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The hydrodynamic resistance of stepped planing hulls under different geometrical and physical conditions

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Key words: towing tank test, planing hull, transverse step, hydrodynamic resistance, Fridsma, height of the step

Abstract

In this paper, the hydrodynamic resistance of one-step planing craft has been experimentally investigated under different geometrical and physical conditions. For this to be accomplished, a Fridsma body model with different deadrise angles was considered. Moreover, the effect of the longitudinal distance of the step from the transom and the step height on the hydrodynamic resistance of a stepped planing craft has been evaluated at different hull velocities. According to the experimental results, frictional resistance can be enhanced by decreasing the height of the step. However, a greater total resistance can be obtained by increasing the longitudinal distance of the step from the transom. Moreover, it was found that the proportionality of the longitudinal distance of the step from the transom to the step height has a remarkable effect on the hydrodynamic efficiency of the step in stepped planing craft.

Introduction

The use of transverse steps on the bottom of planing craft is one of the main ways to improve the hydrodynamic behavior of these types of vessels. Indeed, the occurrence of fluid flow separation on the step will result in a smaller wetted area and a lower total resistance of these vessels. In addition, a more uniform pressure distribution in the longitudinal direction of these stepped planing craft is visible and causes a delay in undesirable phenomena proposed in the literature (Doctors, 1985; Savitsky & Morabito, 2010). However, the geometrical characteristics of transverse steps and physical conditions such as hull velocities (i.e., Froude number) have a significantly impressive effect on the hydrodynamic behavior of stepped planing craft. Therefore, evaluation of the geometric parameters of transverse steps at different hull velocities is necessary to achieve an efficient transverse step.

Up to now, various experimental, numerical and analytical research has been conducted by scholars to investigate the hydrodynamic behavior of stepped planing craft. The experimental work of Clement and Blount (Clement & Blount, 1963) and Savitsky (Savitsky, 1964) are pioneering studies in the field of planing craft. In the Savitsky (Savitsky, 1964) study, some formulas have been presented in order to estimate the drag and lift forces of a simple body form of a planing craft without a transverse step. Following the Savitsky (Savitsky, 1964) and Shuford (Shuford, 1958) studies, the drag and lift components of the planing surface were studied numerically by Brizzolara and Serra (Brizzolara & Serra, 2007). Savitsky et al. (Savitsky, Delorme & Datla, 2007) investigated the effects of whisker spray on the total resistance of planing hulls by conducting both experimental and analytical studies. In 2010, the aftbody surface wakes of planing craft were also formulated based on an experimental test by Savitsky and Morabito (Savitsky & Morabito, 2010).

In recent years, the effect of wave-piercing and spray rails on resistance components and the sea keeping of a planing craft has been studied experimentally by Seo et al. (Seo et al., 2016). Jiang et al. (Jiang et al., 2016) conducted both an experimental and CFD analysis to investigate the hydrodynamic behavior of a trimaran planing hull at different hull velocities. In 2017, De Marco et al. (De Marco et al., 2017) investigated the fluid flow around a stepped planing craft with one transverse step using laboratory tests and CFD simulations. The effect of artificial air injection on the resistance of stepped planing craft was also studied experimentally by Cucinotta et al. (Cucinotta, Guglielmino & Sfravara, 2017).

In the literature, there have been several experimental works (Clement & Pope, 1961; Clement & Koelbel, 1992; Taunton, Hudson & Shenoi, 2010; Taunton Hudson & Shenoi, 2011; Lee, Pavkov & Mccue-Weil, 2014; Timmins, 2014) and numerical studies (Makasyeyev, 2009; Lotfi, Ashrafizaadeh & Esfahan, 2015; Nourghasemi, Bakhtiari & Ghassemi, 2017) that evaluated the geometric parameters of transverse steps, such as their height and their distance from the transom. Based on the cited works, the lack of a study on the effects of the height and longitudinal distance of the step from the transom on the hydrodynamic resistance of stepped planing craft is evident. Therefore, in this study, the effects of the longitudinal distance of the step from the transom and the step height on the resistance component of one-step planing craft have been investigated experimentally at different hull deadrise angles and velocities.

