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Calm-water performance of a boat with two swept steps at high-speeds: Laboratory measurements and mathematical modeling

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Abstract

Laboratory measurements are performed to find the performance in calm water of a planing hull with two swept steps. Furthermore, a mathematical model, based on the 2D+T theory, is adapted to provide a fast and accurate simulation for performance prediction of this craft. The trim angle of the vessel is seen to reach to two peaks, one in pre-planing and on in the early planing speed, then converges to a small value around 2 degrees. A small wetted area is seen to appear near the chine of the middle body of the vessel at early planing speed. Laboratory measurements and mathematical computations are seen to be in good agreement, especially at very high-speeds. Overall, the mathematical model is found to be a useful tool for performance prediction of boats with swept steps, which can have different, but better performance in comparison with stepless and boats with transverse steps.

Keywords: Swept steps; planing hulls; calm water performance; laboratory measurments; 2D+T method

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1. Introduction

Stepped planing hulls have sparked up tremendous interest in recent years, and many researchers have tried to provide understanding about their performance in smooth/rough water. These vessels are well known for their special body form, which allows them to operate at higher speeds in a more stable condition (the centre of pressure is shifted toward the transom). A very important advantage of stepped hull respect to a monohull is great longitudinal stability in rough water too. This stability is inside in this hull and respect to the catamaran and the hydrofoil do not need any stability system as reported in [1].

The presence of a step on the bottom of a planing hull has been found to lead inflow (water) separation. Subsequently, the wetted surface of the vessel decreases and another pressure area (accompanied by significant vertical force) emerges in the reattachment region (where the water reaches the bottom) [2, 3]. The step height and its position are found to have significant effects on the performance of the vessel [4, 5]. When the step is located very close to the transom, it may just decrease the resistance of the vessel [6]. Larger step height has been observed to increase the ventilation length, which can also increase the lift force of the vessel. Increasing the number of steps has been seen to be effective, i.e., two steps can make the vessel more stable, while the resistance decreases [7]. Many authors have tried to measure the performance of double-stepped planing hulls (hulls with two

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steps), commenting on the optimum location of the step (see e.g. in [8-10]). But these measurements all helped us to understand the effects of step position on the performance of the vessel. The shape of the step, which can be swept (facing transom/bow) also affects the performance of the vessel [11]. Such an effect has been poorly understood and needs to be investigated. Laboratory measurements that can be performed in the towing tests can be used to provide an early understanding of the performance of boats with swept steps. But, in addition to measurements, we need a method that can provide us with the performance of the vessel rapidly [12].

Different methods have been developed to predict the performance of stepped planing hulls in calm water and waves. Empirical methods, which are developed by adapting Savitsky's method [13] to estimate running attitudes of planing hulls are the first, but the simplest, group of techniques used to model stepped boats in calm water condition. When empirically based equations are used, the most important challenge is to find the free surface elevation behind the step, which may provide us with the wetted area of the lifting surface locating behind it [14]. Some authors have used the empirically based equation proposed by Savitsky and Morabito to find the mentioned wetted area (see e.g. in [15]). But some other authors have used a linear estimation for the wake behind the step (see e. g. in [16]). The former assumption has been found to work well for the case of the one-step hull and the latter is found to work properly for the case of double-stepped planing hulls [17, 18].

Boundary Element Method (BEM), that can solve the linear or fully nonlinear ideal fluid flow around a planing hull is the second technique that can be used to model the performance of a planing hull [19]. Such a method has been previously used to model the stepless vessels (non-step hulls) and has been recently used to simulate the stepped boats [20]. But, most of the methods focus on the prediction of lift force, and neglect performance prediction. In other words, authors rarely used BEM to find the equilibrium condition (while they can), and compute the hydrodynamic pressure acting on the boat. One of the main reasons for doing so is that the BEM can be time-consuming when we need to find the equilibrium condition [21].

Computational Fluid Dynamics (CFD), which offers the numerical simulation of viscous laminar/turbulent two phases flow [22] around a planing hull is another method that can be used to model stepped planing hulls in water and waves [23-26]. The method has good accuracy in the prediction of running attitudes of the boat if proper mesh and model set-up is used [27, 28]. However, the only concern with the method is time. It can be highly time-consuming, needing High-Performance Computers (HPC) to run different cases.

2D+T method is a mathematically based method that can be considered as the last option to model the performance of a stepped planing hull [29]. A transverse plane is assumed to be in the path of the vessel and boat is supposed to pass through it [30]. As a result, the three-dimensional planing problem is reduced to a two-dimensional water entry problem, needed to be solved in time-domain [31]. The method has been used since the 1970s, and provided simulations for different planing problem, from steady performance [32-35] to manoeuvring simulations [36-38]. It has been recently observed that 2D+T method can be used to model the performance of a stepped planing hull operating in water and waves [39-41]. The method has been seen to have reasonable accuracy in prediction of the resistance of the vessel (comparisons were made against laboratory measurements of Ref. [8-10]) and nonlinear behaviour of the vessel in waves.

