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Obtaining the Practical Formula for the Trim-tab Dimensions to Reach the Minimum Drag for Planing Boat

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Abstract Trim-tab is a device for controlling and stabilizing planing boats in different sea conditions. This paper presents to find dimensions of the trim-tab at various speeds of the boat to reach the minimum drag. The speed of the boat is from15 m/s to 30m/s. Drag of the boat is calculated by Stavisky's method. The minimum drag is found based on the optimum the trim angle. A Matlab program code is prepared for these calculations and all the all results such as drag, dimensions of the trim-tab, longitudinal center of pressure and time angle at different speeds of the boat are presented and discussed.

Keywords: *trim-tab, drag, planing boat, Stavisky's method*

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1. Introduction

The shape and form of the planing body is one of the most effective factors of fast boats. To design the shape of the body of fast boats, it is necessary to predict the forces acting on the planing body. It is also very important to know the hydrodynamic characteristics and seakeeping performance at different conditions. Both geometrical dimensions and form of the body are affected in the pressure distribution acted on the hull and cause trim and rise of center of gravity. It is clear that if the longitudinal center of distribution and longitudinal center of gravity are adapted on the same point at an optimum trim angle, it will significantly reduce the drag of the body. To find the optimum trim angle, it is needed to use control system for adapting these two points. Also, to reach good seakeeping performance needs control surface to provide longitudinal dynamic stability.

Boat movement at different speeds changes the dynamic pressure distribution, trim, and boat's draft. Trim changes may increase drag and instability in planing boats. Therefore, one of the most important design principles is the control of trim in planing boats. In fast boats, if the thrust force is sufficient, the boat can reach the planing conditions from semi-displacement mode and reach its minimum drag in an optimal trim. Since most of the forces are dynamic in these conditions, also the center of pressure and the center of mass are not at the same point, it is necessary to use the trim-tab to maintain the condition and stability.

In planing boats, control tools such as interceptor, wedge, flap, trim-tab, etc. are used to control the trim. Among the trim-tab control tools, it is one of the most widely used tools to control the trim and improve the performance of the planing boat. The trim-tab is used as an active tool to control the operating conditions at the end of the boat and adjusts the trim and wetted length to achieve minimum drag. trim-tab, as a tool that connects to the boat, has frictional and pressure drag, so one of the ways to reduce boat drag is to optimize the dimensions and parameters of trim-tab to reduce the total drag of the boat.

The initial work on the planing boats was presented by Baker [1]. Then, it was extended wide attention by other researchers like Sottorf [2] Shoemaker [3], and Sambraus [4]. The first important study of planing phenomenon took place in Davison Laboratory at Steven institute of technology in 1964 by Savitsky [5]. This study resulted in several technical reports including definition of planing surface lift, wetted area, pressure distribution, wake shape, etc. Brown [6], Brawn and Savitsky [7] worked on the experimental and theoretical of planing surfaces with trim flaps. Humphree [8] studied the effect of trim-tab on planing hulls and suggested that the basic principle of the interceptor trim-tab is to create pressure underneath the hull, at the stem of the boat. The pressure is created when the blade is deployed into the water flow underneath the hull. Metcalf et al [9] conducted an experimental research for analyzing the U.S. Coast Guard planing boats. They presented the trim angle and resistance of four models in various conditions including different displacements, the various center of gravity, etc. Taunton et al [10] further developed a new series of planing boats including six models. These models consisted step and step-less crafts. They also presented their experimental data. Begovic and Bertorello [11] study the effect of variation of deadrise angle and introduced four hulls. In three models, deadrise angle varied from the stem to the bow of the craft. Their observation indicated the complex behavior of the wetted area and the stagnation line angle. They also showed that keel wetted length increases by an increase in the speed of the warped hulls, while it decreases in the prismatic body. On the other hand, three different planing boats were introduced by Kim et al. [12] for improving the performance and sea keeping of the planing boats. Performance of the planing trimaran was also considered as a subject of research by Ma et al. [13] and they presented experimental results related to the trim angle and resistance for the craft. They also examined the effect of step on the performance of trimaran. Step is another parameter that affects the performance of planing hulls experimentally studied by Lee et al [14] and the best height of the step for decreasing the resistance was achieved. Here, also additional research on the planing boat carried out by other researchers. A very comprehensive textbook of hydrodynamics on the high-speed marine vehicles published by Faltinsen in 2005 [15]. A parametric study on the effects of trim-tabs on the running trim and resistance of planing hulls was conducted by Ghadimi [16] et al. The effects of trim-tab in two different practical situations were examined. The results for both high-speed boats with an optimized deflection angle show that if the planing hull is constructed and difficulties occur with the trim angles, the best way to save the hull is to use either a fixed or a controllable trim-tab. However, this approach may increase the resistance Mansoori and Fernandes [17] study the combination of an interceptor and trim-tab to prevent the negative effects of the interceptor. Their results prove that the combination of an interceptor with a trim-tab shows better performance than either an interceptor or a trim-tab alone. Also, instead of increasing the interceptor height to gain more lift, which could result in an intense negative trim, the use of an interceptor integrated with a trim tab is better. In 2008-2017, comprehensive research on the planing boat carried out by Ghassemi and his colleagues. They worked on various planing hull and tunnel hull using the boundary element method (BEM) and CFD solvers. They have presented the hydrodynamics of the planing hull using BEM to find pressure resistance, induced resistance, and many related to hydrodynamic characteristics [18,19,20,21,22]. Ghassabzadeh and Ghassemi employed a NURBS to design the hull of tunnel ships [23,24,25,26]. Also, many numerical results on the planing hull carried out by CFD solver [27,28,29]. Drag minimization using trim-tab control system carried out by Ghassemi et al. [30,31,32] on the planing boat.