Experimental setup

The towing tests were conducted in the National Iranian Marine Laboratory (NIMALA), Tehran, Iran (the main specifications of this lab have been listed in Table 1) based on the guidelines of the ITTC, 2002 (Committee, 2002). These tests were done under the conditions of calm water, a water temperature of 293.15 K, a water density of 1002 kg/m^3 and a water viscosity of 1.19E–6 m^2/s.

The Fridsma planing craft has been considered in this study. The dimensions of the model were obtained according to the geometric and dynamic similarities, as well as the parameters and the blockage factor. In Table 2, the dimensions and the main characteristics of the full scale version and the model

Table 1. Dimensions and features of the NIMALA towing tank

Variable	Value
Length (m)	392
Width (m)	6
Water depth (m)	4
Maximum carriage speed (m/s)	19
Maximum capacity of the force gauge (N)	600
Accuracy of the force gauge (FS)	0.02% (maximum force)
Maximum measurement range of the potentiometer (degree)	±30
Accuracy of the potentiometer (degree)	0.01

Table 2. Dimensions and characteristics of the full scale and hull model

Characteristics	Main hull	Model
λ	1	1:8
LoA (m)	20	2.5
B (m)	4	0.5
TFrom keel (m)	2.5	0.312
L/B	5	5
Deadrise angle (deg)	15°, 20°, 30°	15°, 20°, 30°
Δ (ton)	25	0.048
Velocity range (m/s)	14.1–39.6	5–14
LCG	36% LoA from the transom	

of the Fridsma have been tabulated. Based on Table 2, the scale factor was 8 and the model's hull velocity was in the range of 5 m/s up to 14 m/s. A fabricated hull model without a transverse step has also been shown in Figure 1. The Fridsma hull model that was considered is formed from three separate parts including the forebody module, the aftbody module and the connecting block. Fiberglass composite was used for forebody module. High strength Teflon was the material the connecting block was made from. The aftbody module was fabricated as multiple movable blocks that provide the ability to change the longitudinal position and height of the step. The Teflon connecting block that was connected to the forebody module and the aftbody before assembly has been shown in Figure 2.

A schematic of the fabricated model and some locations considered for the step from the transom have been depicted in Figure 3. Table 3 also shows the laboratory tests that were conducted.

In the following sections, the Laboratory test results of the resistance of a stepped planing craft under different geometrical and physical conditions have been presented and discussed.