In the current research, we use the laboratory tests to measure the running attitudes of a planing hull with two swept steps in calm water conditions, which can provide us with meaningful information about the hydrodynamic of such vessels. Besides, we adapt the 2D+T method to provide a reliable fast mathematical tool for computation of the performance of these vessels. The rest of the paper is organized as follows. The experimental model is described in Section 2. The vessel, the materials, and the test plans are all explained this Section. We have formalized the mathematical model in Section 3. Section 4 presents the main results of the current paper, including measurements and computations. We compare measurements against computations and comment on the accuracy of the 2D+T method in this section. A summary of the current research is presented in Section 5.

Nomenclature

B	Beam of the boat
C_f	Frictional coefficient of the i_{th} body
Fr_B	Beam Froude number
L	Length of the boat
L_{CG}	Longitudinal Center of Gravity
S_W	Wetted area of the i_{th} body
V	Forward moving velocity of the boat
β	Deadrise angle of the boat
β_L	Local deadrise angle of the boat of the i_{th} body
Δ	Weight of boat
τ_L	Local trim angle of the i_{th} body
θ	Dynamic trim angle of the hull
R_f	Frictional drag on pressure area
R_s	Frictional drag of Whisker spray
R_p	Pressure drag
R_t	Total resistance of the vessel
g	Gravitational constant
p	Pressure of the i_{th} body
ρ_w	Water density
c	Half beam of spray in transverse plane
C_r	Transom/ step reduction
$f_{\mathcal{HD}}^{2D}$	Hydrodynamic force of each section of the i_{th} body
$f_{\mathcal{HS}}^{2D}$	Hydrostatic force of each section
l	distance from wedge apex in the direction of wedge wall
t	Time
w	Impact velocity
y	Lateral distance from wedge apex
x, y, z	longitudinal (positive forward), transverse (positive starboard), and vertical distances (positive downward) from CG (Oxyz)
ξ, η, ζ	longitudinal (positive forward), transverse (positive starboard), and vertical distances (positive downward)
Subscript z	force component in heave direction
Subscript θ	force component in pitch direction

2. **Experimental model**

2.1 The planing model

A two stepped planing model is built by MV Marine S.r.l. and tests are developed in the towing tank of the University of Naples "Federico II". The vessel has a length of 0.935 m and a (chine) beam of 0.22 m. The maximum beam of the vessel is 0.335 m. The model has two steps. The front step (first step) is located at 0.400 *L* (from transom) and the rear step (second step) is located at 0.158 *L* (from transom). Both steps are swept with an angle of 66.06 degrees and face bow of the vessel. The heights of front and rear steps are respectively 0.0064 *L* and 0.0064 *L*. The vessel is made up of Fiber Reinforced Plastic (FRP). The centre of mass the vessel is located at 0.33 m (from the transom) and 0.085 m (from the bottom). The weight of the vessel is 30.51 N. The body plan of the vessel is shown in Figure 1. Details of the hull model scale are reported in Table 1. A picture of the model, taken in the towing tank, is illustrated in Figure 2.

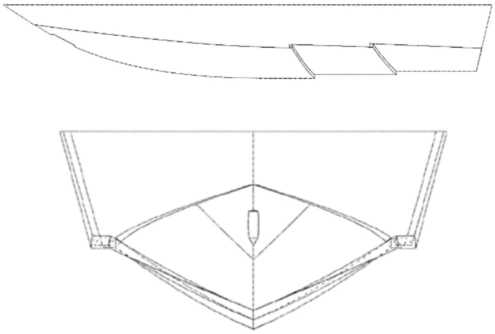


Fig. 1. The body plan of the planing model with two swept steps.

Table 1. The C07 model details.

Parameter	Value
Length overall: L_{OA} (m)	0.935
Breadth max: B_{MAX} (m)	0.335
Deadrise angle at transom (°)	23,0
Steps height (mm)	6
Displacement (N)	30.51
L_{CG} (%L)	35.3
Model scale	1:10

Fig. 2. A picture of the planing model with two swept steps from the top view.

2.2. Test material

Laboratory measurements are performed in the towing tank of the University of Naples "Federico II". The towing tank is 137 m length and 9 m wide. The depth of the tank is 4.25 m. The tank is filled with fresh water with a density of 1000 kg/m^3. A picture showing the tank is displayed in Figure 3. The tank is equipped with different facilities and a wide range of tests, including resistance and wave-induced motions tests can be carried out there. Many different experimental tests have been performed in this tank (see e.g. in [27]). The vessel is towed with a carriage, which can reach a speed up to 10 m/s, attached to the bow of the vessel. A camera moves at the same time, which can take photos from the top view of the vessel. The load cell, located on the towing carriage and connected to the model through a wire, can measure the resistance force acting on the hull model. The calm water resistance experiments were conducted using the "down-thrust" (DT) methodology with a towed point located in the hull bow, more details about this procedure are available in the papers Refs. [27] and [42]. The running attitudes of the vessel, including the trim angle and sinkage, are measured using an accelerometer and lasers, respectively locating on the hull model and on the carriage.

