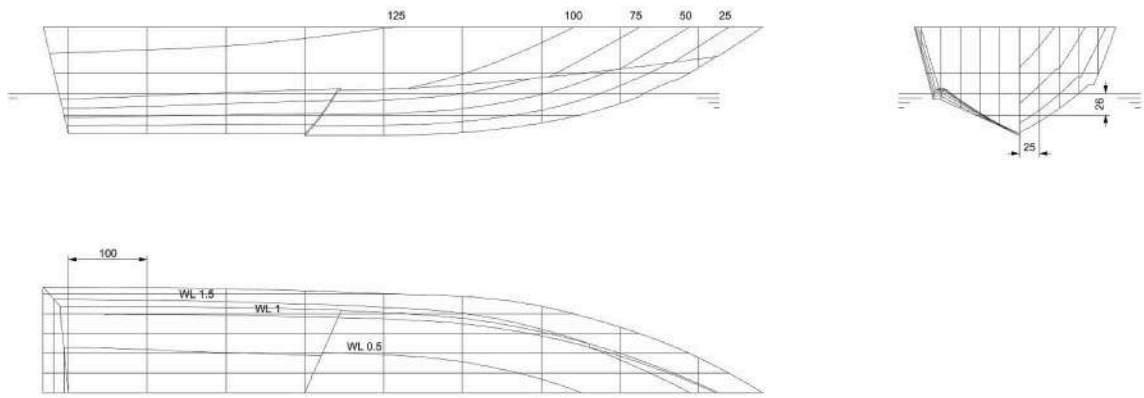

Fig. 5. C02 model lines plan: Sheer Plan, body plan, half breadth plan. Transversal section every 0.100 m, buttock line every 0.025 m, water lines every 0.026 m.

Hull model C02_1_20_0 - calm water towing tank test data

C2 evenkeel	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.46	−7.39	−19.99	0.100	−0.051	5.55
	2.36	14.49	0.87	1.968	4.13	5.31	−16.29	0.169	0.036	5.39
	3.13	19.25	1.15	2.614	4.99	14.46	−10.44	0.203	0.099	4.68
	4.63	28.47	1.70	3.865	3.84	19.46	1.26	0.259	0.133	3.99
	5.37	33.00	1.97	4.482	3.32	36.69	11.12	0.306	0.251	3.77
	6.34	38.98	2.33	5.290	3.04	23.77	7.87	0.382	0.162	3.36
	7.30	44.88	2.68	6.095	2.99	28.20	13.30	0.452	0.193	3.00
	8.05	49.49	2.96	6.724	3.16	30.56	14.36	0.498	0.209	2.75
C2 trimmed aft	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.64	−2.55	−16.95	0.104	−0.017	5.10
	2.36	14.49	0.87	1.968	4.53	7.68	−15.72	0.176	0.053	4.95
	3.13	19.25	1.15	2.614	2.46	5.06	−6.64	0.223	0.035	4.84
	4.63	28.47	1.70	3.865	2.41	18.33	6.63	0.296	0.125	4.71
	5.37	33.00	1.97	4.482	2.41	19.24	7.24	0.317	0.132	4.11
	6.34	38.98	2.33	5.290	2.46	28.85	16.85	0.365	0.197	3.20
	7.30	44.88	2.68	6.095	2.29	32.19	20.49	0.429	0.220	2.79
	8.05	49.49	2.96	6.724	2.46	31.25	19.25	0.472	0.214	2.55
C2 trimmed fore	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.24	−8.18	−18.68	0.088	−0.056	6.04
	2.36	14.49	0.87	1.968	4.08	−0.93	−20.73	0.169	−0.006	5.87
	3.13	19.25	1.15	2.614	5.29	24.28	−1.82	0.206	0.166	5.09
	4.63	28.47	1.70	3.865	4.77	38.09	14.99	0.264	0.260	4.27
	5.37	33.00	1.97	4.482	4.36	39.93	15.33	0.313	0.273	4.09
	6.34	38.98	2.33	5.290	4.13	22.22	−0.88	0.400	0.152	3.66
	7.30	44.88	2.68	6.095	4.02	41.41	21.88	0.483	0.283	3.23
	8.05	49.49	2.96	6.724	4.07	48.15	25.35	0.524	0.329	2.91

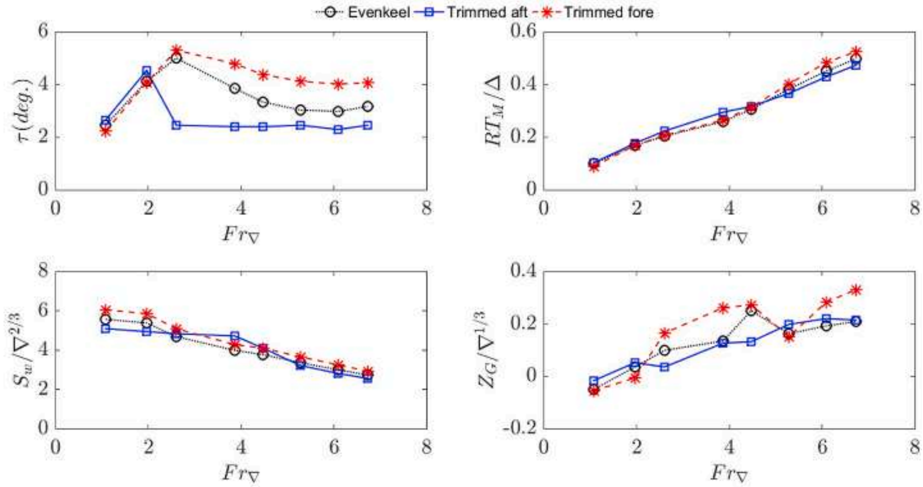

Fig. 6. Results of C02 hull for dynamic trim, resistance, wetted surface, and dynamic sinkage at states of even keel, trimmed aft, and trimmed fore.

Hull model C03_1_60_0

ID number	Steps Number; N_S	Step Height; H_S [mm]	Longitudinal Step Position; LSP [mm]	Longitudinal Center of Buoyancy; LCB [mm]
C03_1_60_0	**1**	**6**	**0:** **step 1 = 301 mm**	**291**

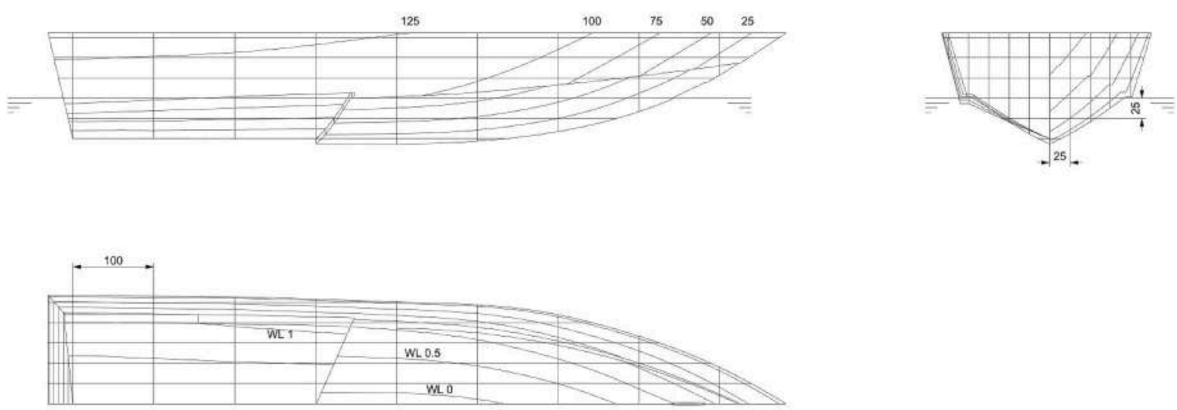

Fig. 7. C03 model lines plan: Sheer Plan, body plan, half breadth plan. Transversal section every 0.100 m, buttock line every 0.025 m, water lines every 0.025 m.

Hull model C03_1_60_0 - calm water towing tank test data.

C3 evenkeel	**V_M [m/s]**	**V_S [Knots]**	Fr_L	Fr_∇	**τ [deg]**	**Z_G [mm] + up**	Z_O [mm] **+ up**	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.290	7.93	0.474	1.077	2.23	−11.68	−22.26	0.088	−0.080	6.48
	2.357	14.49	0.866	1.968	3.55	1.52	−17.99	0.178	0.010	6.29
	3.131	19.25	1.151	2.614	4.42	6.95	−15.30	0.204	0.048	4.32
	4.629	28.47	1.702	3.865	3.27	12.37	6.16	0.256	0.085	3.57
	5.368	33.00	1.973	4.482	2.87	20.39	7.20	0.312	0.139	3.33
	6.336	38.98	2.330	5.290	2.69	21.50	8.14	0.407	0.147	3.09
	7.301	44.88	2.683	6.095	2.52	22.15	9.07	0.491	0.151	2.62
	8.054	49.49	2.958	6.724	2.58	26.44	13.41	0.556	0.181	2.48
C3 trimmed aft	**V_M [m/s]**	**V_S [Knots]**	Fr_L	Fr_∇	**τ [deg]**	**Z_G [mm] + up**	Z_O [mm] **+ up**	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.47	−5.26	−18.26	0.116	−0.036	6.07
	2.36	14.49	0.87	1.968	4.21	7.12	−14.78	0.189	0.049	5.89
	3.13	19.25	1.15	2.614	4.26	9.67	−3.23	0.209	0.066	4.59
	4.63	28.47	1.70	3.865	2.64	26.47	13.57	0.265	0.181	3.76
	5.37	33.00	1.97	4.482	2.18	23.39	13.49	0.305	0.160	3.00

(*continued on next page*)

(*continued*)