In this paper, the effect of trim-tab chord and span dimensions on boat drag, boat trim, angle of trim-tab, frictional, and pressure drag of trim-tab are investigated separately and a formula is presented for calculating the optimal span and chord. A comprehensive Matlab code is prepared to design of the planing boat with minimum drag, good seakeeping performance, and optimize its active control system such as interceptor and trim-tab.

2. Mathematical Formula

Among the numerical calculation methods, one of the best methods is to use Savitsky formulas to forecast the behavior of planing boats. To investigate the parameters of the trim-tab, this method has been applied to calculate the optimal trim. This method has several steps that must be followed. To start the calculations, first, a trim angle is guessed and then the accuracy of this guess is measured using the following formulas.

After guessing the trim, using the following 5 formulas, a nonlinear equation in terms of λ_w, $C_{L\beta}$, L_{cp} and C_{L0} is created, which by solving this equation, λ_w is computed.

$$C_{L\beta} = C_{L0} - 0.0065\beta C_{L0}^{0.6} \tag{1}$$

$$C_{L0} = \frac{F_{L0}}{0.5.\rho.V^2.B^2} = \tau^{1.1}\left(0.012\lambda_w^{0.5} + 0.0055\frac{\lambda_w^{2.5}}{Fn_B^2}\right). \tag{2}$$

$$\frac{L_{cp}}{\lambda_w.B} = 0.75 - \frac{1}{5.21\frac{Fn_B^2}{\lambda_w^2} + 2.39} \tag{3}$$

$$F_{L\beta}.L_{cp} = Mg.Lcg \tag{4}$$

$C_{L\beta}$ is the lift coefficient at the deadrise angle is β and τ of boat trim. L_{cp} is the center length of the dynamic pressure and Lcg is the center length of mass. Fn_B is also a transverse Froude number.

Fn_B is calculated as follows:

$$Fn_B = \frac{V}{\sqrt{g.B}} \tag{5}$$

V is the speed and B is the width of the boat.

In the following, we obtain the frictional and pressure drag using the following formulas.

$$D_P = F_{L\beta}.\tau \tag{6}$$

$$D_F = 0.5.\rho.V^2.S_{tot}.C_F \tag{7}$$

$$C_F = C_{F.ITTC} + \Delta C_F \tag{8}$$

D_P is the pressure drag and D_F is the frictional drag. S_{tot} is also the wet surface area of the boat.

The coefficient of frictional drag of $C_{F.ITTC}$ is estimated by the proposed formula of ITTC-57. Also, ΔC_F is calculated as follows.

$$\Delta C_F = \left[111\left(AHR.V_s\right)^{0.21} - 404\right].C^2{}_{F.ITTC} \tag{9}$$

ΔC_F is the increase in friction coefficient due to the roughness of the body.