Fig. 3. A view of the towing tank in the University of Naples "Federico II".

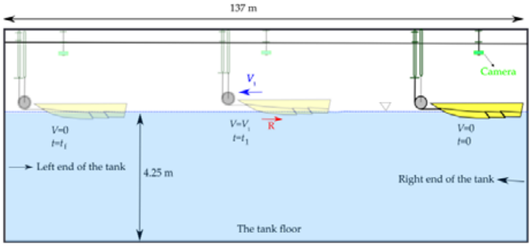


Fig. 4. The schematic of experiments performed to measure the running attitudes and resistance of the vessel.

2.3. The test plans

Tests are performed at eight different speeds covering planing and semi-planing regimes. The minimum tested speed is 1.29 m/s and the maximum tested speed is 8.05 m/s. At each speed, the resistance of the vessel and its running attitudes are measured. Each test is performed several times to assure that the measurements are reliable. To run each test, the vessel is towed in the whole tank. Measurements are calibrated, and the data of the equilibrium is used. The equilibrium condition data corresponding to the condition the longitudinal acceleration of the vessel is zero. The mean value of the recorded resistance and trim angle are set to be the final values. A schematic of the test plan is shown in Figure 4. Note that, the equilibrium condition is set for a length of around 80 m in each test.

3. Mathematical model

3.1. The steady performance of a planing hull

To establish the mathematical model, it is assumed that the vessel is moving with speed V in equilibrium condition as shown in Figure 5 (see the upper panel). Two coordinate systems of $Oxyz$ and $G\zeta\eta\xi$ are considered. The former is a hydrodynamic-frame, which is attached to the vessel but only have longitudinal motion. The latter is a body-frame and can have any motion (see e.g. in Ref. [43]). The thrust force is assumed to pass through the CG of the boat, and thus it doesn't have any influence on the performance of the vessel at all (see similar assumptions in Refs [13] and [44]). The vessel obeys the rigid-body dynamic law, and the governing equation in the equilibrium condition can be established as

$$\sum F_z = 0 \rightarrow W - \mathcal{F}_z = 0 \tag{1}$$

and

$$\sum F_\theta = 0 \rightarrow \mathcal{F}_\theta = 0. \tag{2}$$

for heave (linear vertical) and pitch (angular vertical) directions. F refers to the force or moment acting on the vessel. $\mathcal{F}$ denotes the force or moment caused by the pressure (which can be caused by hydrostatic and hydrodynamic pressure). The resistance of the vessel is assumed to be composed of three components, including the friction (f), spray (s) and pressure (p) [45, 46]. It can be formulated as

$$R_t = R_f + R_p + R_s \tag{3}$$

The body of the vessel is divided into three lifting surfaces, including the fore (shown with i=1), central (shown with i=2), and aft (shown with i=3) bodies. Forces, including pressure forces (in vertical directions) and resistance force acting on the whole planing surface, are assumed to be summations of forces acting on each planing body as

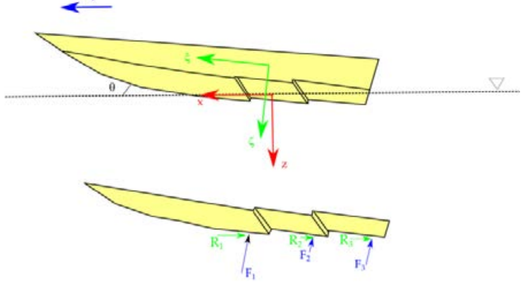


Fig. 5. The planing hull moving forward in calm water condition (upper panel) and forces acting at each lifting surface (lower panel).

$$F_z = \sum_{i=0}^{3} F_{z_i} \tag{4}$$

$$F_\theta = \sum_{i=1}^{3} F_{\theta_i} \tag{5}$$

$$R_f = \sum_{i=1}^{3} R_{f_i} \tag{6}$$

$$R_s = \sum_{i=1}^{3} R_{s_i} \tag{7}$$

$$R_p = \sum_{i=1}^{3} R_{p_i} \tag{8}$$

3.2. 2D+T theory for the double-stepped hull

The pressure forces acting on each lifting surface are found using the 2D+T theory. As explained earlier, when 2D+T theory is used, it is assumed that the vessel passes through a 2D transverse plane. Accordingly, we assume that each lifting surface passes through a plane as shown in Figure 6 [47]. We deal with three water entry problems. For the case of each water entry problem, a solid wedge with a beam of B enters water with vertical speed of

$$w = V \sin(\theta + \tau_L). \tag{9}$$

where θ is the trim angle of the vessel and τ_L is the local trim angle of the lifting surface (see details in Refs. [15, 16]). The time is converted to a longitudinal position using

$$\xi = -\frac{Vt}{\cos(\theta + \tau_L)} + L_{CG}. \tag{10}$$

where L_{CG} is the longitudinal position of CG.

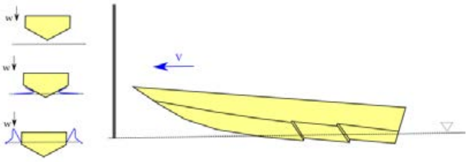


Fig. 6. 2D+T theory for a planing hull.