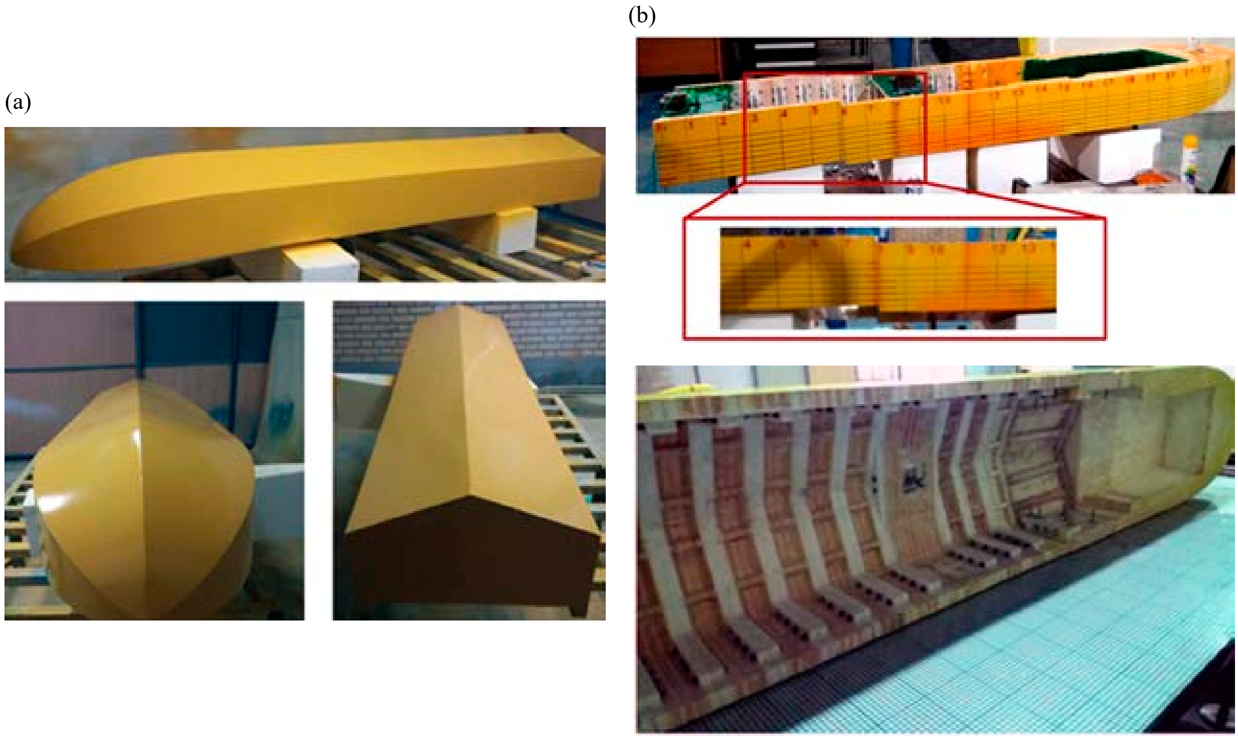

Figure 1. Fabricated hull model of the Fridsma: (a) without a transverse step and (b) one-step planing craft

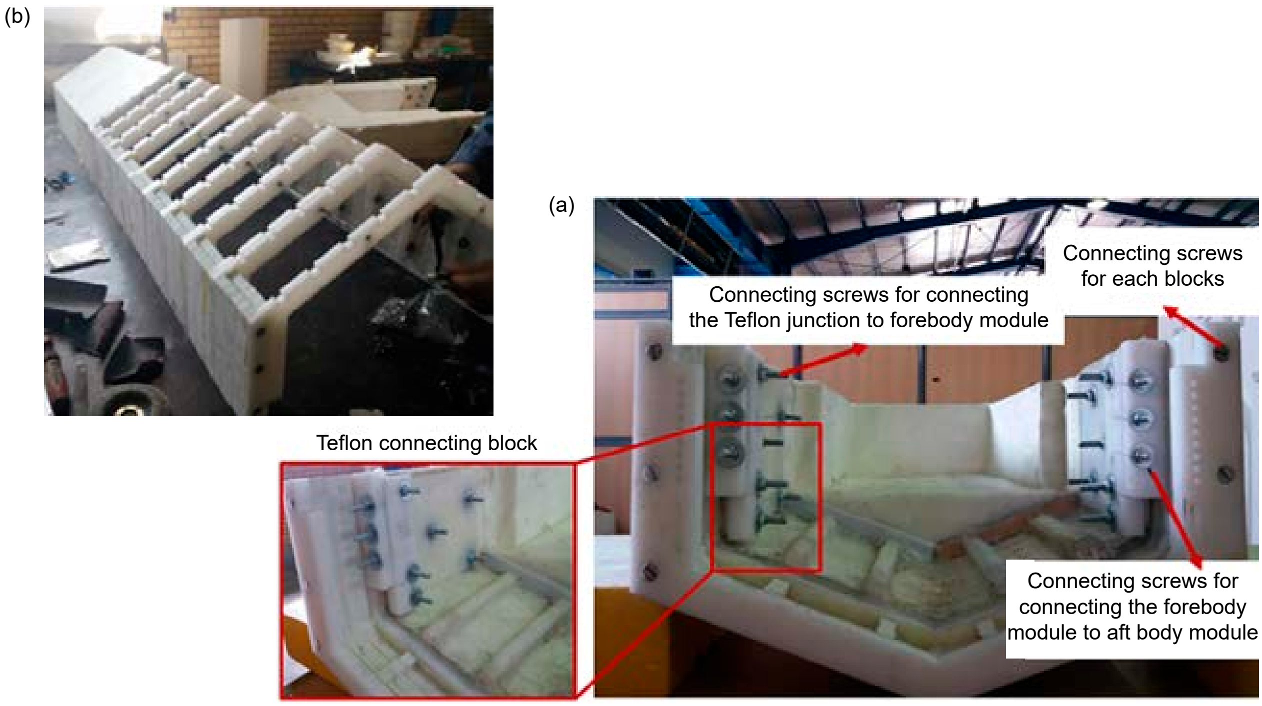

Figure 2. Teflon connecting block connected to the forebody module (a) and aftbody before assembly (b)