	6.34	38.98	2.33	5.290	1.89	25.51	15.61	0.369	0.174	2.32
	7.30	44.88	2.68	6.095	2.12	32.80	21.40	0.443	0.224	2.24
	8.05	49.49	2.96	6.724	2.18	29.83	18.13	0.486	0.204	2.16
C3 trimmed fore	**V_M [m/s]**	**V_S [Knots]**	Fr_L	Fr_∇	**τ [deg]**	**Z_G [mm] + up**	**Z_O** [mm] **+ up**	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	1.89	−9.83	−16.73	0.090	−0.067	6.01
	2.36	14.49	0.87	1.968	3.67	2.11	−18.59	0.189	0.014	5.84
	3.13	19.25	1.15	2.614	3.95	0.41	−20.59	0.270	0.003	4.83
	4.63	28.47	1.70	3.865	4.24	19.23	−3.87	0.269	0.131	3.81
	5.37	33.00	1.97	4.482	3.95	4.77	5.97	0.332	0.033	3.62
	6.34	38.98	2.33	5.290	3.72	20.35	−0.35	0.413	0.139	3.04
	7.30	44.88	2.68	6.095	3.66	20.59	−0.11	0.500	0.141	3.02
	8.05	49.49	2.96	6.724	3.66	25.68	5.28	0.558	0.176	2.99

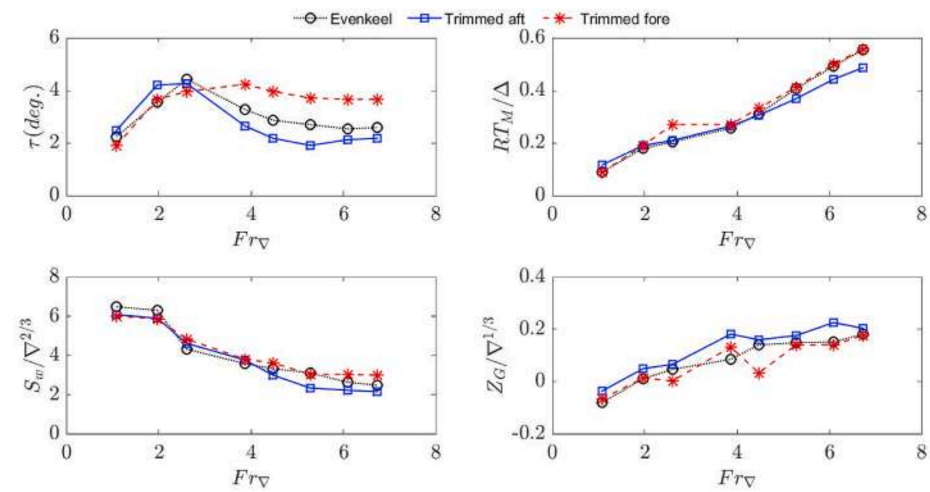

Fig. 8. Results of C03 hull for dynamic trim, resistance, wetted surface, and dynamic sinkage at states of even keel, trimmed aft, and trimmed fore.

Hull model C04_1_20_1

ID number	Steps Number; N_S	Step Height; H_S [mm]	Longitudinal Step Position; LSP [mm]	Longitudinal Center of Buoyancy; LCB [mm]
C04_1_20_1	**1**	**2**	**+1.4:** **step 1 = 440 mm**	**276**

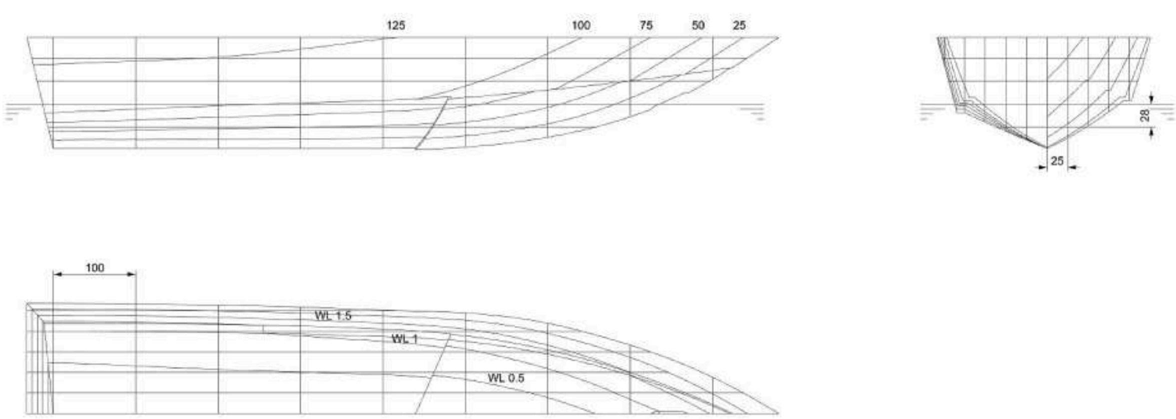

Fig. 9. C04 model lines plan: Sheer Plan, body plan, half breadth plan. Transversal section every 0.100 m, buttock line every 0.025 m, water lines every 0.028 m.

Hull model C04_1_20_1 - calm water towing tank test data.

	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
C4 evenkeel										
	1.29	7.93	0.47	1.077	2.47	−6.84	−18.54	0.097	−0.047	5.59
	2.36	14.49	0.87	1.968	4.14	2.97	−17.73	0.172	0.020	5.42
	3.13	19.25	1.15	2.614	4.94	20.54	−6.16	0.213	0.140	4.82
	4.63	28.47	1.70	3.865	3.84	24.36	3.36	0.280	0.167	3.86
	5.37	33.00	1.97	4.482	3.44	28.43	10.43	0.322	0.194	3.78
	6.34	38.98	2.33	5.290	3.21	26.71	9.01	0.378	0.183	3.46
	7.30	44.88	2.68	6.095	3.15	27.12	12.12	0.447	0.185	3.34
	8.05	49.49	2.96	6.724	3.09	31.58	16.61	0.491	0.216	3.20
C4 trimmed aft	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.58	−5.19	−17.79	0.107	−0.035	5.69
	2.36	14.49	0.87	1.968	4.59	6.79	−17.81	0.187	0.046	4.49
	3.13	19.25	1.15	2.614	4.71	21.18	−3.42	0.215	0.145	3.96
	4.63	28.47	1.70	3.865	3.21	28.73	14.43	0.266	0.196	3.72
	5.37	33.00	1.97	4.482	2.74	26.78	11.48	0.304	0.183	3.25
	6.34	38.98	2.33	5.290	2.52	28.79	16.69	0.359	0.197	3.22
	7.30	44.88	2.68	6.095	2.35	27.32	15.32	0.418	0.187	2.95
	8.05	49.49	2.96	6.724	2.29	35.35	23.44	0.451	0.242	2.71
C4 trimmed fore	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	1.15	−7.43	−19.43	0.081	−0.051	6.20
	2.36	14.49	0.87	1.968	4.01	−1.04	−22.04	0.167	−0.007	6.02
	3.13	19.25	1.15	2.614	5.17	10.28	−16.72	0.212	0.070	5.73
	4.63	28.47	1.70	3.865	4.65	22.85	−1.15	0.288	0.156	4.48
	5.37	33.00	1.97	4.482	4.24	24.92	0.92	0.319	0.170	4.26
	6.34	38.98	2.33	5.290	4.07	22.42	1.42	0.400	0.153	3.99
	7.30	44.88	2.68	6.095	4.01	27.78	6.78	0.463	0.190	3.41
	8.05	49.49	2.96	6.724	3.96	27.84	6.84	0.513	0.190	3.27

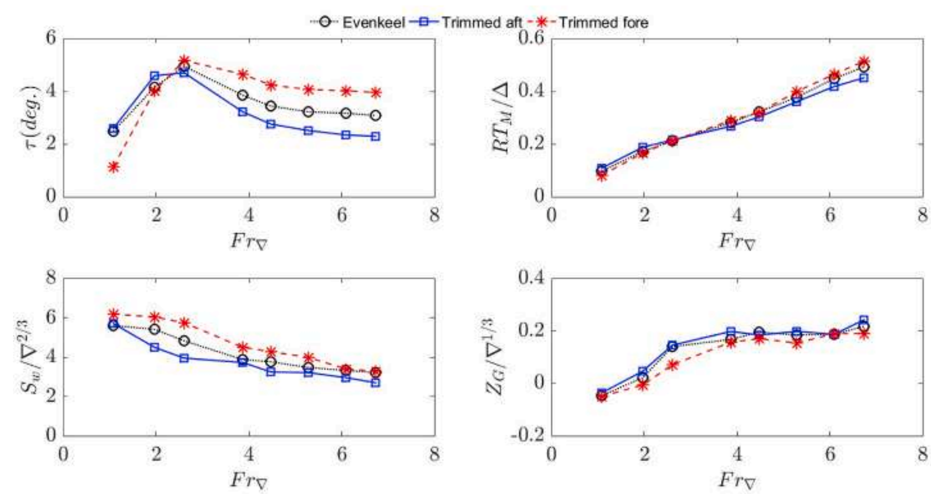

Fig. 10. Results of C04 hull for dynamic trim, resistance, wetted surface, and dynamic sinkage at states of even keel, trimmed aft, and trimmed fore.

Hull model C05_1_60_1

ID number	Steps Number; N_S	Step Height; H_S [mm]	Longitudinal Step Position; LSP [mm]	Longitudinal Center of Buoyancy; LCB [mm]
C05_1_60_1	**1**	**6**	**+1.4:** **step 1 = 441 mm**	**286**

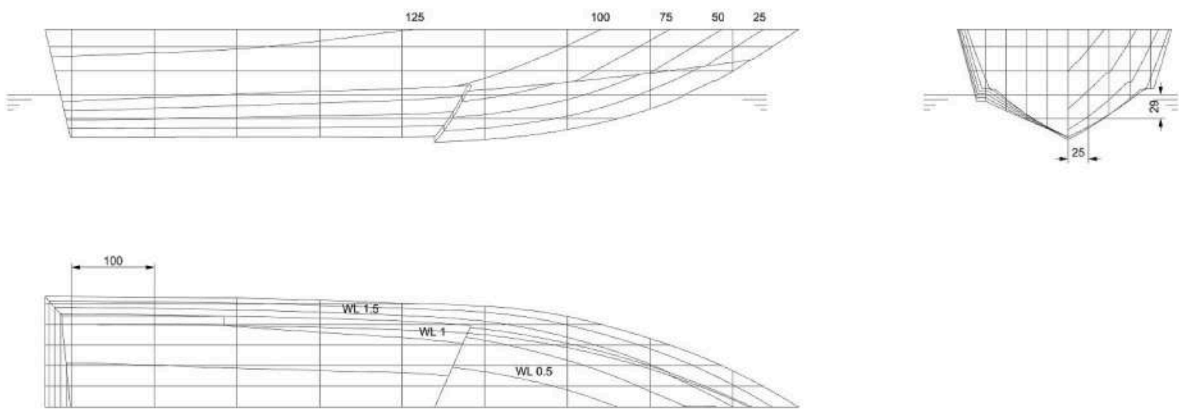

Fig. 11. C05 model lines plan: Sheer Plan, body plan, half breadth plan. Transversal section every 0.100 m, buttock line every 0.025 m, water lines every 0.029 m

Hull model C05_1_60_1 - calm water towing tank test data.