The hydrodynamic pressure acting on the wedge is computed using the Bernoulli equation and Wagner solution as

$$p = \rho_w \left(wc\dot{c}(c^{2} - y^2)^{-1/2} - 0.5w^2 y^2 (c^{2} - y^2)^{-1} \right) \tag{11}$$

where ρ_w is the water density. c and $\dot{c}$ respectively refer to the spray position root and its time rate, which depend on the deadrise angle of the section [48, 49]. The formulation for the determination of these two parameters is presented in [39]. Here, y refers to the transverse distance from the centre of the section. The sectional hydrodynamic forces are found by integrating the pressure over the wetted area of the wedge as [50],

$$f_{\mathcal{HD}}^{2D} = \int_{\ell} \left(p\cos\left(\beta + \beta_L\right)\right) d\ell . \tag{12}$$

where β_L is the local deadrise angle of the lifting surface (details are given in Ref. [16]). The sectional hydrostatic force of the lifting surface is computed as

$$f_{\mathcal{HS}}^{2D} = \rho g \mathcal{A}, \tag{13}$$

where $\mathcal{A}$ is the wetted area of the wedge, which is found by assuming the water-pile up (see details in [51]). The final force acting on each section is computed by integrating the sectional force over the length of the lifting surface as

$$\mathcal{F}_z = \int_{L_K} -C_r\left(\xi\right)\left(f_{\mathcal{HD}}^{2D}\, sin\left(\theta + \tau_L\right) + f_{\mathcal{HS}}^{2D}\right) d\xi \tag{14}$$

where $C_r\left(\xi\right)$ is an empirical function that is used to implement the influences of the step/transom (Kutta boundary condition) on the pressure [52, 53]. The pitching moment of each planing surface is found by

$$\mathcal{F}_\theta = \left(\begin{array}{l} -\int_{Lk} C_r(\xi) f_{\mathcal{HD}}^{2D} \cos(\theta + \tau_L)\xi d\xi \\ \qquad - \int_{Lk} C_r(\xi) f_{\mathcal{HD}}^{2D} \xi d\xi \end{array} \right) \tag{15}$$

3.3. 2D+T theory for the double-stepped hull with swept steps

The frictional resistance of the vessel is computed by

$$R_f = \frac{1}{2}\rho S_w V^2 C_f ; \tag{16}$$

where S_w is the wetted surface of the *i*-th lifting surface and is found by

$$S_w = \int_{\xi_k}^{\xi_c} \frac{c}{\cos(\beta + \beta_L)} d\xi + \int_{\xi_c}^{\xi_{T \text{ or } S}} \frac{b}{\cos(\beta + \beta_L)} d\xi ; \tag{17}$$

where ξ_k and ξ_c refer to the longitudinal sections at which the keel and the chine get wetted for the very first time. C_f is the frictional force coefficient and is computed using the ITTC 78 [54]. The frictional force caused by the spray is estimated using

$$R_s = \frac{1}{2}\rho S_s V^2 C_f \tag{18}$$

where

$$S_s = \int_{\xi_k}^{\xi c} \frac{\{\xi \tan(1.5(\tan^{-1}(c/\xi))) - c\}}{\cos(\beta + \beta_L)} d\xi + \int_{\xi c}^{\xi_{T \text{ or S}}} \frac{(b-c)}{\cos(\beta + \beta_L)} d\xi \tag{19}$$

The pressure drag is computed by

$$R_p = -\int_{Lk} C_r(\xi) f_{\mathcal{HD}}^{2D}\, sin(\theta + \tau_L) d\xi \tag{20}$$

3.4. Guideline for performing the computations

Running attitudes of the vessel along with its resistance are found using an iterative scheme. Initial values for the trim angle and keel wetted length of the vessel are first guessed. Then the mathematical method is used, and heave force acting on the vessel is found. It is checked whether the computed heave force leads to equilibrium condition in heave direction or not. The equation

$$\left|F_z - W\right| < \varepsilon \tag{21}$$

helps us to do so. If the Eq. 21 was not satisfied, a new keel wetted length is guessed. This loop last as long as the equation is not satisfied. As the equilibrium condition in the heave equation was found, it is evaluated whether the computed pitch moment satisfies the equilibrium condition through

$$\left|F_\theta\right| < \varepsilon . \tag{22}$$

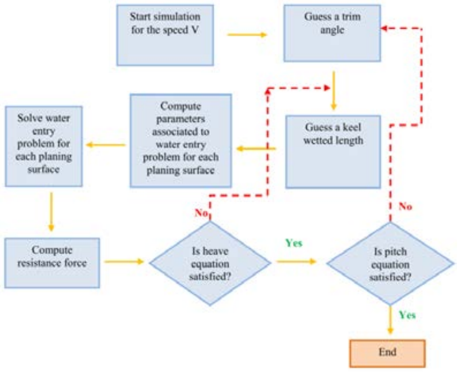


Fig. 7. The computation algorithm used for computation of the calm-water performance of the vessel.