Results and discussion

Without the step planing craft

First, the drag obtained from the Fridsma planing hull for the case without a step at three different deadrise angles has been shown in Figure 4. As can be seen in Figure 4, the drag of the models tested increased with the increase of the hull velocity. Moreover, a comparison between the models at different deadrise angles (see Figure 4 (d)) showed that the change of the deadrise angle had an insignificant effect on the drag in the case without a step planing hull. Indeed, a higher deadrise angle resulted in a negligible increase in the drag for a lower hull velocity, while, for $V > 10$ m/s, a smaller drag was

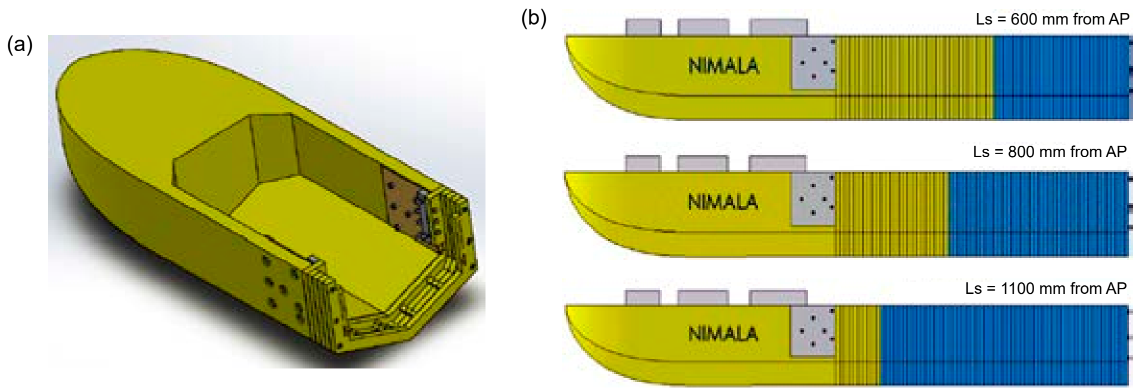

Figure 3. Schematic of the fabricated model and some locations considered for the step from the transom

Table 3. Laboratory test cases

Case	Deadrise angle β (deg)	Longitudinal position of the step from the transom Ls (mm)	Height of the step Hs (mm)	Hull velocity V (m/s) [Fr]
Effect of the geometrical parameters of the step	20	600	10	2–4 [0.903–1.806], 7 [3.161], 8 [3.612] and 10 [4.515]
		600	20	
		600	30	
		800	10	
		800	20	
		800	30	
		1100	10	
		1100	20	
		1100	30	
Effects of the deadrise angle	20	800	10	2 [0.903], 2.5 [1.129], 3 [1.355], 3.5 [1.580], 4 [1.806], 7 [3.161], 8 [3.612] and 10 [4.515]
	30		20	