The frictional drag is calculated after calculating the coefficient of frictional drag and wet surface.

$$S_{tot} = S_1 + S_2 \tag{10}$$

$$S_1 = \frac{\tau}{\sin\beta}\left(1 + \frac{Z_{max}}{V.t}\right)X_S^2 \quad (11)$$

$$S_2 = \frac{B}{\cos\beta}L_C \quad (12)$$

$$X_S = \frac{B.\tan\beta}{\pi.\tau}. \quad (13)$$

The total drag can now be calculated as follows.

$$D_{total} = D_F + D_P \quad (14)$$

To obtain the total minimum drag, we perform these calculations for other trims as well. After obtaining the optimal trim, if Lcg and L_{cp} do not apply to Equation (15), create the hydrodynamic force of an instantaneous trim, and to correct this momentary trim, we use the lift force created by the trim-tab, the moment is calculated using formula (16).

$$\frac{\left|L_{cp} - Lcg\right|}{Lcg} \leq 10^{-3} \quad (15)$$

$$M_T = F_{L\beta}\left(Lcg - L_{cp}\right) \quad (16)$$

The trim-tab lift force is calculated as follows.

$$L_{trimtab} = \frac{1}{2}.\rho.V^2.C_{L.tt}.S_{tt}. \quad (17)$$

S_{tt} is wet surface area and $C_{L.trimtab}$ is the lift factor of trim-tab.

Since only one side of the trim-tab is in contact with water, we get $C_{L.trimtab}$ as follows.

$$C_{L.tt} = 0.5(2.\pi.\alpha) \quad (18)$$

α = angle of trim-tab.

If we consider the center of the lift force in 0.75.chord from trailing edge, the moment created by trim-tab can be written as follows.

$$M_T = L_{trimtab}.x_t \quad (19)$$

$$x_t = (1.chord - 0.75.chord) + Lcg \quad (20)$$

$$M_T = 0.5.\rho.V^2.chord.span.\pi.\alpha.(0.25.chord + Lcg) \quad (21)$$

Also, total drag of the trim-tab can be calculated as follows.

$$D_{total.tt} = D_{F.tt} + D_{P.tt} \quad (22)$$

$$D_{P.tt} = L_{trimtab}.\alpha \quad (23)$$

$$D_{F.tt} = 0.5.\rho.V^2.S_{tt}.C_{F.ITTC} \quad (24)$$

$D_{P.tt}$ is the pressure drag of trim-tab, $D_{F.tt}$ is the frictional drag of trim-tab, and S_{tt} is the area of trim-tab.

3. Results

To determine the effect of effective parameters and dimensions of trim-tab, we perform various calculations on trim-tab parameters. The specifications of the model used are written in Table 1.

Table 1. Dimensions of the planing boat

parameter	value
Length [m]	22.5
Beam [m]	4.27
Mass [kg]	27000
Deadrise [degree]	**10**°
Lcg [m]	8.84

3.1. Case 1 - Change chord and span

First, we examine the effect of the span and chord of trim-tab on the amount of drag and the angle of trim-tab at 20 different speeds, From 15 to 30 m/s with steps of 0.75 (Figure 1). In this case, as the amount of chord or span increases, the amount of drag and angle of trim-tab decreases (Figure 2 - Figure 5). In the following, the total drag outputs and boat trim are also examined (Figure 6 and Figure 7).