If equation 22 is not satisfied, a new value for the trim angle is guessed. The iterations are performed until the correct trim angle and is found. The resistance of the vessel is then found by substituting the computed values for trim angle and wetted length in equations 16 through 20.

4. Results

Measured and mathematically computed values of resistance, trim angle and wetted area of the vessel are reported in this section.

Figure 8 shows the values of resistance at different Froude Numbers (*R* vs. Fr_B). The resistance of the vessel is seen to be increased by the increase in Froude Number as expected. As seen, the resistance of the vessel slightly increases at beam Froude Numbers ranging from 0.71 to 2.55, and then the slope of the increase in resistance grows ($Fr_B > 2.96$). Results of 2D+T method (circle symbols) are seen to agree with measured data (plus symbols) at most of the speeds. Mathematical results are seen to follow the experimental results. The largest error is seen to occur at beam Froude Number of 1.72 (see Table 2). Note that, this Froude Number doesn't correspond to the fully planing regime. The error can be attributed to the transition from pre-planing to fully planing, which is needed to be further investigated in future.

Table 2. Errors of the 2D+T method in prediction resistance, trim angle and wetted area at different speeds.

V (m/s)	Fr_B	E_τ%	E_R%	E_{S_w} %
V (m/s)	0.71	8.17	-0.36	17.93
1.29±0.0015	1.30	-5.23	4.55	17.47
2.36±0.0036	1.73	-3.28	23.55	14.70
3.13±0.0056	2.55	14.59	6.19	15.99
4.63±0.0106	2.96	-5.67	7.57	14.30
5.37±0.0129	3.50	-3.61	4.17	8.03
6.34±0.0145	4.03	11.03	1.17	-0.81
7.30±0.0177	4.44	-9.25	7.15	5.60

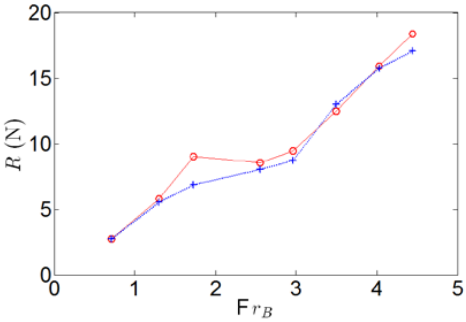


Fig. 8. The resistance of the studied planing model at different Froude Numbers. Circle and plus markers respectively refer to the laboratory measurements and mathematical results. Average experimental precision error measurement of model resistance, performed in accordance with [55], is 0,42% of resistance measured.

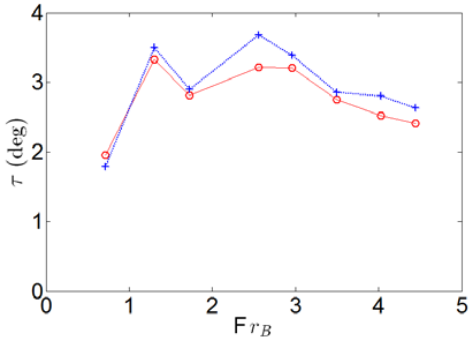


Fig. 9. As of Fig. 8, but for the trim angle. Average experimental precision error measurement of trim angle, performed in accordance with [55], is ±0,012 deg.

As shown in the legend, measured (plus symbols) and computed (circle symbols) values of trim angle are presented in Figure 9. The trim angle of the vessel is seen to increase from 1.8 degrees to 3.4 degrees as Fr_B increases from 0.71 to 1.3. Then, the trim angle is seen to decreases and reaches 2.7. But the trim angle again increases as the Beam Froude Number increases from 1.73 to 2.55. At larger Froude Numbers, the trim angle slightly decreases and converges to 2 degrees. Mathematical predictions are observed to be in good agreement with experimental data. The 2D+T method under-predicts trim angles at most of the speeds, but the error never goes beyond 15 percentage. The maximum error is seen to occur at beam Froude Number of 2.55. Note that the resistance was predicted with fair accuracy at this speed. Overall, the accuracy of the 2D+T method in the prediction of the resistance of the vessel is satisfactory. Moreover, both mathematical and experimental observations showed two peaks exists in the τ vs. Fr_B plots, which is not common for the case of non-stepped planing hull and doubled-stepped planing hulls with transverse steps.

The wetted area of the vessel is reported in Figure 10. Both measurements and computations are presented in this figure. The wetted area of the vessel is seen to decrease by the increase in speed but finally converges to a constant value. At the smallest speed, the results of 2D+T method and measured values don't fit. But, by the increase in the speed, the converge to each other, and match. Overall, the 2D+T method has favourable accuracy in the prediction of the wetted area of the planing boat with two swept steps.