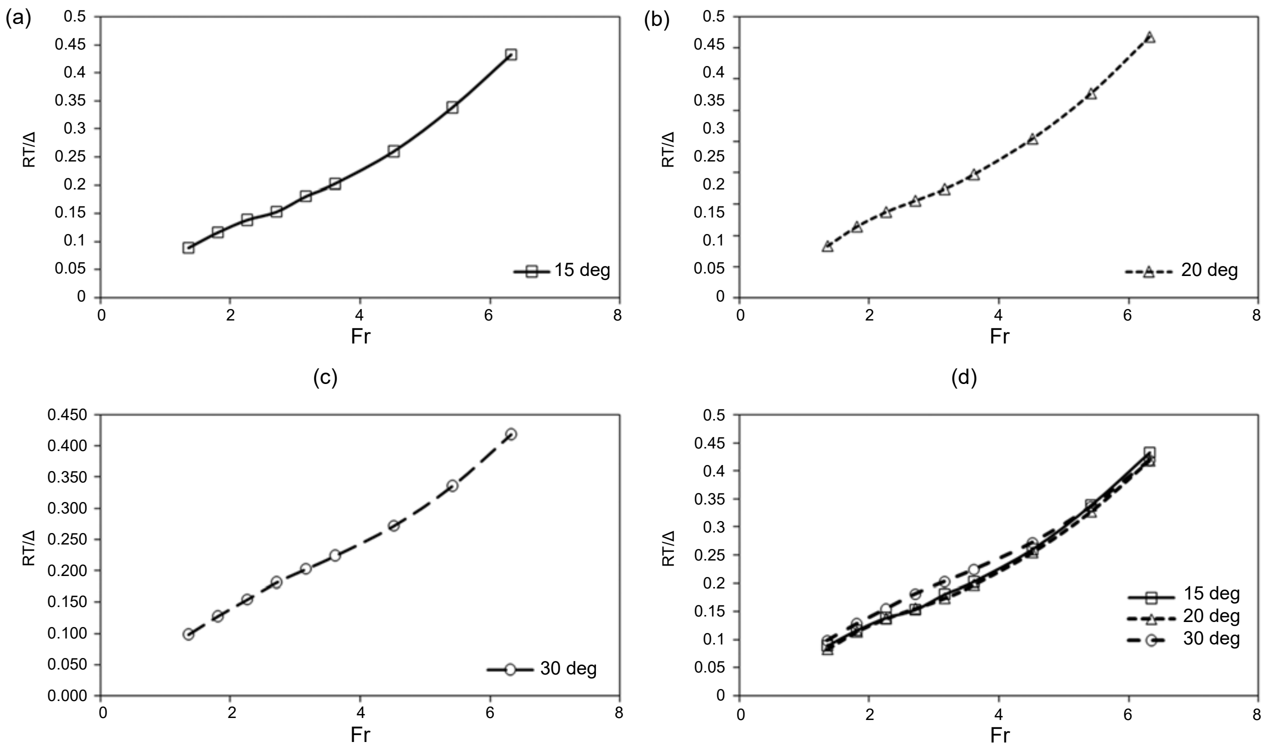

Figure 4. Non-dimensional total resistance vs. Froude number for the Fridsma model in the case without a step at a deadrise angle of (a) $\beta = 15°$, (b) $\beta = 20°$, (c) $\beta = 30°$ and (d) a comparison of the different deadrise angles

achieved for β = 30° compared to β = 15° and 20°. The reason for this fact may be related to the hull area having a reduced interaction with the water for a greater deadrise angle in the planing condition.

In the following sections, the effects of different deadrise angles, the heights of the step (Hs) and the longitudinal locations of the step from the transom (Ls) on the resistance of one-step planing craft have been investigated.

Effects of different deadrise angles

Figure 5 shows the drag of a stepped planing craft at two different deadrise angles β = 20° and β = 30° under Hs = 20 mm and Ls = 800 mm. As illustrated in Figure 5, the resistance was increased by an increase in the deadrise angle. The reason for this fact may be related to the hull sinking more for an increase in the deadrise angle. A comparison between Figures 4 and 5 shows a decrease in hull drag when using the transverse step. Detailed values of resistance at different deadrise angles of β = 20° and β = 30° under Hs = 20 mm and Ls = 800 mm have also been tabulated in Table 4.

Figure 6 has shown the drag of a stepped planing craft at two different deadrise angles β = 20° and β = 30° under Hs = 10 mm and Ls = 800 mm. Generally, a lower deadrise angle may result in greater lift and a reduced wetted area that will cause a decrease in the drag of a stepped planing hull. However, the proper longitudinal position and height of the step is significantly important in achieving this positive response. For example, as can be seen in Figure 6, when V > 8 m/s, a greater drag in the case of β = 20° was achieved compared to when β = 30°, that was because of the inappropriate position and height of the transverse step that was used. Table 5 shows the details of the resistance value for different deadrise angles of β = 20° and β = 30° under Hs = 10 mm and Ls = 800 mm.