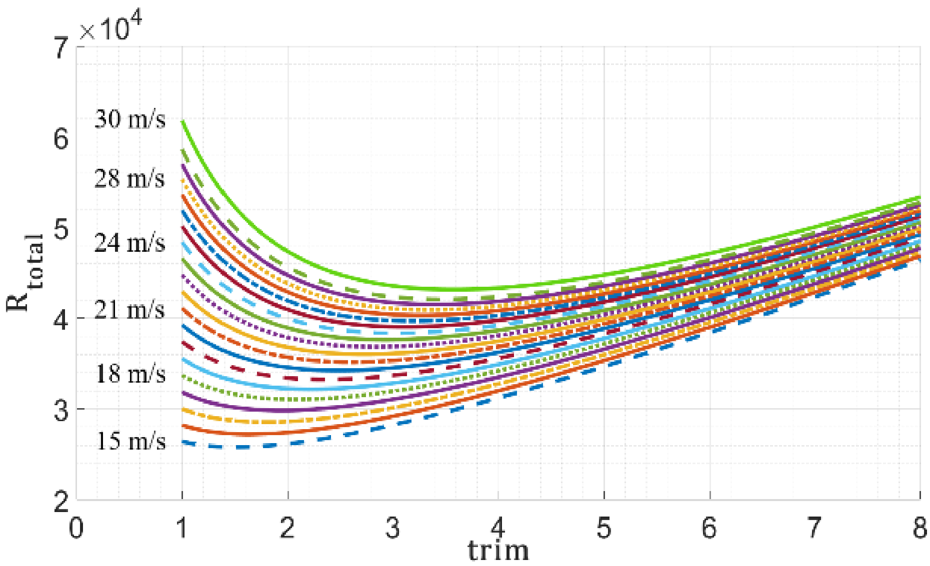

Figure 1. Drag diagrams in terms of trim at various speed

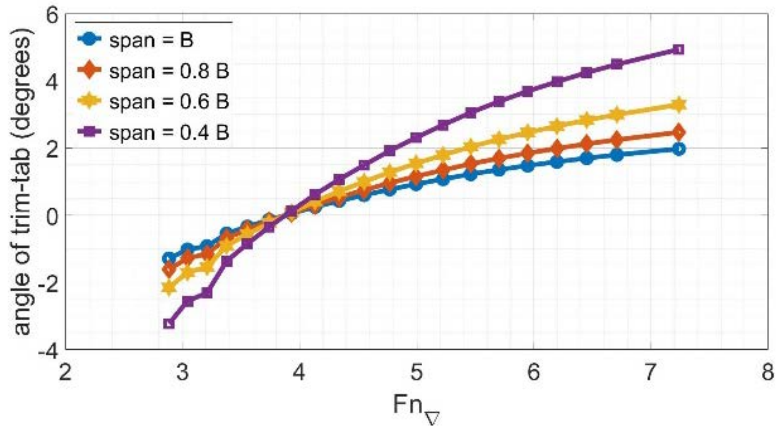

Figure 2. Effect of the span on angle of trim-tab (chord=0.2B)

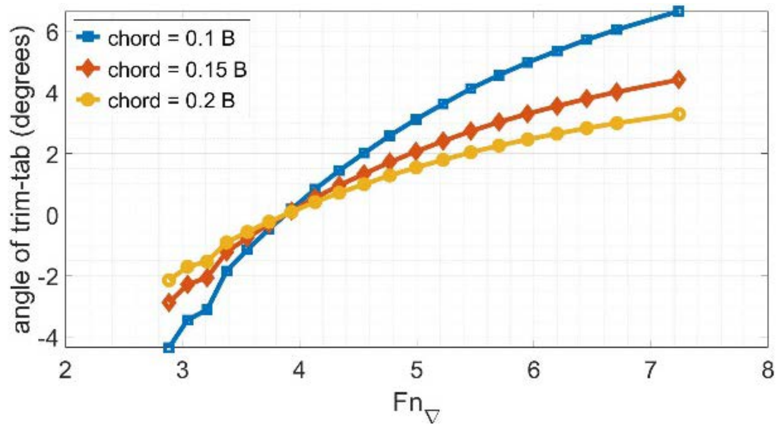

Figure 3. The effect of the chord on angle of trim-tab (span=0.6B)

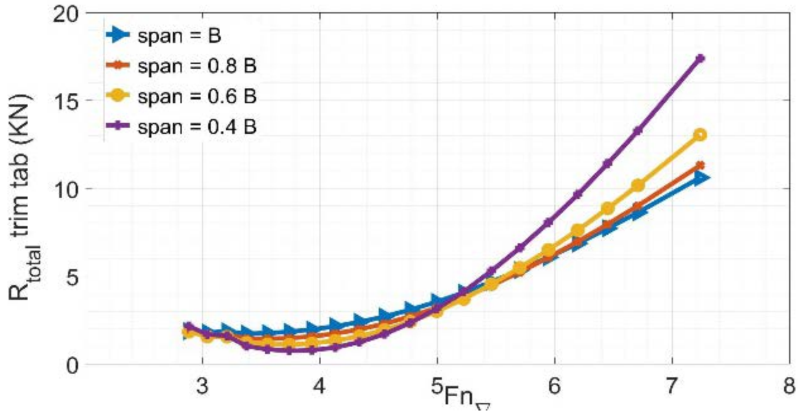

Figure 4. Effect of the span on trim-tab drag (chord=0.2B)

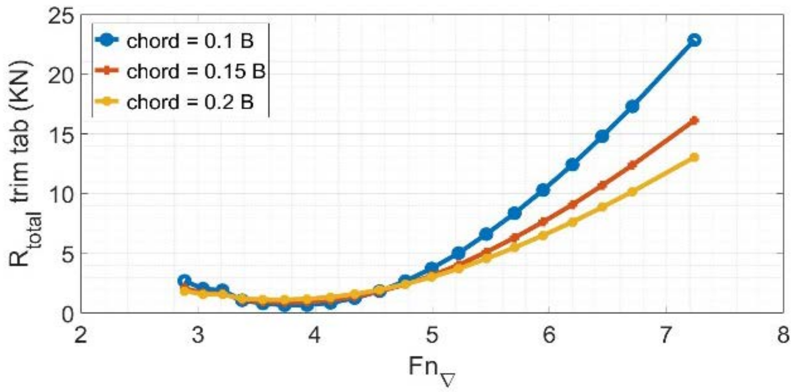

Figure 5. Effect of the chord on trim-tab drag (span=0.6B)