C5 evenkeel	$\mathbf{V_M}$ **[m/s]**	$\mathbf{V_S}$ **[Knots]**	Fr_L	$\mathbf{Fr_\nabla}$	**τ [deg]**	$\mathbf{Z_G}$ **[mm] + up**	$\mathbf{Z_O}$ [mm] **+ up**	$\frac{\mathbf{RT_M}}{\Delta}$	$\frac{\mathbf{Z_G}}{\nabla^{1/3}}$	$\frac{\mathbf{S_W}}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.30	−4.07	−17.02	0.103	−0.028	5.87
	2.36	14.49	0.87	1.968	3.75	7.10	−13.21	0.186	0.049	5.33
	3.13	19.25	1.15	2.614	3.85	13.30	−4.51	0.200	0.091	4.94
	4.63	28.47	1.70	3.865	2.58	19.17	12.15	0.258	0.131	4.18
	5.37	33.00	1.97	4.482	2.18	19.43	10.91	0.301	0.133	3.81
	6.34	38.98	2.33	5.290	1.78	21.72	11.39	0.378	0.148	3.31
	7.30	44.88	2.68	6.095	1.70	31.58	14.96	0.453	0.216	2.83
	8.05	49.49	2.96	6.724	1.61	27.58	14.83	0.525	0.189	2.45
C5 trimmed aft	$\mathbf{V_M}$ **[m/s]**	$\mathbf{V_S}$ **[Knots]**	Fr_L	$\mathbf{Fr_\nabla}$	**τ [deg]**	$\mathbf{Z_G}$ **[mm] + up**	$\mathbf{Z_O}$ [mm] **+ up**	$\frac{\mathbf{RT_M}}{\Delta}$	$\frac{\mathbf{Z_G}}{\nabla^{1/3}}$	$\frac{\mathbf{S_W}}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.52	−2.51	−14.91	0.112	−0.017	5.84
	2.36	14.49	0.87	1.968	4.08	9.04	−11.86	0.191	0.062	5.67
	3.13	19.25	1.15	2.614	3.78	4.99	−4.52	0.204	−0.034	4.42
	4.63	28.47	1.70	3.865	2.58	42.25	−2.17	0.256	0.289	3.88
	5.37	33.00	1.97	4.482	1.32	18.62	19.10	0.293	0.127	3.57
	6.34	38.98	2.33	5.290	0.92	21.32	21.84	0.365	0.146	2.93
	7.30	44.88	2.68	6.095	0.75	23.11	22.99	0.449	0.158	2.70
	8.05	49.49	2.96	6.724	0.69	24.19	24.53	0.511	0.165	2.21
C5 trimmed fore	$\mathbf{V_M}$ **[m/s]**	$\mathbf{V_S}$ **[Knots]**	Fr_L	$\mathbf{Fr_\nabla}$	**τ [deg]**	$\mathbf{Z_G}$ **[mm] + up**	$\mathbf{Z_O}$ [mm] **+ up**	$\frac{\mathbf{RT_M}}{\Delta}$	$\frac{\mathbf{Z_G}}{\nabla^{1/3}}$	$\frac{\mathbf{S_W}}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.00	−5.65	−17.85	0.093	−0.039	5.78
	2.36	14.49	0.87	1.968	3.61	4.93	−18.43	0.192	0.034	5.56
	3.13	19.25	1.15	2.614	3.36	8.42	−13.09	0.220	0.058	5.19
	4.63	28.47	1.70	3.865	3.43	18.98	0.69	0.265	0.130	4.62
	5.37	33.00	1.97	4.482	3.09	19.18	0.64	0.308	0.131	3.90
	6.34	38.98	2.33	5.290	2.92	22.73	4.18	0.382	0.155	3.44
	7.30	44.88	2.68	6.095	2.69	26.24	8.38	0.495	0.179	2.97
	8.05	49.49	2.96	6.724	2.52	28.97	9.68	0.569	0.198	2.61

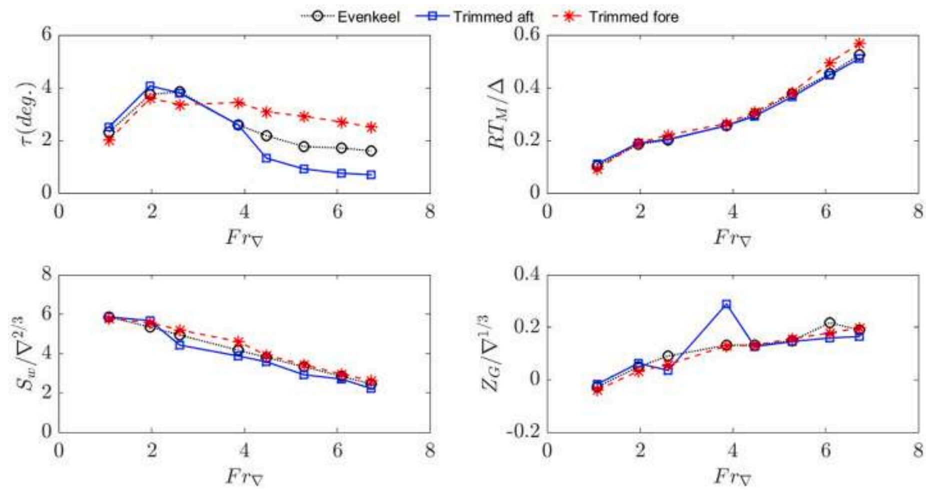

Fig. 12. Results of C05 hull for dynamic trim, resistance, wetted surface, and dynamic sinkage at states of even keel, trimmed aft, and trimmed fore.

Hull model C06_2_20_0

ID number	Steps Number; N_S	Step Height; H_S [mm]	Longitudinal Step Position; LSP [mm]	Longitudinal Center of Buoyancy; LCB [mm]
C06_2_20_0	**2**	**2**	**0:** **step 1 = 147 mm** **step 2 = 300 mm**	**283**

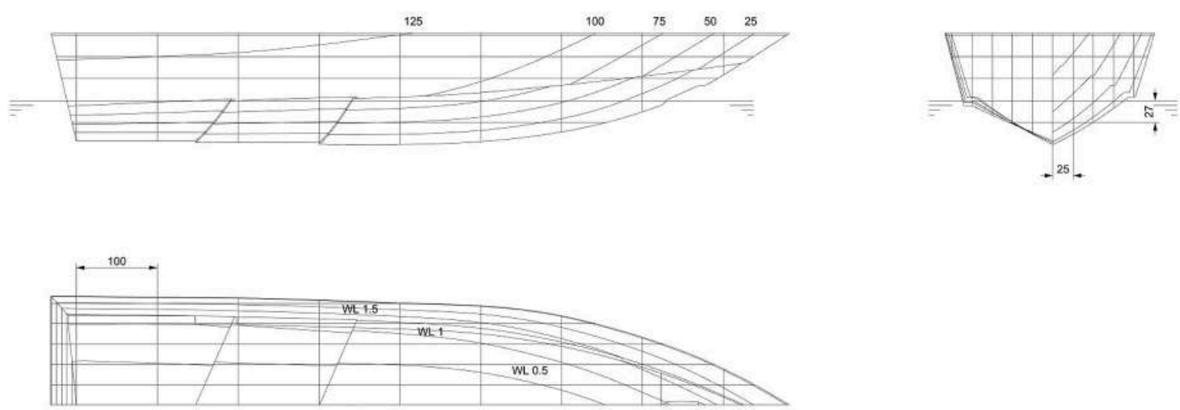

Fig. 13. C06 model lines plan: Sheer Plan, body plan, half breadth plan. Transversal section every 0.100 m, buttock line every 0.025 m, water lines every 0.027 m

Hull model C06_2_20_0 - calm water towing tank test data.

C6 evenkeel	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.18	−16.00	−17.00	0.090	−0.109	5.93
	2.36	14.49	0.87	1.968	3.50	−9.71	−16.71	0.163	−0.066	5.76
	3.13	19.25	1.15	2.614	3.68	−8.54	−14.54	0.236	−0.058	5.42
	4.63	28.47	1.70	3.865	3.85	10.17	1.12	0.284	0.070	4.45
	5.37	33.00	1.97	4.482	3.33	6.78	0.78	0.341	0.046	4.24
	6.34	38.98	2.33	5.290	3.10	15.00	3.00	0.427	0.103	3.89
	7.30	44.88	2.68	6.095	3.04	7.18	4.18	0.514	0.049	3.64
	8.05	49.49	2.96	6.724	3.04	24.75	8.39	0.589	0.169	3.30
C6 trimmed aft	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.60	−10.37	−19.62	0.101	−0.071	5.26
	2.36	14.49	0.87	1.968	3.75	−0.18	−14.52	0.168	−0.001	5.10
	3.13	19.25	1.15	2.614	4.73	9.36	−6.39	0.204	0.064	4.68
	4.63	28.47	1.70	3.865	3.05	13.54	10.43	0.273	0.093	3.75
	5.37	33.00	1.97	4.482	2.59	14.06	11.38	0.323	0.096	3.68

(continued on next page)

(*continued*)