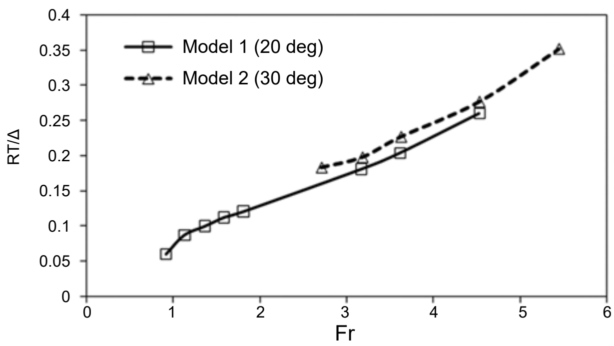

Figure 5. Non-dimensional total resistance vs. the Froude number of a stepped planing craft at two different deadrise angles β = 20° and β = 30° under Hs = 20 mm and Ls = 800 mm

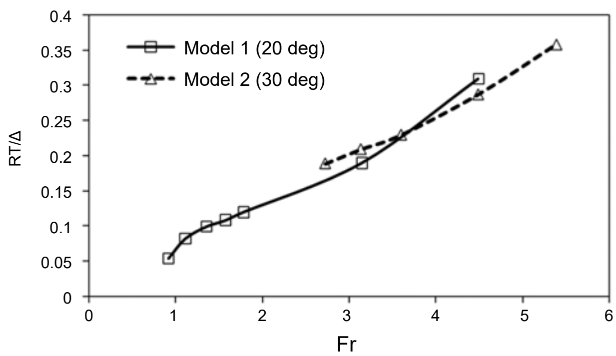

Figure 6. Non-dimensional total resistance vs. the Froude number of a stepped planing craft at two different deadrise angles β = 20° and β = 30° under Hs = 10 mm and Ls = 800 mm

Table 4. Detailed values of the non-dimensional total resistance at different deadrise angles of β = 20° and β = 30° under Hs = 20 mm and Ls = 800 mm

Case No.	V = 2 (Fr= 0.903)	V = 2.5 (Fr = 1.129)	V = 3 (Fr = 1.355)	V = 3.5 (Fr = 1.580)	V = 4 (Fr = 1.806)	V = 7 (Fr = 3.161)	V = 8 (Fr = 3.612)	V = 10 (Fr = 4.515)
Model 1 (R_T/Δ)	0.060	0.088	0.100	0.113	0.121	0.181	0.204	0.260
Case No.				V = 6 (Fr = 2.709)	V = 7 (Fr = 3.180)	V = 8 (Fr = 3.625)	V = 10 (Fr = 4.528)	V = 12 (Fr = 5.444)
Model 2 (R_T/Δ)				0.183	0.198	0.227	0.277	0.352

Table 5. Detailed values of the non-dimensional total resistance at different deadrise angles of β = 20° and β = 30° under Hs = 10 mm and Ls = 800

Case No.	V = 2 (Fr = 0.903)	V = 2.5 (Fr = 1.129)	V = 3 (Fr = 1.355)	V = 3.5 (Fr = 1.580)	V = 4 (Fr = 1.806)	V = 7 (Fr = 3.161)	V = 10 (Fr = 4.515)
Model 1 (R_T/Δ)	0.055	0.083	0.100	0.109	0.121	0.190	14.2
Case No.			V = 6 (Fr = 2.709)	V = 7 (Fr = 3.180)	V =8 (Fr = 3.625)	V =10 (Fr = 4.528)	V =12 (Fr = 5.444)
Model 2 (R_T/Δ)			0.189	0.210	0.230	0.288	0.359

Effect of the height of the step (Hs)

Figures 7, 8 and 9 show the drag of a stepped planing craft at three different heights of the step Hs = 10 mm, Hs = 20 mm and Hs = 30 mm under Ls = 600 mm, Ls = 800 mm and Ls = 1100 mm, respectively. As can be seen in Figures 7, 8 and 9, when Fr < 3 (i.e., before the planing condition of the considered hull), the hydrodynamic resistance of the planing hull was increased by using a transverse step compared to the case without a step, especially for a greater height of the step. However, the resistance of the stepped planing hull decreased compared to the case without a step under the hull planing condition (i.e., for Fr > 3). In addition, it can be concluded that the resistance was decreased by an increase in the height of the step.