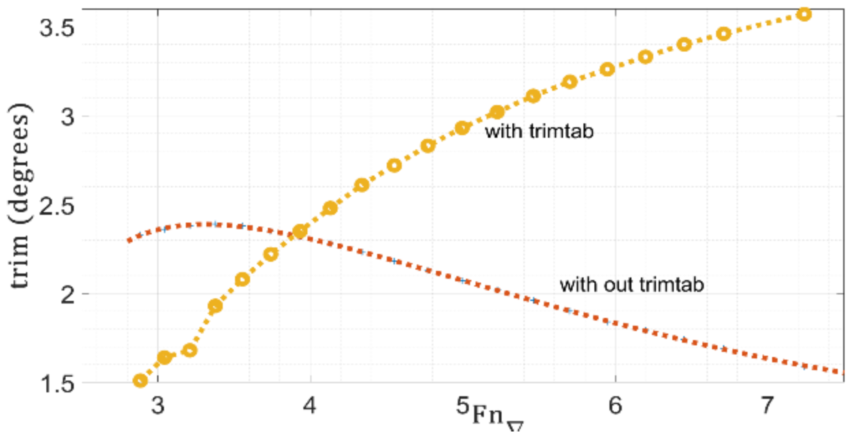

Figure 6. Trim changes in 2 modes with trim-tab and without trim-tab

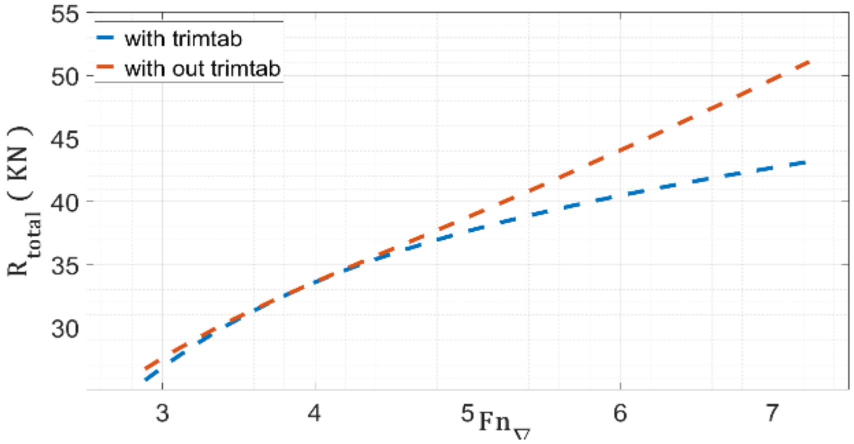

Figure 7. Drag changes in 2 modes with trim-tab and without trim-tab

3.2. Case 2 - Change area of trim-tab

In this condition, we consider the value of speed the same and perform calculations with different Areas (Figure 9 - Figure 11). According to the results, in a chord with a fixed span, the drag decreases with the increasing Area of the trim-tab and gradually increases after reaching a minimum value. In fact, in this situation, with increasing area, three factors are influential:

- Increased frictional drag due to increased area
- Increased pressure drag due to increased area
- Reduction of pressure drag due to the reduction of the required angle of trim-tab, which is also the result of increasing the area.

Initially, due to the large decrease in the angle of trim-tab due to the increase in area, the impact of factor 3 is very high compared to factors 1 and 2.

As the area increases, the angle of trim-tab decreases, which reduces the effect of factor 3 relative to factors 1 and 2 and increases drag again (Figure 8 - Figure 11). These results show the large role of pressure drag in the total size of the trim-tab drag. As the angle of the trim-tab decreases, the value of $\frac{C_{L.tt}}{C_{P.tt}}$ increases and this factor indicates an increase in the efficiency of the trim-tab (Figure 12).