	6.34	38.98	2.33	5.290	2.07	16.70	13.75	0.399	0.114	3.32
	7.30	44.88	2.68	6.095	2.01	21.27	19.17	0.473	0.145	3.12
	8.05	49.49	2.96	6.724	2.01	24.99	21.42	0.527	0.171	2.90
C6 trimmed fore	**V_M [m/s]**	**V_S [Knots]**	Fr_L	**Fr_∇**	**τ [deg]**	**Z_G [mm] + up**	**Z_O [mm] + up**	**$\frac{RT_M}{\Delta}$**	**$\frac{Z_G}{\nabla^{1/3}}$**	**$\frac{S_W}{\nabla^{2/3}}$**
	1.29	7.93	0.47	1.077	1.90	−12.79	−17.83	0.073	−0.087	5.69
	2.36	14.49	0.87	1.968	3.62	−2.27	−19.66	0.153	−0.016	5.53
	3.13	19.25	1.15	2.614	3.68	1.26	−18.27	0.234	0.009	5.48
	4.63	28.47	1.70	3.865	4.88	15.43	−7.78	0.279	0.105	4.71
	5.37	33.00	1.97	4.482	4.54	16.64	−5.46	0.338	0.114	4.19
	6.34	38.98	2.33	5.290	4.02	19.51	−1.32	0.424	0.133	3.99
	7.30	44.88	2.68	6.095	3.96	23.21	−1.46	0.511	0.159	3.78
	8.05	49.49	2.96	6.724	3.73	28.23	9.16	0.582	0.193	2.75

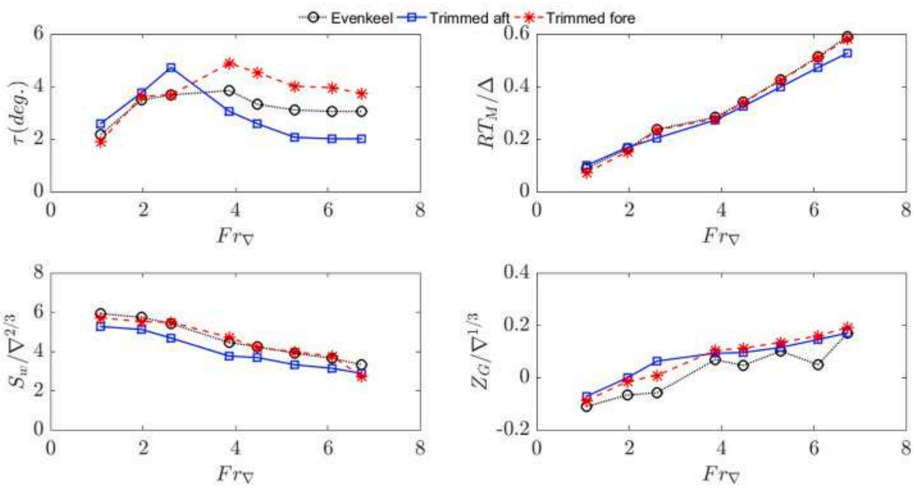

Fig. 14. Results of C06 hull for dynamic trim, resistance, wetted surface, and dynamic sinkage at states of even keel, trimmed aft, and trimmed fore.

Hull model C07_2_60_0

ID number	Steps Number; N_S	Step Height; H_S [mm]	Longitudinal Step Position; LSP [mm]	Longitudinal Center of Buoyancy; LCB [mm]
C07_2_60_0	**2**	**6**	**0:** **step 1 = 149 mm** **step 2 = 302 mm**	**307**

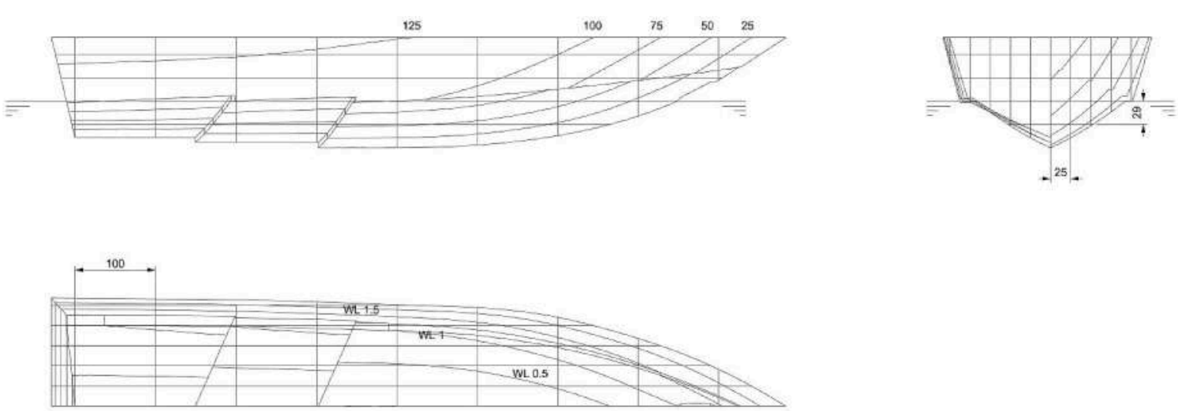

Fig. 15. C07 model lines plan: Sheer Plan, body plan, half breadth plan. Transversal section every 0.100 m, buttock line every 0.025 m, water lines every 0.029 m.

Hull model C07_2_60_0 - calm water towing tank test data.

C7 evenkeel	**V_M [m/s]**	**V_S [Knots]**	Fr_L	**Fr_∇**	**τ [deg]**	**Z_G [mm] + up**	**Z_O [mm] + up**	**$\frac{RT_M}{\Delta}$**	**$\frac{Z_G}{\nabla^{1/3}}$**	**$\frac{S_W}{\nabla^{2/3}}$**
	1.29	7.93	0.47	1.077	1.95	−11.75	−21.73	0.089	−0.080	5.74
	2.36	14.49	0.87	1.968	3.33	−0.68	−18.05	0.189	−0.005	5.51
	3.13	19.25	1.15	2.614	3.15	6.51	−7.47	0.294	0.045	5.17
	4.63	28.47	1.70	3.865	3.21	21.94	5.68	0.279	0.150	4.64
	5.37	33.00	1.97	4.482	3.21	18.68	1.83	0.308	0.128	4.25
	6.34	38.98	2.33	5.290	2.75	21.67	7.31	0.406	0.148	3.75
	7.30	44.88	2.68	6.095	2.52	21.56	8.23	0.519	0.147	3.27
	8.05	49.49	2.96	6.724	2.41	22.60	10.27	0.599	0.154	2.91
C7 trimmed aft	**V_M [m/s]**	**V_S [Knots]**	Fr_L	**Fr_∇**	**τ [deg]**	**Z_G [mm] + up**	**Z_O [mm] + up**	**$\frac{RT_M}{\Delta}$**	**$\frac{Z_G}{\nabla^{1/3}}$**	**$\frac{S_W}{\nabla^{2/3}}$**
	1.29	7.93	0.47	1.077	2.30	−4.72	−14.30	0.104	−0.032	5.85
	2.36	14.49	0.87	1.968	3.29	4.55	−9.50	0.196	0.031	5.57
	3.13	19.25	1.15	2.614	3.80	12.33	−1.43	0.222	0.084	5.34
	4.63	28.47	1.70	3.865	2.88	22.28	11.33	0.261	0.152	4.60
	5.37	33.00	1.97	4.482	2.41	21.60	11.67	0.302	0.148	4.19
	6.34	38.98	2.33	5.290	1.95	28.38	11.76	0.401	0.194	3.64
	7.30	44.88	2.68	6.095	1.67	24.13	19.79	0.514	0.165	3.21
	8.05	49.49	2.96	6.724	1.72	24.64	19.95	0.605	0.168	2.86
C7 trimmed fore	**V_M [m/s]**	**V_S [Knots]**	Fr_L	**Fr_∇**	**τ [deg]**	**Z_G [mm] + up**	**Z_O [mm] + up**	**$\frac{RT_M}{\Delta}$**	**$\frac{Z_G}{\nabla^{1/3}}$**	**$\frac{S_W}{\nabla^{2/3}}$**
	1.29	7.93	0.47	1.077	1.72	−9.87	−18.38	0.084	−0.067	5.73
	2.36	14.49	0.87	1.968	3.50	−4.43	−22.74	0.189	−0.030	5.50
	3.13	19.25	1.15	2.614	3.82	0.23	−14.83	0.296	0.002	5.17
	4.63	28.47	1.70	3.865	4.24	12.39	−12.12	0.292	0.085	4.67
	5.37	33.00	1.97	4.482	4.19	14.08	−7.88	0.336	0.096	4.34
	6.34	38.98	2.33	5.290	3.90	18.48	−1.88	0.429	0.126	3.88
	7.30	44.88	2.68	6.095	3.56	17.94	−1.18	0.548	0.123	3.38
	8.05	49.49	2.96	6.724	3.33	22.17	4.69	0.646	0.152	3.03

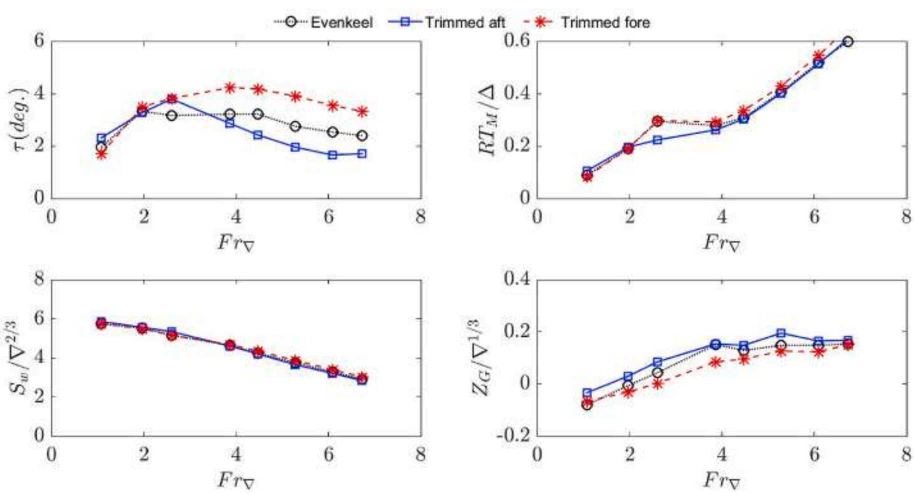

Fig. 16. Results of C07 hull for dynamic trim, resistance, wetted surface, and dynamic sinkage at states of even keel, trimmed aft, and trimmed fore.