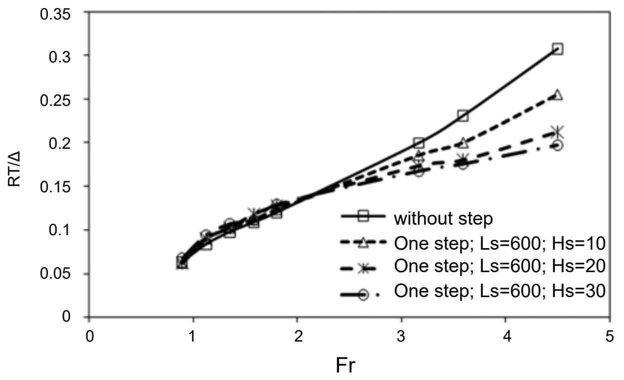

Figure 7. Non-dimensional total resistance vs. the Froude number of a stepped planing craft at three different heights Hs = 10, Hs = 20, Hs = 30 under Ls = 600 and *β* = 20°

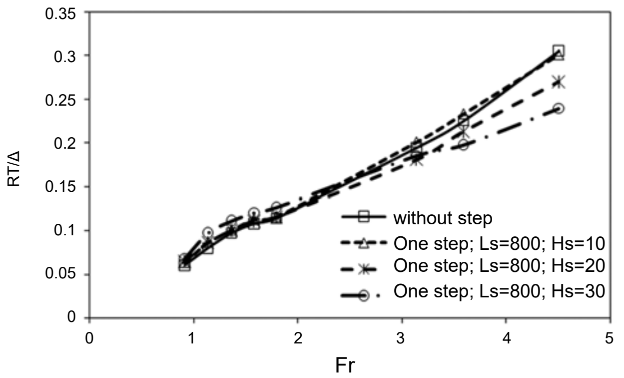

Figure 8. Non-dimensional total resistance vs. the Froude number of a stepped planing craft at three different heights Hs = 10, Hs = 20, Hs = 30 under Ls = 800 and *β* = 20°

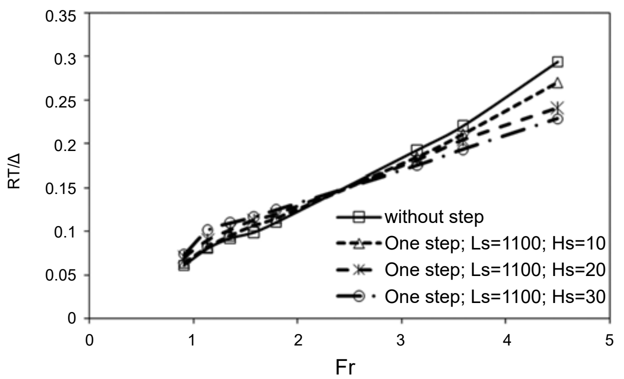

Figure 9. Non-dimensional total resistance vs. the Froude number of a stepped planing craft at three different heights Hs = 10, Hs = 20, Hs = 30 under Ls = 1100 and *β* = 20°

Effect of the longitudinal locations of the step from the transom (Ls)

Another important parameter for the hydrodynamic resistance of a stepped planing hull is the longitudinal position of the step from the transom. Proper justification of the longitudinal location of the step from the transom with the height of the step will results in a lower drag to lift ratio and a higher longitudinal stability of the vessel. Resistance vs. hull velocity of a stepped planing craft at three different longitudinal position of Ls = 600 mm, 800 mm and 1100 mm under Hs = 10 mm, 20 mm and 30 mm have been presented in Figures 10, 11 and 12, respectively. As can be seen in Figures 10, 11 and 12, the

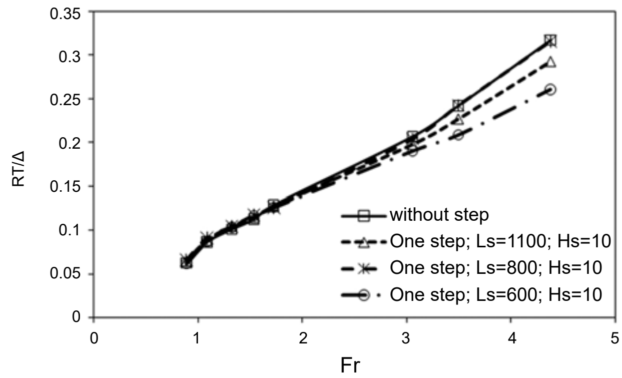

Figure 10. Non-dimensional total resistance vs. Froude number of stepped planing craft at three different Ls = 600, Ls = 800, Ls = 1100 under Hs = 10 mm and *β* = 20°