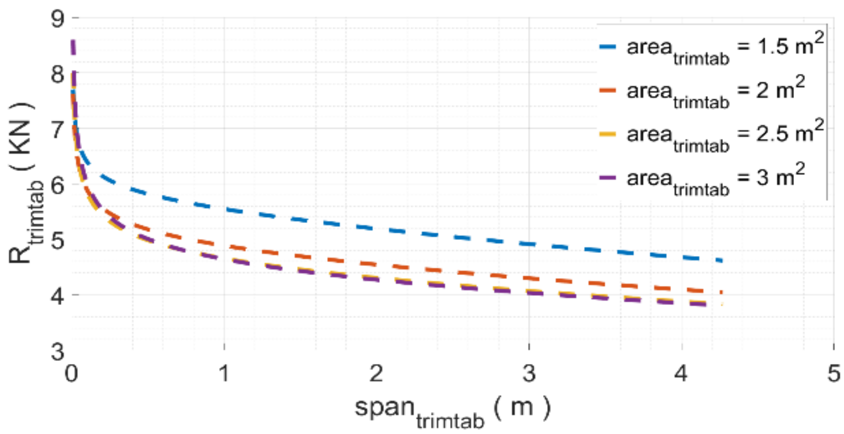

Figure 8. Effect of the area on trim-tab drag

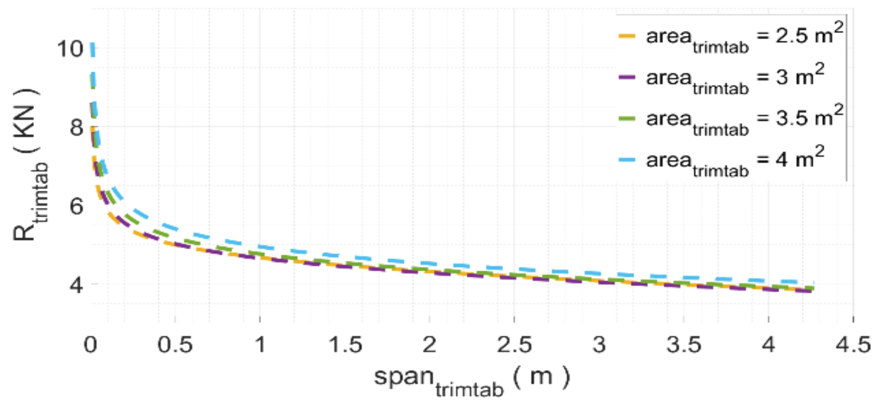

Figure 9. Effect of the area on trim-tab drag

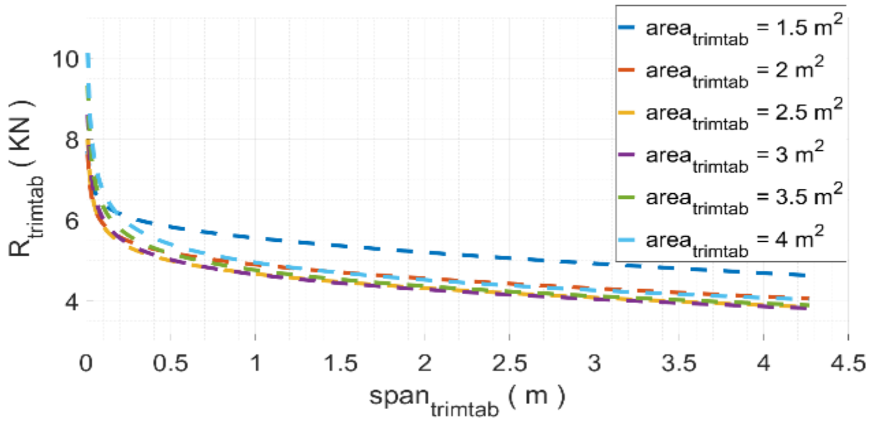

Figure 10. Effect of the area on trim-tab drag

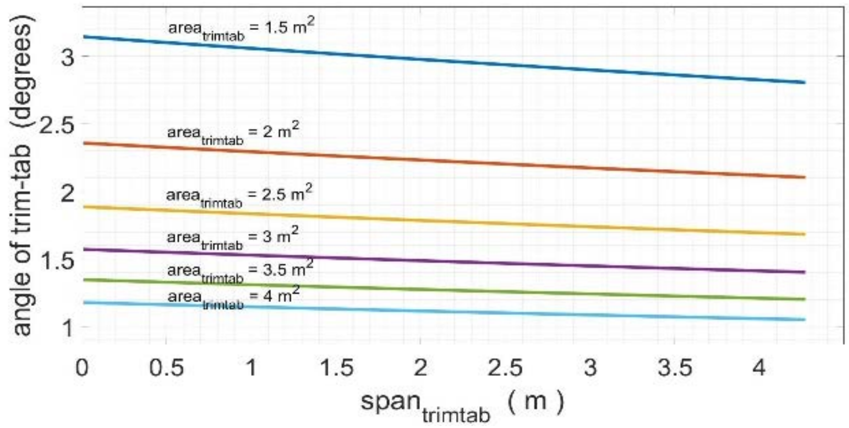

Figure 11. Effect of the area on the angle of trim-tab

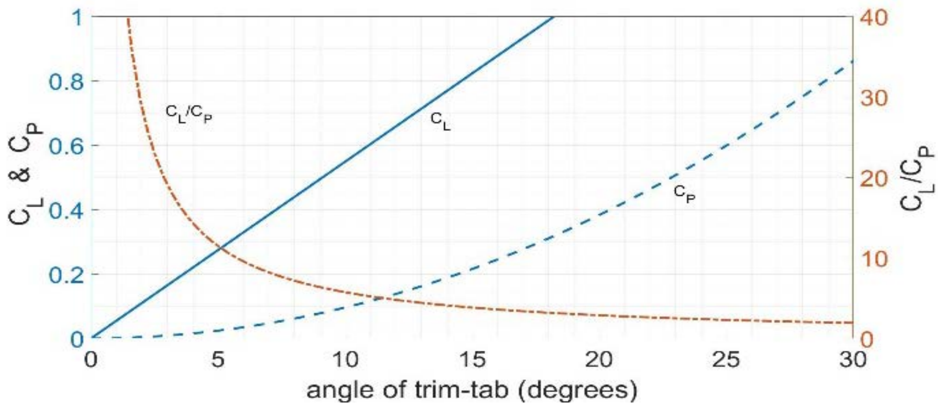

Figure 12. changes in lift coefficient of trim-tab and average pressure coefficient of trim-tab in terms of angle of trim-tab

According to the formulas $D_{total.tt} = f$ (span, chord, Lcg, V, M_T) and calculate the optimal span value, we derive from Equation (22) relative to the span and chord as follows:

For chord is constant, the span is obtained by

$$\frac{d(D_{tot.tt})}{d(span)} = \frac{d}{d(span)}\left(D_{P.tt} + D_{F.tt}\right) = 0 \quad (25)$$

When chord is constant, the span is calculated by

$$Span = \frac{|M_T|}{\left[\begin{array}{l}0.5 \times \rho \times V^2 \times chord \times \sqrt{c_{F.ITTC} \times \pi} \\ \times (0.25 \times chord + Lcg)\end{array}\right]} \quad (26)$$

Using the formula (16) it can be rewritten as follows.