Hull model C08_2_20_1

ID number	Steps Number; N_S	Step Height; H_S [mm]	Longitudinal Step Position; LSP [mm]	Longitudinal Center of Buoyancy; LCB [mm]
C08_2_20_1	**2**	**2**	**+1.4:** **step 1 = 288 mm** **step 2 = 441 mm**	**282**

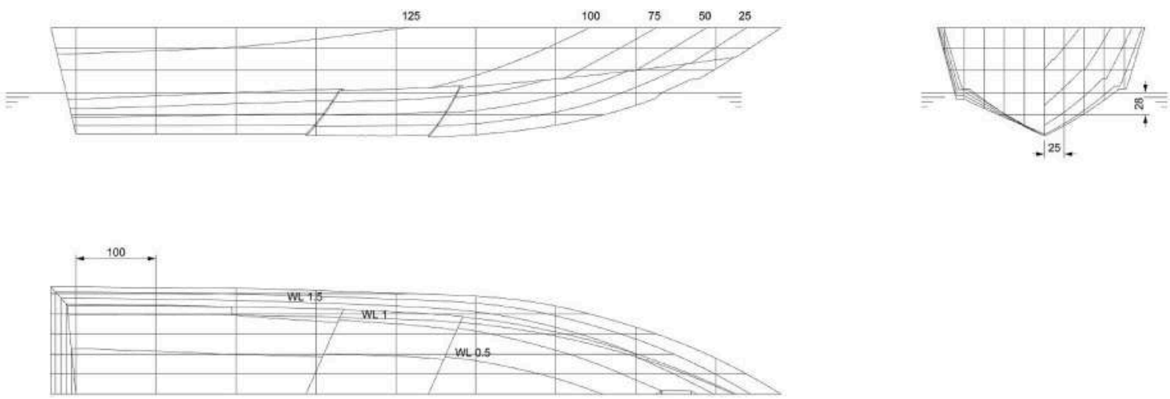

Fig. 17. C08 model lines plan: Sheer Plan, body plan, half breadth plan. Transversal section every 0.100 m, buttock line every 0.025 m, water lines every 0.028 m.

Hull model C08_2_20_1 - calm water towing tank test data.

C8 evenkeel	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.42	−8.48	−20.11	0.101	−0.058	5.76
	2.36	14.49	0.87	1.968	3.74	−0.24	−17.82	0.175	−0.002	5.59
	3.13	19.25	1.15	2.614	4.54	9.54	−8.92	0.216	0.065	4.92
	4.63	28.47	1.70	3.865	3.28	20.99	6.03	0.296	0.143	4.18
	5.37	33.00	1.97	4.482	2.82	19.35	8.16	0.347	0.132	4.01
	6.34	38.98	2.33	5.290	2.64	19.97	8.57	0.419	0.137	3.85
	7.30	44.88	2.68	6.095	2.58	21.45	10.63	0.485	0.147	3.42
	8.05	49.49	2.96	6.724	2.64	28.20	18.06	0.536	0.193	3.04
C8 trimmed aft	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.59	−10.00	−17.69	0.111	−0.068	5.15
	2.36	14.49	0.87	1.968	4.37	3.11	−13.23	0.189	0.021	5.00
	3.13	19.25	1.15	2.614	4.20	9.32	−2.08	0.218	0.064	4.28
	4.63	28.47	1.70	3.865	2.64	12.34	11.70	0.279	0.084	3.66
	5.37	33.00	1.97	4.482	2.12	13.12	12.26	0.324	0.090	3.39
	6.34	38.98	2.33	5.290	1.84	16.40	15.50	0.390	0.112	3.14
	7.30	44.88	2.68	6.095	1.72	20.97	19.61	0.459	0.143	3.03
	8.05	49.49	2.96	6.724	1.84	24.67	21.50	0.491	0.169	2.62
C8 trimmed fore	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.290	7.93	0.47	1.077	2.25	−7.58	−18.84	0.091	−0.052	5.87
	2.357	14.49	0.87	1.968	3.80	−0.74	−19.03	0.173	−0.005	5.70
	3.131	19.25	1.15	2.614	4.55	5.61	−15.70	0.222	0.038	5.20
	4.629	28.47	1.70	3.865	3.85	18.46	−1.49	0.306	0.126	4.53
	5.368	33.00	1.97	4.482	3.57	19.00	2.99	0.359	0.130	4.06
	6.336	38.98	2.33	5.290	3.28	19.82	4.98	0.437	0.135	3.73
	7.301	44.88	2.68	6.095	3.22	24.17	10.17	0.508	0.165	3.37
	8.054	49.49	2.96	6.724	3.27	24.08	10.14	0.556	0.165	3.18

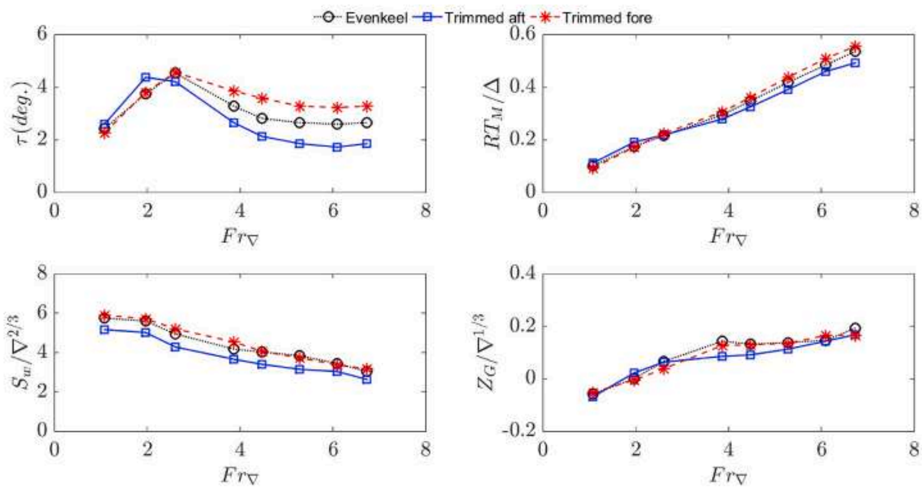

Fig. 18. Results of C08 hull for dynamic trim, resistance, wetted surface, and dynamic sinkage at states of even keel, trimmed aft, and trimmed fore.

Hull model C09_2_60_1

ID number	Steps Number; N_S	Step Height; H_S [mm]	Longitudinal Step Position; LSP [mm]	Longitudinal Center of Buoyancy; LCB [mm]
C09_2_60_1	**2**	**6**	+**1.4:** **step 1 = 290 mm** **step 2 = 443 mm**	**310**

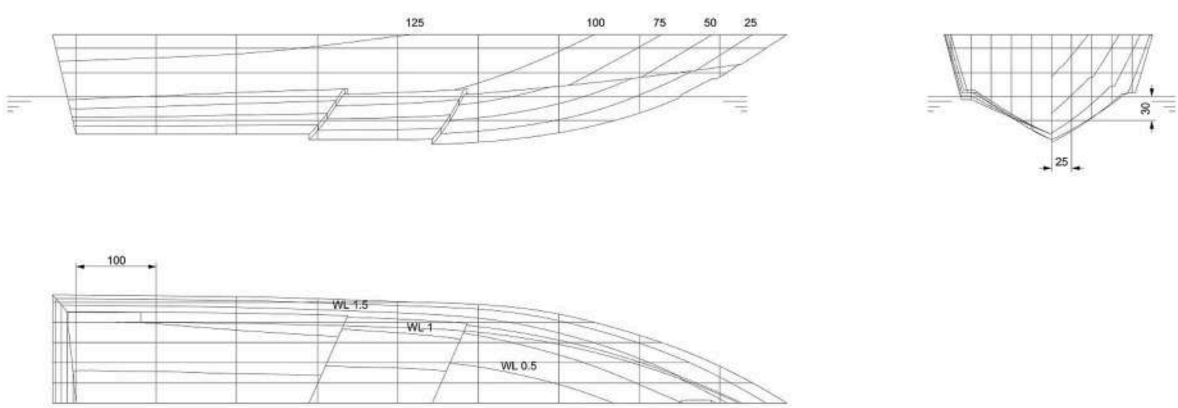

Fig. 19. C09 model lines plan: Sheer Plan, body plan, half breadth plan. Transversal section every 0.100 m, buttock line every 0.025 m, water lines every 0.030 m.

Hull model C09_2_60_1 - calm water towing tank test data.