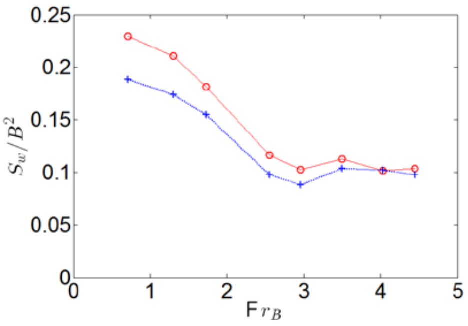
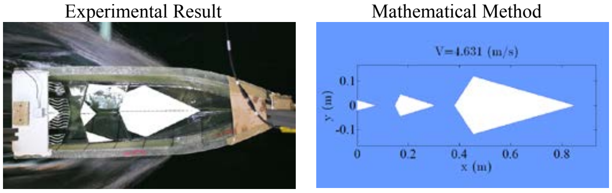


Fig. 10. As of Fig. 8, but for the wetted area.


Experimental Result

Mathematical Method

Fig. 11. Comparison of the wetted area pattern found in experiments (upper panel) against what was observed in computations (lower panel) at beam Froude Number of 2.55. The line area near the transom is a mixed air/water flow.

Figure 11 shows the top view of the measured (upper pane) and computed the wetted surface of the vessel at the speed of 4.61 m/s, which corresponds to the beam Froude Number of 2.55. The wetted area of the front area of the vessel is seen to be like the measured wetted area. The computed wetted area of the middle lifting surface is seen to be different from what was observed in laboratory measurements. In the measurements, a wetted area is observed to emerge, which is not found by mathematical simulations. The wetted area near the keel, however, is seen to be larger. Overall, the area of the wetted surface of the middle body is found to be like experimentally measured value.

5. Conclusion remarks

In the current paper, the calm water performance of a planing model with two swept steps was studied to improve the understanding of the performance of the stepped hull. The performance of the model was tested in a towing tank, located in the University of Naples “Federico II”, at different speeds, ranging from pre-planing to clean planing. A mathematical method was also developed using the 2D+T theory, which can provide us with a fast tool for simulation of the steady performance of boats with swept steps.

Results indicated that two peaks exist in the trim angle vs. Froude Number plot of the vessel, which is not common for the stepless boats. The wetted area of the boat, as well as its trim angle, were found to converge by the increase in the beam Froude Number of the vessel. Results of the 2D+T method were seen to agree with the laboratory measurements, especially at very high-speeds. The accuracy of the 2D+T method in the pre-planing regime was satisfactory. Pictures taken from the top view of the vessel showed that a small wetted surface appears near the chine of the middle lifting surface, which misses in the mathematical computations.

Overall, swept steps can lead to a larger hydrodynamic lift in the middle and rear lifting surfaces of the vessel, reducing the resistance of the vessel. They can be used for different aims, especially when we are seeking for higher speeds. The 2D+T method can be very helpful in prediction of the performance of these boats, but its accuracy in prediction of the wetted area is needed to be increased in the future.

Future works

This paper is a part of a research project with the aim of the validation of the abovementioned mathematical model for the evaluation of performance in still water and wave condition of the planing hull and in particular the stepped hull. The on-going work is about a wide validation campaign involving the mathematical model output, the CFD results, and experimental data of double-stepped hull. These results will be published in an incoming paper.

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References

[1] Giallanza, A., Cannizzaro, L., Porretto, M., Marannano, G., Design of the stabilization control system of a High-Speed craft, Lecture Notes in Mechanical Engineering, 2017, 575-584

[2] Clement, EP, Koelbel JO., Optimized designs for stepped planing monohulls and catamarans. Paper presented at: HPMV-92, Intersociety High Performance Marine Vehicles Conference and Exhibit; Washington (DC), USA, 1992.

[3] Clement, EP, Koelbel, JO. Progress during the past century toward the development of efficient, load-carrying, stepped planing boats. Paper presented at: 5th Biennial Power Boat Symposium. The Society of Naval Architects and Marine Engineers; Miami (FL), USA, 1992.

[4] Dashtimanesh, A., Roshan, F., Tavakoli, S., Kohansal, A., Barmala B., Effects of step configuration on hydrodynamic performance of one-and doubled-stepped planing flat plates: A numerical simulation, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, Published Online, 2019, DOI: 10.1177/1475090219851917.

[5] Garland, WR, Maki, KJ, A numerical study of a two-dimensional stepped planing surface, Ship Production and Design, 2012, 28: 60-72

[6] Clement, EP, Pope, JD., Stepless and stepped planing hulls graphs for performance prediction and design. Bethesda (MD): David Taylor Model Basin, US Naval surface Warfare Center, 1961.

[7] Ghadimi, P., Panahi, S., Tavakoli, S., Hydrodynamic study of a double-stepped planing craft through numerical simulations, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2019, 41(1): 1-15.

[8] Lee E, Pavkov M, Mccue-Weil W., The systematic variation of step configuration and displacement for a double-step planing craft. J Ship Prod Des, 2014, 30: 89–97.

[9] Taunton, D.J., Hudson, D.A. and Shenoi, R.A., Characteristics of a Series of High-speed Hard Chine Planing Hulls Part 1: Performance in Calm Water, International Journal of Small Craft Technology, 2010, 152: B55–B75.