$$\text{optimal } Span = \frac{C_{L\beta} \times B^2 \times \left(\left|Lcg - L_{cp}\right|\right)}{chord \times \sqrt{c_{F.ITTC} \times \pi} \times (0.25 \times chord + Lcg)} \quad (27)$$

In this equation, the value of the optimal chord can be obtained at the desired speed by quantifying the span and other parameters and solving the created equation in terms of the chord.

The flowchart is presented in Figure 13. Final results of the trim-tab dimensions as well as drag and trim angle of the boat are given in Table 2.

Table 2. Optimal values of the trim-tab with span=B and optimal values of the boat (Lcg=8.84 m)

Speed (m/s)	Speed (knot)	$Chord_{optimum}$ (m)	Angle (degree)	$D_{total.tt}$ (kN)	$D_{total.boat}$ (kN)	$trim_{optimum}$ (degree)	L_{cp} (m)
15	29.16	0.7510	-0.0257	0.1862	25.97972	1.5075	9.9645
16.5	32.08	0.5410	-1.4714	0.1663	28.74732	1.6848	9.798
18	34.99	0.2015	-1.4719	0.0816	31.13216	2.0762	9.2366
19.5	37.91	0.0306	1.4725	0.019	33.2624	2.3513	8.7732
21	40.82	0.2511	1.4733	0.133	35.29577	2.6081	8.2384
22.5	43.74	0.4490	1.474	0.254	37.10356	2.8282	7.6817
24	46.66	0.6254	1.4748	0.387	38.73598	3.0178	7.1275
25.5	49.57	0.7844	1.4754	0.533	40.23431	3.189	6.5878
27	52.49	0.9169	1.476	0.685	41.62386	3.3296	6.0973
28.5	55.40	1.0327	1.4765	0.847	42.93317	3.458	5.6432
30	58.32	1.1320	1.4770	1.016	44.17749	3.5742	5.2303