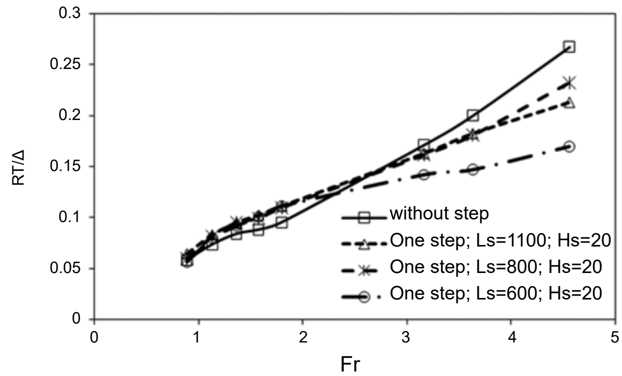

Figure 11. Non-dimensional total resistance vs. Froude number of stepped planing craft at three different Ls = 600, Ls = 800, Ls = 1100 under Hs = 20 mm and *β* = 20°

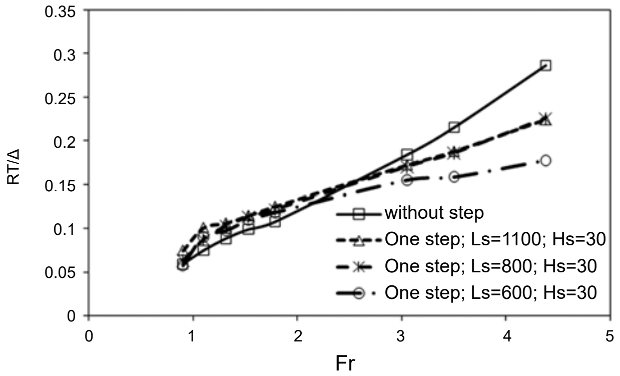

Figure 12. Non-dimensional total resistance vs. Froude number of stepped planing craft at three different Ls = 600, Ls = 800, Ls = 1100 under Hs = 30 mm and *β* = 20°

resistance was decreased by a decrease in the longitudinal position of the step from the transom. This happened is in accordance with a decrease in the wetted area caused by a reduction in the longitudinal position of the step from the transom. However, it is notable that the transverse step approaching the transom may be the cause of the lower longitudinal stability of the vessel. Therefore, both drag reduction and longitudinally stability should be simultaneously considered in the design. According to Figures 10, 11 and 12, unexpectedly, it was found that the resistance for Ls = 800 mm was approximately equal to or greater compared to Ls = 1100 mm. The reason for this fact is related to the disproportional change of the longitudinal position of the step from transom with height of the step. It was also found that the effects of the change of the longitudinal locations of the step on the value of the resistance was more significant compared to the change of the step heights of the step.

Finally, it should be noted that the presented results are valid for the simple body form of a one-step Fridsma planing hull and the necessity of further experimental investigation for other complicated body forms and multi-step planing craft is evident.

Conclusions

The hydrodynamic resistance of the Fridsma stepped planing craft has been studied in this paper by conducting experimental towing tank tests. For this purpose, the effect of the longitudinal distance of the step from the transom, the height of the step and the deadrise angles on the resistance of the considered planing craft have been evaluated. Among the important findings from the present study are the following:

1) The hydrodynamic resistance of the stepped planing craft was reduced and a lower aftbody lift was achieved by increasing the height of the step.
2) The hydrodynamic resistance of the stepped planing craft was enhanced by increasing the longitudinal distance of the step from the transom. Therefore, a lower total resistance was obtained as the transverse step became closer to the transom.

In addition, greater aftbody lift and a lower dynamic trim angle were expected as the longitudinal distance of the step from the transom was increased. However, it was found that the proportionality of the longitudinal distance of the step from the transom with the step height had a significant impact on the hydrodynamic efficiency of the step in the stepped planing craft. The results of the current study merits future work. The investigation of the hydrodynamic resistance of two-step planing craft can be regarded as future studies.

Acknowledgments

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Conflict of interests

The authors declare that there are no conflicts of interest regarding the publication of this paper. This paper has never been published before and has not been submitted for publication elsewhere.

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