C9 evenkeel	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	1.55	−10.35	−12.01	0.090	−0.071	6.64
	2.36	14.49	0.87	1.968	3.33	0.23	−15.04	0.188	0.002	6.45
	3.13	19.25	1.15	2.614	3.33	4.67	−11.16	0.213	0.032	3.78
	4.63	28.47	1.70	3.865	3.33	14.59	1.18	0.285	0.100	2.88
	5.37	33.00	1.97	4.482	3.10	17.15	2.57	0.319	0.117	2.44
	6.34	38.98	2.33	5.290	3.04	21.21	5.43	0.393	0.145	2.24
	7.30	44.88	2.68	6.095	2.70	24.47	6.24	0.535	0.167	2.14
	8.05	49.49	2.96	6.724	2.64	27.38	9.47	0.614	0.187	1.99
C9 trimmed aft	V_M [m/s]	V_S [Knots]	Fr_L	Fr_∇	τ [deg]	Z_G [mm] + up	Z_O [mm] + up	$\frac{RT_M}{\Delta}$	$\frac{Z_G}{\nabla^{1/3}}$	$\frac{S_W}{\nabla^{2/3}}$
	1.29	7.93	0.47	1.077	2.01	−10.01	−16.98	0.096	−0.068	6.68
	2.36	14.49	0.87	1.968	3.50	1.00	−14.58	0.209	0.007	6.49
	3.13	19.25	1.15	2.614	3.38	7.05	−4.60	0.216	0.048	4.08
	4.63	28.47	1.70	3.865	2.52	13.14	8.93	0.276	0.090	2.80

(continued on next page)

(*continued*)

	5.37	33.00	1.97	4.482	2.18	15.19	11.50	0.321	0.104	2.54
	6.34	38.98	2.33	5.290	2.01	18.07	11.45	0.409	0.124	2.20
	7.30	44.88	2.68	6.095	1.84	23.54	18.57	0.535	0.161	2.10
	8.05	49.49	2.96	6.724	1.84	26.11	18.68	0.625	0.178	1.86
C9 trimmed fore	**V_M [m/s]**	**V_S [Knots]**	Fr_L	**Fr_∇**	**τ [deg]**	**Z_G [mm] + up**	**Z_O [mm] + up**	**$\frac{RT_M}{\Delta}$**	**$\frac{Z_G}{\nabla^{1/3}}$**	**$\frac{S_W}{\nabla^{2/3}}$**
	1.29	7.93	0.47	1.077	1.49	−10.69	−12.20	0.061	−0.073	6.64
	2.36	14.49	0.87	1.968	3.51	0.00	−18.16	0.188	−0.000	6.44
	3.13	19.25	1.15	2.614	2.76	1.86	−11.87	0.298	0.013	5.80
	4.63	28.47	1.70	3.865	4.03	15.16	−6.13	0.318	0.104	2.93
	5.37	33.00	1.97	4.482	4.03	17.30	−6.46	0.323	0.118	2.72
	6.34	38.98	2.33	5.290	3.85	21.64	−3.05	0.391	0.148	2.28
	7.30	44.88	2.68	6.095	3.97	26.35	−0.28	0.520	0.180	1.98
	8.05	49.49	2.96	6.724	3.22	28.35	8.25	0.648	0.194	1.68

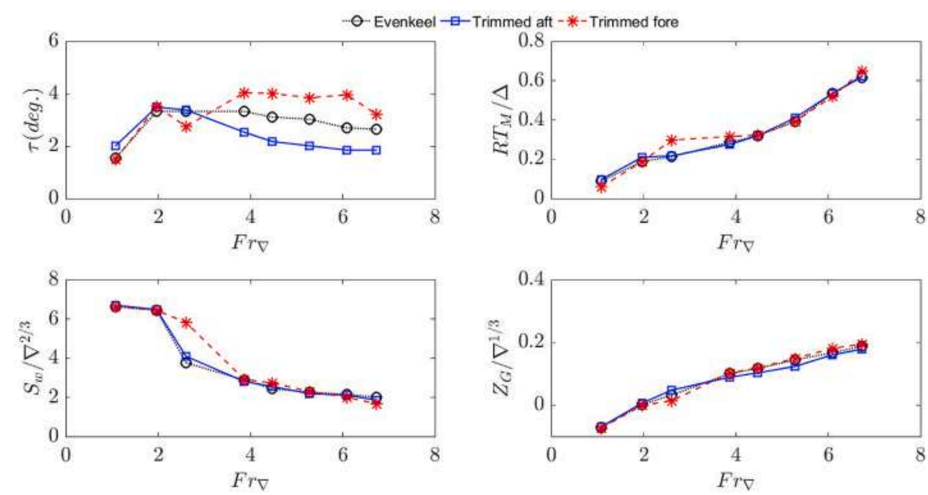

Fig. 20. Results of C09 hull for dynamic trim, resistance, wetted surface, and dynamic sinkage at states of even keel, trimmed aft, and trimmed fore.

Appendix B. Experimental uncertainty analysis

Uncertainty Analysis (UA) in Experimental Fluid Dynamics (EFD) has been also performed according to ITTC (7.5-02-02-02, 2002) only for C03 as reported in De Marco et al. (2017).

The UA was performed in two-phase: in the first phase for each variable *r* (model geometry, displacement, speed, resistance, density, running trim, and sinkage). In a second phase for non-dimensional coefficients (RT_M/Δ, τ, $Z_G/\nabla^{1/3}$, and $S/\nabla^{2/3}$). The methodology proposed for UA is in accordance with Coleman and Steele (1999), considering a confidence interval of 95% and a normal distribution with a large sample size with estimates of:

- bias (B_r), also called systematic uncertainty, is evaluated as the Root Sum of Square (RSS) of each elementary error source (i.e., calibration, data acquisition, data reduction, and conceptual bias) group of bias errors. Before every evaluation the elementary error sources have been divided and separately estimated;
- precision uncertainty, (P_r), also called random uncertainty, is calculated for each run, on the basis of $P_j(S) = K\ SDev_j$ where $K = 2$ is assumed according to the above-mentioned methodology and $SDev_j$ represents the standard deviation of *j*th run;
- total uncertainty U_r is an RSS of bias B_r and precision P_r.

All evaluation of bias, precision, and the uncertainties for non-dimensional coefficients (RT_M/Δ, τ, $Z_G/\nabla^{1/3}$, $S/\nabla^{2/3}$ and Fr_∇) are summarized in Table 6.

The uncertainty is assumed equal for all the other hulls of the VMV systematic series.

Table 6
Experimental uncertainty analysis

Description	Term	Speed								Units
		1.290	2.357	3.131	4.629	5.368	6.336	7.300	8.054	[m/s]
Model Speed										
	Fr_∇	1.077	1.968	2.614	3.864	4.481	5.289	6.094	6.723	[adim]
	B_V	6.97E-04	6.97E-04	3.13E-03	4.62E-03	5.36E-03	6.33E-03	7.29E-03	8.05E-03	[adim]
		22.62%	8.05%	4.73%	2.22%	1.66%	1.20%	0.90%	0.74%	% of $B_{Fr\nabla}$
	B_∇	1.29E-03	2.35E-03	3.13E-03	4.62E-03	5.36E-03	6.33E-03	7.29E-03	8.05E-03	[adim]

(*continued on next page*)

Table 6 (*continued*)

Description	Term	Speed								Units
		1.290	2.357	3.131	4.629	5.368	6.336	7.300	8.054	[m/s]
		77.38%	91.95%	95.27%	97.78%	98.34%	98.80%	99.10%	99.26%	% of $B_{Fr\nabla}$
	$B_{Fr\nabla}$	1.47E-03	2.46E-03	3.20E-03	4.68E-03	5.41E-03	6.37E-03	7.33E-03	8.08E-03	[adim]
		0.14%	0.12%	0.12%	0.12%	0.12%	0.12%	0.12%	0.12%	% of Fr_∇
	$P_{Fr\nabla}$	4.38E-03	4.80E-03	5.22E-03	1.08E-02	1.36E-02	1.41E-02	2.08E-02	2.50E-02	[adim]
	$U_{Fr\nabla}$	4.61E-03	5.39E-03	6.13E-03	1.18E-02	1.47E-02	1.54E-02	2.21E-02	2.63E-02	[adim]
		0.43%	0.27%	0.23%	0.30%	0.33%	0.29%	0.36%	0.39%	% of Fr_∇
Model Resistance Ratio										
	R_{TM}/Δ	0.100	0.178	0.204	0.256	0.312	0.407	0.491	0.555	[N/N]
	B_R	6.62E-04	6.68E-04	6.71E-04	6.78E-04	6.86E-04	7.05E-04	7.25E-04	7.42E-04	[N/N]
		97.49%	97.54%	97.56%	97.61%	97.67%	97.78%	97.90%	98.00%	% of $B^2_{RT/\Delta}$
	B_Δ	1.06E-04	1.06E-04	1.06E-04	1.06E-04	1.06E-04	1.06E-04	1.06E-04	1.06E-04	[N/N]
		2.51%	2.46%	2.44%	2.39%	2.33%	2.22%	2.10%	2.00%	% of $B^2_{RT/\Delta}$
	P_R	4.08E-05	1.54E-07	1.54E-07	3.45E-07	2.25E-06	2.25E-06	2.25E-06	1.53E-06	[N/N]
	$U_{RTM/\Delta}$	6.72E-04	6.76E-04	6.79E-04	6.86E-04	6.95E-04	7.13E-04	7.33E-04	7.50E-04	[N/N]
		0.67%	0.38%	0.33%	0.27%	0.22%	0.18%	0.15%	0.14%	% of R_T/Δ
Trim Angle										
	τ	2.23	3.55	3.27	3.27	2.87	2.69	2.52	2.58	[deg]
	$B_{\tau\text{-cw}}$	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	[deg]
		0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	% of B^2_τ
	$B_{\tau\text{-ix}}$	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	[deg]
		33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	% of B^2_τ
	$B_{\tau\text{-iy}}$	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	[deg]
		33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	% of B^2_τ
	$B_{\tau\text{-iz}}$	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	[deg]
		33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	33.33%	% of B^2_τ
	B_τ	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	[deg]
		3.88%	2.44%	2.65%	2.65%	3.02%	3.22%	3.44%	3.36%	% of B^2_τ
	P_τ	0.004	0.003	0.003	0.004	0.012	0.014	0.012	0.012	[deg]
	U_τ	0.087	0.087	0.087	0.087	0.087	0.088	0.087	0.087	[deg]
		3.89%	2.44%	2.65%	2.65%	3.04%	3.26%	3.47%	3.39%	% of τ
Sinkage										
	$Z/\nabla^{1/3}$	−0.080	0.010	0.048	0.085	0.139	0.147	0.151	0.181	[mm/mm]
	$B_{ZCG\text{-cw}}$	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	[mm]
		3.3E-03	3.3E-03	3.3E-03	3.3E-03	3.3E-03	3.3E-03	3.3E-03	3.3E-03	% of B^2_{ZCG}
	$B_{ZCG\text{-lf}}$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	[mm]
		0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	% of B^2_{ZCG}
	$B_{ZCG\text{-la}}$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	[mm]
		0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	% of B^2_{ZCG}
	$B_{ZCG\text{-lb}}$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	[mm]
		0.332	0.332	0.332	0.332	0.332	0.332	0.332	0.332	% of B^2_{ZCG}
	B_{ZCG}	1.735	1.735	1.735	1.735	1.735	1.735	1.735	1.735	[mm]
		14.85%	114.14%	24.96%	14.03%	8.51%	8.07%	7.83%	6.56%	% of B^2_{ZCG}
	P_{ZCG}	6.365	7.120	6.846	4.046	8.755	5.870	6.556	4.864	[mm]
	$B^{1/3}_{Z/\nabla}$	0.016	0.012	0.014	0.017	0.023	0.024	0.025	0.028	[mm/mm]
		20.64%	115.04%	28.79%	20.06%	16.67%	16.45%	16.34%	15.77%	% of $Z/\nabla^{1/3}$
	$P^{1/3}_{Z/\nabla}$	0.025	0.024	0.024	0.019	0.036	0.030	0.032	0.032	[mm/mm]
	$U^{1/3}_{Z/\nabla}$	0.030	0.027	0.028	0.025	0.043	0.038	0.040	0.043	[mm/mm]
		−37.26%	261.37%	58.95%	29.82%	30.96%	26.01%	26.56%	23.52%	% of $Z/\nabla^{1/3}$
Model geometry										
	$S/\nabla^{2/3}$	6.730								
	B_S	0.284								[m^2/m^2]
		80.81%								% of $B^2_{S/\nabla 2/3}$
	$B^{2/3}_\nabla$	0.138								[m^2/m^2]
		19.19%								% of $B^2_{S/\nabla 2/3}$
	$P^{2/3}_{S/\nabla}$	0.032								[m/m]
	$U^{2/3}_{S/\nabla}$	0.317								[m^2/m^2]
		4.72%								%of $S/\nabla^{2/3}$
Density										
	ρ	1000								[kg/m^3]
	B_{r1}	0.071								[kg/m^3]
		1.15%								% of B^2_ρ
	B_{r2}	0.07								[kg/m^3]
		1.12%								% of B^2_ρ
	B_{r3}	0.655								[kg/m^3]
		97.74%								% of B^2_ρ
	B_r	0.663								[kg/m^3]
		0.066%								% of B_r
	P_r	1.00								[kg/m^3]
	U_ρ	1.20								[kg/m^3]
		0.12%								% of r