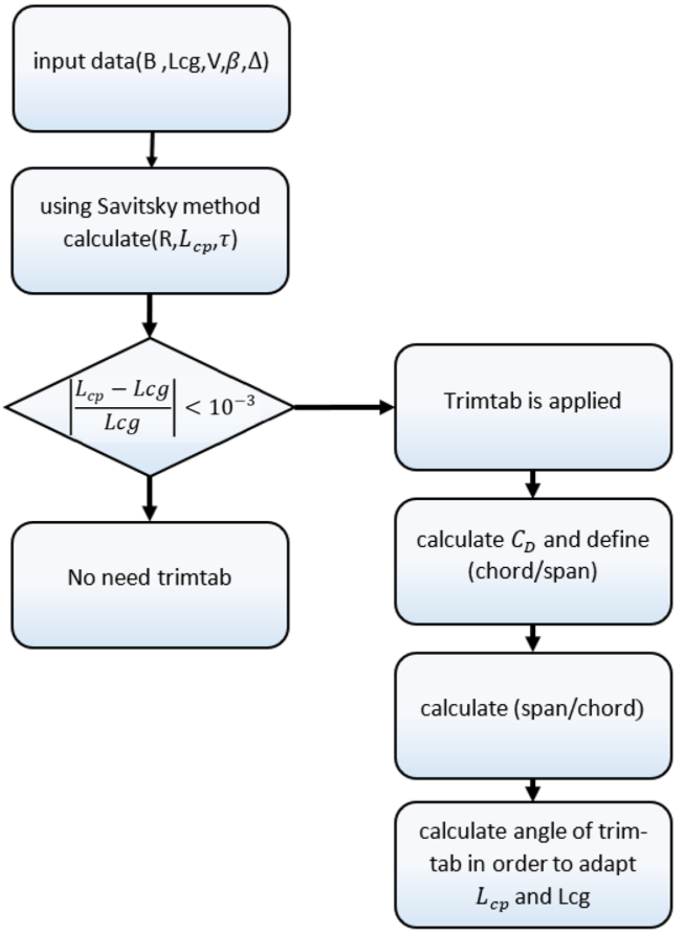

Figure 13. Flowchart of the computational process

4. Conclusion

In the calculations, the effects of all parameters affecting the planing boat drag of planing boat as well as the effects of the dimensions of the trim-tab on the angle of trim-tab, and the total drag of the boat were investigated and according to Computational results, the following conclusion can be drawn:

- As the value of the chord or span of trim-tab increases, the amount of the angle of trim-tab decreases. It was also found that increasing the size of the span and trim-tab reduces the overall drag of the trim-tab.
- At a constant speed, by increasing the area of the trim-tab, first the total drag of the trim-tab decreases and then gradually increases. Therefore, the best way to reduce the planing boat drag is to increase the trim-tab area to the appropriate level.
- It is better to choose a trim-tab that has a longer span or chord length to have a smaller angle of trim-tab because of a smaller angle of trim-tab causes less pressure drag.
- At a low angle of trim-tab, the trim-tab has a higher ratio of $\frac{C_{L.tt}}{C_{P.tt}}$. Therefore, the efficiency in this area is high.

Nomenclature

B	Beam of the boat
$C_{L\beta}$	Lift coefficient
C_{L0}	Lift coefficient at zero deadrise angle
$C_{F.ITTC\ 57}$	Frictional drag coefficient (ITTC 57)
$C_{L.tt}$	Lift coefficient of trim-tab
$C_{P.tt}$	Pressure drag coefficient of trim-tab
$chord$	Chord length of trim-tab
D_P	Pressure drag
D_F	Frictional drag
D_{total}	Total drag of the boat w/o the trim-tab
$D_{total\ .boat}$	Total drag of the boat with the trim-tab
$D_{P.tt}$	Pressure drag of trim-tab
$D_{F.tt}$	The frictional drag of trim-tab
$D_{total\ .tt}$	Total drag of trim tab
$F_{L\beta}$	Hydrodynamic force
F_{L0}	$F_{L\beta}$ at zero deadrise angle
Fn_B	Beam Froude number
$L_{trimtab}$	Lift of trim-tab
Lcg	Longitudinal center of Mass
L_{cp}	Longitudinal center of pressure
M	Displacement of boat
M_T	Moment of the trim-tab
Rn	Reynolds number
S_{tot}	Wetted surface of the boat
$Span$	Span length of trim-tab
S_{tt}	Wetted surface of the trim-tab
x_l	Distance from Lcp to Lcg
β	Deadrise angle
ρ	Density of water
λ_w	Mean wetted length-to-beam ratio
α	Angle of the trim-tab
τ	Trim angle of the boat

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