[10] Lee, Evan J., Advancements of Stepped Planing Hulls. PhD Dissertation at Virginia Polytechnic Institute and State University, 2014.

[11] Morabito, On the spray and bottom pressure of planing surfaces, PhD Thesis, 2010.

[12] Niazmand Bilandi, R., Mancini S., Dashtimanesh, A., Tavakoli, S., De Carlini, M., A numerical and analytical way for double-stepped planing hull in regular wave, viii international conference on computational methods in marine engineering marine 2019, Goteborg, Sweden, 2019.

[13] Savitsky, D., Hydrodynamic design of planing hulls, Marine Technology, 1964, 1: 71-94.

[14] Savitsky, D., Morabito, M., Surface wave contours associated with the fore body wake of stepped planing hulls, Marine Technology, 2010, 47(1): 1-16.

[15] Svahn D., Performance prediction of hulls with transverse steps [thesis]. Stockholm: Marina System Centre for Naval Architecture, KTH University, 2009.

[16] Danielsson, J., Strømquist, J., Conceptual design of a high speed superyacht tender hull form analysis and structural optimization [thesis]. Stockholm: Marina System Centre for Naval Architecture, KTH University, 2012.

[17] Dashtimanesh, A., Tavakoli, S., Sahoo, P., Development of a simple mathematical model for calculation of trim and resistance of two stepped planing hulls with transverse steps, In Proceedings of 1st International Conference on Ships and Offshore Structures, Hamburg, Germany, 2016.

[18] Dashtimanesh, A., Tavakoli, S., Sahoo, P., A simplified method to calculate trim and resistance of a two-stepped planing hull, Ships and Offshore Structures, 2017, 12: S317-S329.

[19] Lai, C, Troesch, AW, A vortex lattice method for high-speed planning, International Journal for Numerical Methods in Fluids 1996, 22 (6): 495-513.

[20] Matveev, KI, Two-dimensional modeling of stepped planing hulls with open and pressurized air cavities, International Journal of Naval Architecture and Ocean Engineering, 2012, 4 (2): 162-171.

[21] Bari GS, Matveev KI, Hydrodynamics of single-deadrise hulls and their catamaran configurations, International Journal of Naval Architecture and Ocean Engineering, 2016, 9 (3): 305-314.

[22] Frederick Stern, Zhaoyuan Wang, Jianming Yang, Hamid Sadat-Hosseini, Maysam Mousaviraad, et al., Recent progress in CFD for naval architecture and ocean engineering, Journal of Hydrodynamics, 2015, 27 (1): 1-23.

[23] Dashtimanesh, A., Esfandiari, A., Mancini, S, Performance Prediction of Two-Stepped Planing Hulls Using Morphing Mesh Approach. Journal of Ship Production and Design, 2018, 10.5957/JSPD.160046.

[24] Esfandiari, A., Tavakoli, S., Dashtimanesh, A., Comparison between the Dynamic Behavior of the Non-stepped and Double-stepped Planing Hulls in Rough Water: A Numerical Study, Journal of Ship Production and Design, Published Online, 2019, DOI: 10.5957/JSPD.11170053.

[25] Ghadimi, P., Dashtimanesh, A., Farsi, M., Najafi, S., Investigation of free surface flow generated by a planing flat plate using smoothed particle hydrodynamics method and FLOW3D simulations, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 2013, 227(2): 125-135.

[26] Dashtimanesh, A., Ghadimi, P., A three-dimensional SPH model for detailed study of free surface deformation, just behind a rectangular planing hull, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2013, 35(4): 369-380.

[27] De Marco, A., Mancini, S., Miranda, S., Scognamiglio, R., Vitiello, L., Experimental and numerical hydrodynamic analysis of a stepped planing hull, Applied Ocean Research, 2017, 64: 135-154.

[28] De Luca, F., Mancini, S., Miranda, S., Pensa, C., An extended verification and validation study of CFD simulations for planing hulls, Journal of Ship Research, 2017, 60 (2): 101-118.

[29] Ghadimi, P., Tavakoli, S. and Dashtimanesh, A., Calm water performance of hard-chine vessels in semi-planing and planing regimes. Polish Maritime Research, 2016, 4: 23-45.

[30] Ghadimi, P., Tavakoli, S., Dashtimanesh, A., Taghikhani P, Dynamic response of a wedge through asymmetric free fall in 2 degrees of freedom, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 2019, 223: 229-250.

[31] Iafrati, A. and Broglia, R., May. Comparisons between 2D+ T potential flow models and 3D RANS for planing hull hydrodynamics. In Proceedings of 25th international workshop on water waves and floating bodies, Harbin, China, 2010.

[32] Ghadimi, P., Tavakoli, S., Dashtimanesh, A., Coupled heave and pitch motions of planing hulls at non-zero heel angles. Applied Ocean Research, 2016, 59: 286-303.

[33] Ghadimi, P., Tavakoli, S., Dashtimanesh, A., An analytical procedure for time domain simulation of roll motion of the warped planing hulls. Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment, 2016, 230(4): 600-615.