Appendix C. Visualization of the fluid flow on the bottom of stepped hulls

For a better understanding of wetted surfaces and flow separation phenomenon on the aft body behind the step of stepped hulls under analysis, the top-view snapshot in trimmed forward condition at all speed are shown.

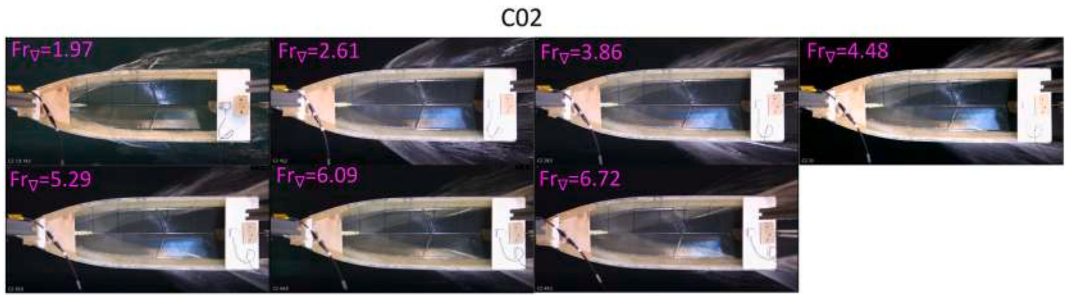

Fig. 21. Wetted surfaces of C02 stepped hull at the different tested speeds - trimmed forward condition.

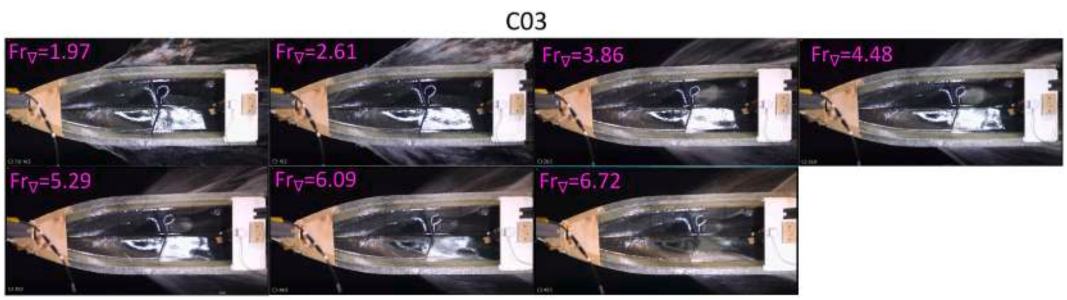

Fig. 22. Wetted surfaces of C03 stepped hull at the different tested speeds - trimmed forward condition.

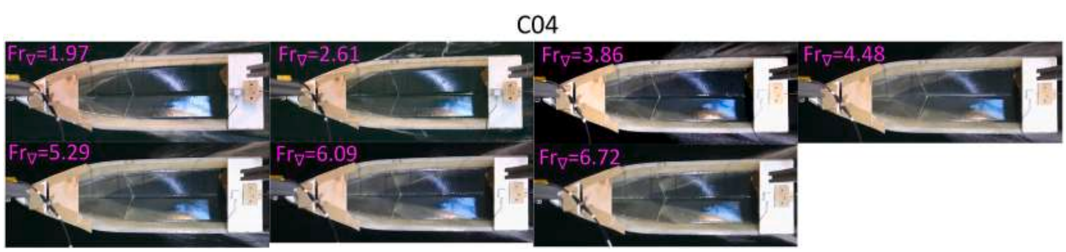

Fig. 23. Wetted surfaces of C04 stepped hull at the different tested speeds - trimmed forward condition.

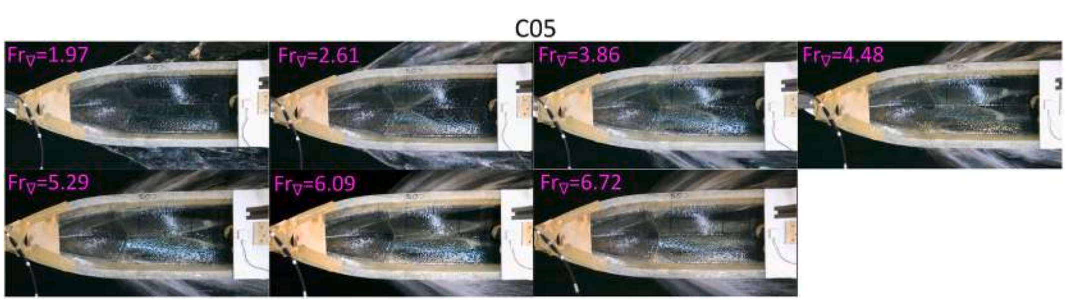

Fig. 24. Wetted surfaces of C05 stepped hull at the different tested speeds - trimmed forward condition.

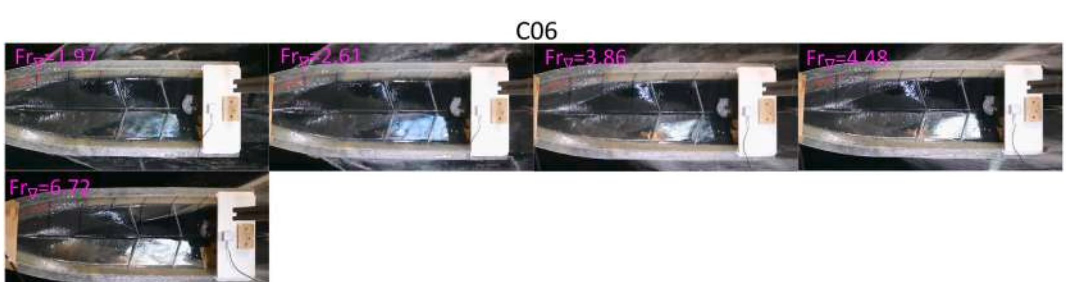

Fig. 25. Wetted surface of C06 stepped hull at the different tested speeds - trimmed forward condition.

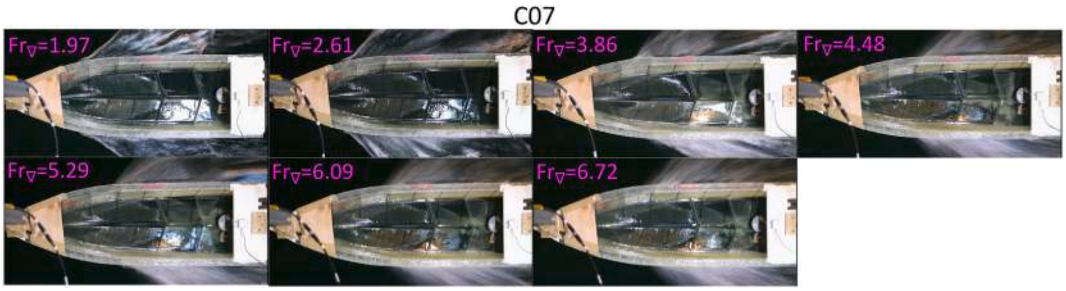

Fig. 26. Wetted surfaces of C07 stepped hull at the different tested speeds - trimmed forward condition.

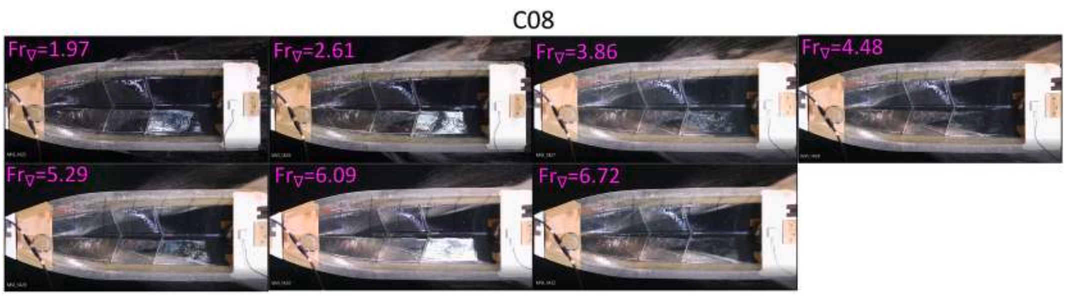

Fig. 27. Wetted surfaces of C08 stepped hull at the different tested speeds - trimmed forward condition.

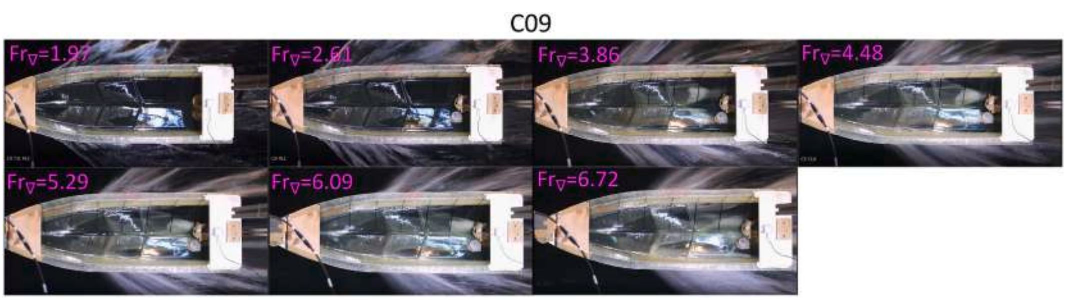

Fig. 28. Wetted surfaces of C09 stepped hull at the different tested speeds - trimmed forward condition.

References

Acampora, B., Racer, S.M., 1995. Design and operation of one of the World's Fastest Monohulls. Mar. Technol. 32.
Akers, 2003. Dancing a Fine Line. Professional BoatBuilder.
Brizzolara, S., Federici, A., 2013. Designing of planing hulls with longitudinal steps: CFD in support of traditional semi-empirical methods. In: Proceedings, Design, Construction & Operation of Super and Mega Yachts Conference, May 8–9, Genoa, Italy.
Clement, E.P., Pope, J.D., 1961. Stepless and Stepped Planing Hulls Graphs for Performance Prediction and Design. David Taylor Model Basin, US Naval Surface Warfare Center, Bethesda (MD).
Clement, E.P., 1964. A Lifting Approach to Planing Boat Design, DTMB Rep 1902.
Clement, E.P., Blount, D.L., 1963. Resistance tests of a systematic series of planing hull forms. Trans SNAME 71, 491–579.
Clement, E.P., Desty, D.H., 1980. The BP Dynaplane high-speed research boat. In: Paper Presented at High-Speed Surface Craft. Third International Hovering Craft and Hydrofoil Exhibition, Brighton, UK.
Clement, E.P., Koelbel, J.O., 1991. Effects of step design on the performance of planing motorboats. In: Paper Presented at Fourth Biennial Power Boat Symposium. The Society of Naval Architects and Marine Engineers, Miami, (FL), USA.
Clement, E.P., Koelbel, J.O., 1992. Optimized designs for stepped planing monohulls and catamarans. In: Paper Presented at HPMV-92, Intersociety High-Performance Marine Vehicles Conference and Exhibit; Washington (DC), USA.
Clement, E.P., 2003. A Configuration for a Stepped Planing Boat Having Minimum Drag. David Taylor Model Basin, US Naval Surface Warfare Center, Bethesda (MD).
Coleman, H.W., Steele, W.G., 1999. Experimentation and Uncertainty Analysis for Engineers. A Wiley Interscience Publication.
Danielsson, J., Strųmquist, J., 2012. Conceptual Design of a High-Speed Superyacht Tender Hull Form Analysis and Structural Optimization [thesis]. Marina System Centre for Naval Architecture, KTH University, Stockholm.
Dashtimanesh, A., Tavakoli, S., Sahoo, P., 2017. A simplified method to calculate resistance and trim of a two stepped planing hull. J Ship Offshore Struct 12 (Suppl. 1), 317–329.
Dashtimanesh, A., Esfandiari, A., Mancini, S., 2018. Performance prediction of two-stepped planing hulls using morphing mesh approach. J Ship Prod Des 34 (3), 236–248.
De Luca, F., Pensa, C., 2017. The Naples warped hard chine hulls systematic series. Ocean Eng 139, 205–236.
De Marco, A., Mancini, S., Miranda, S., Scognamiglio, R., Vitiello, L., 2017. Experimental and numerical hydrodynamic analysis of a stepped planing hull. Appl. Ocean Res. 64, 135–154. https://doi.org/10.1016/j.apor.2017.02.004.
Gabrielli, G., von Kàrmàn, T., 1950. What price speed? Specific power required for propulsion of vehicles. Mech. Eng. ASME 72 (10).
Grigoropoulos, G.J., Loukakis, T.A., 2002. Resistance and seakeeping characteristics of a systematic series in the pre-planing condition (Part I). Trans. SNAME 110, 77–113.
Hubble, E.N., 1974. Resistance of Hard-Chine, Stepless Planing Craft with Systematic Variation of Hull Form, Longitudinal Center of Gravity, and Loading, NSRDC Report 4307.
ITTC, 2002a. Recommended Procedures and Guidelines, 7.5-01-01-01.
ITTC, 2002b. Recommended Procedures and Guidelines, 7.5-02-02-02.
ITTC, 2011. Recommended Procedures and Guidelines, 7.5-02-02-01.
Keuning, J.A., Gerritsma, J., 1982. Resistance tests of a series of planing hull forms with 25 degrees deadrise angle. Int. Shipbuild. Prog. 29 (337).
Keuning, J.A., Gerritsma, J., van Tervisga, P.F., 1993. Resistance Tests of a Series Planing Hull Forms with 30 Degrees Deadrise Angle, and a Calculation Model Based on This and Similar Systematic Series, vol. 25. MEMT, Delft, The Netherlands.
Kowalyshyn, D.H., Metcalf, A., 2006. USCG Systematic Series of High-Speed Planing Hulls, vol. 114. Transactions of the Society of Naval Architects and Marine Engineers, Jersey City, USA.
Lee, E., Pavkov, M., Mccue-Weil, W., 2014. The systematic variation of step configuration and displacement for a double-step planing craft. J Ship Prod Des 30, 89–97.

Miranda, S., Vitiello, L., 2014. Propulsive performance analysis of a stepped hull by model test results and sea trial data. In: High-Speed Marine Vehicles Symposium. Naples.
Moore, W.L., 1967. Cambered Planing Surfaces for Stepped Hulls – Some Theoretical and Experimental Results. David Taylor Model Basin, US Naval Surface Warfare Center, Bethesda (MD).
Niazmand Bilandi, R., Dashtimanesh, A., Tavakoli, S., 2019. Development of a 2D+T theory for performance prediction of double-stepped planing hulls in calm water, Proceedings of the Institution of Mechanical Engineers, Part M. J. Eng. Marit Environ. 233 (3), 886–904.
Niazmand Bilandi, R., Vitiello, L., Mancini, S., Nappo, V., Roshan, F., Tavakoli, S., Dashtimanesh, A., 2020a. Calm-water performance of a boat with two swept steps at high-speeds: laboratory measurements and mathematical modeling. Procedia Manuf. 42, 467–474.
Niazmand Bilandi, R., Dashtimanesh, A., Tavakoli, S., 2020b. Hydrodynamic study of heeled double-stepped planing hulls using CFD and 2D+ T method. Ocean Eng 196, 106813.
Niazmand Bilandi, R., Tavakoli, S., Dashtimanesh, A., 2021. Seakeeping of double-stepped planing hulls. Ocean Engineering 236, 109475. https://doi.org/10.1016/j.oceaneng.2021.109475.
Norman, Skene, 1938. Elements of Yacht Design, sixth ed. Kennedy Bros., New York.
Peters, M., 2010. Peter on (Fast) Powerboats Part 2. Professional BoatBuilder, p. 127.
Savitsky, D., 1964. Hydrodynamic design of planing hull. Mar. Technol. 1, 71–95.
Savitsky, D., Morabito, M., 2010. Surface wave contours associated with the forebody wake of stepped planing hulls. Mar. Technol. 47, 1–16.
Sheingart, Z., 2014. Hydrodynamics of High-Speed Planing Hulls with Partially Ventilated Bottom and Hydrofoils. Master of Science thesis. Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge.
Svahn, D., 2009. Performance Prediction of Hulls with Transverse Steps [thesis]. Marina System Centre for Naval Architecture, KTH University, Stockholm.
Sverchkov, A., 2010. Application of air cavities on high-speed ships in Russia. In: International Conference on Ship Drag Reduction (SMOOTH-Ships), Istanbul.
Taunton, D.J., Hudson, D.A., Shenoi, R.A., 2010. Characteristics of a series of high-speed hard chine planing hulls – part 1: performance in calm water. Trans. R. Inst. Nav. Archit. Part B Int. J. Small Craft Technol. 152 (2), B55–B74. https://doi.org/10.3940/rina.ijsct.2010.b2.96.
Taunton, D.J., Hudson, D.A., Shenoi, R.A., 2011. Characteristics of a series of high-speed hard chine planing hulls part 2: performance in waves. Trans. R. Inst. Nav. Archit. Part B Int. J. Small Craft Technol. 153 (1), B1–B22. https://doi.org/10.3940/rina.ijsct.2011.b1.97.
Vitiello, L., 2022. Github stepped hulls towing tank test [Online]. Available: https://github.com/LuigiVitielloDII/Stepped-Hulls-Towing-Tank-Test.git.
Vitiello, L., Miranda, S., 2016. Towing tank test of stepped hull C03 - university of Naples Federico II, Italy [Online]. Available: https://dx.doi.org/10.6084/m9.figshare.3466010.v1 [Accessed 2016].
Vitiello, L., Miranda, S., Balsamo, F., Bove, A., Caldarella, S., 2012. Stepped hulls: model experimental tests and sea trial data. In: 17th International Conference on Ships and Shipping Research – NAV2012; Naples, Italy.
White, G., Beaver, W., Vann, D., 2012. An experimental analysis of the effects of steps on high-speed planing boats. In: Paper Presented at the Third Chesapeake Power Boat Symposium; Annapolis (MD), USA.