[34] Ghadimi, P., Tavakoli, S., Dashtimanesh, A., Zamanian, R., Steady performance prediction of heeled planing boat in calm water using asymmetric 2D+T model. Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment, 2017, 231(1): 234-257.

[35] Tavakoli, S., Ghadimi, P., Dashtimanesh, A., A non-linear mathematical model for coupled heave, pitch and roll motions of a high-speed planing hull. Journal of Engineering Mathematics, 2017, 104(1): 157-194.

[36] Tavakoli, S., Dashtimanesh, A., Sahoo, PK., An oblique 2D+T approach for hydrodynamic modeling of yawed planing boats in calm water, Journal of Ship Production and Design, Published Online, 2017, DOI: 10.5957/JSPD.160032.

[37] Dashtimanesh, A., Enshaei, H. and Tavakoli, S., Oblique-Asymmetric 2D+ T Model to Compute Hydrodynamic Forces and Moments in Coupled Sway, Roll, and Yaw Motions of Planing Hulls. Journal of Ship Research, 2018.

[38] Tavakoli, S. and Dashtimanesh, A., Mathematical simulation of planar motion mechanism test for planing hulls by using 2D+ T theory. Ocean Engineering, 2018, 169: 651-672.

[39] Niazmand Bilandi, R., Dashtimanesh, A., Tavakoli, S., 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: Journal of Engineering for the Maritime Environment, 2018.

[40] Niazmand Bilandi, R., Mancini, S., Vitiello, L., Miranda S., De Carlini, M, A validation of symmetric 2D+ T model based on single-stepped planing hull towing tank tests, Journal of Marine Science and Engineering, 2018, 6 (4): 136.

[41] Niazmand Bilandi, R., Dashtimanesh, A., Tavakoli, S., A Nonlinear Mathematical Model for Hydrodynamic Analysis of Unsteady Vertical Motion of Double-Stepped Planing Boats in Regular Waves, Ship Research, Revised, 2019.

[42] Vitiello, L., Scognamiglio, R., Miranda, S., Propulsive performance Analysis of a Stepped Hull by Model Test Results and Sea Trial Data, High Speed Marine Vehicles Symposium, Naples, 2014, ISBN 9788890611216.

[43] Tavakoli S, Dashtimanesh A, A six-DOF theoretical model for steady turning maneuver of a planing hull, Ocean Engineering, 2019, 189: 106328.

[44] Ghadimi, P., Tavakoli, S., Feizi-Chekab MA, Dashtimanesh, A., Introducing a particular mathematical model for predicting the resistance and performance of prismatic planing hulls in calm water by means of total pressure distribution, Journal of Naval Architecture and Marine Engineering, 2015, 12: 73-94.

[45] Savitsky, D., DeLorme, M.F. and Datla, R., Inclusion of whisker spray drag in performance prediction method for high-speed planing hulls. Marine Technology, 2007, 44(1): 35-56.

[46] Ghadimi, P., Tavakoli, S., Dashtimanesh, A. and Pirooz, A., Developing a computer program for detailed study of planing hull's spray based on Morabito's approach. Journal of Marine Science and Application, 2014, 13(4): 402-415.

[47] Tavakoli, S., Najafi S., Amini E, and Dashtimanesh, A., Performance of high-speed planing hulls accelerating from rest under the action of a surface piercing propeller and an outboard engine. Applied Ocean Research, 2018, 77: 45-60.

[48] Izadi M, Ghadimi P, Fadavi M, Tavakoli S, Hydroelastic analysis of water impact of flexible asymmetric wedge with an oblique speed, 2018, 53: 2585-2617.

[49] Javanmardi N, Ghadimi P, Tavakoli S, Probing into the effects of cavitation on hydrodynamic characteristics of surface piercing propellers through numerical modeling of oblique water entry of a thin wedge, Brodogradnja: Teorija i praksa brodogradnje i pomorske tehnike, 2018, 69 (1): 151-168.

[50] Niazmand Bilandi, R., Jamei, S., Roshan, F., Azizi, M., Numerical simulation of vertical water impact of asymmetric wedges by using a finite volume method combined with a volume-of-fluid technique. Ocean Engineering, 2018, 160: 119-131.

[51] Tavakoli, S. and Dashtimanesh, A., and Sahoo, P., Prediction of Hydrodynamic Coefficients of Coupled Heave and Pitch Motions of Heeled Planing Boats by Asymmetric 2D+ T Theory, In: ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering, Madrid, Spain, 2018.

[52] Garme, K., Improved time domain simulation of planing hulls in waves by correction of near-transom lift. International Journal of Shipbuilding Progress, 2005, 52: 201-230.

[53] Tavakoli S, Dashtimanesh A, Running attitudes of yawed planing hulls in calm water: development of an oblique 2D+T approach, Journal of Ships and Offshore Structures, 2017, 12(8), 1086-1099.

[54] ITTC, Recommended Procedures and Guidelines 7.5-02-02-01, 2011.

[55] ITTC, Recommended Procedures and Guidelines 7.5-02-02-02, 2002.