Parametric Study of the Effects of Trim Tabs on Running Trim and Resistance of Planing Hulls

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***Abstract*-Trim tab is a useful apparatus for improving the performance of planing hulls and is considered an important element in the design of planning vessels. In this paper, usage of trim tab is mathematically investigated and empirical equations are utilized. A flowchart is proposed for determination of the running trim tab and resistance of the vessel. To validate the proposed algorithm and the developed computer program, the obtained results are compared against available data for a planing boat with trim tab. To accomplish the main goal of this paper, two different planing hulls are considered; a small and light planing hull and a heavy planning hull with different parameters. Effects of span length on the resistance and dynamic trim angle of the small boat are examined. Also, Effects of deflection angle of the trim tab on the performance is undertaken as a subject of study. Based on the performed hydrodynamic analyses and the obtained results, it can be concluded that deflection angle affects the trim angle and the required horse power of both hulls, and it is necessary to optimize deflection angle of the trim tab. A simple method is proposed for determination of the optimized deflection angle in order to reduce the running trim angle for two different planing crafts. Finally, by using the optimized deflection angle, effective horse power (EHP) and trim angle for both planing hulls are computed and compared against the values of EHP and trim angle of the vessels without using the trim tab. It is demonstrated that as a result of using a trim tab, trim angle decreases, while EHP increases in both cases.**

Keywords- Planing Hulls; Mathematical Investigation; Savitsky's Method; Trim Angle; Trim Tab; Parametric Study

I. INTRODUCTION

One of the most important issues in naval architecture is the design of planing hulls. Planing hulls have different behaviours in different situations. Hence, predicting their performance in different conditions is of great importance. As a definition, a planing hull is a hull which performs only by hydrodynamic forces. Perhaps the best and most simplest definition of planing hull is given by Benford [1] which states that "A planing craft is one that, when driven at high enough speed, rides up on the water surface, supported primarily by impact of the water on its bottom". This definition also indirectly refers to the hydrodynamic force which is the impact of water on the hull.

Study of planing hulls was initiated by Baker [2]. This study then received wide attention from other researchers like Sottorf [3], Shoemaker [4] and Sambraus [5] among others. The first important study of planing phenomenon took place in Davison Laboratory at Steven institute of technology in 1947 by Savitsky [6]. This study resulted in several technical reports including definition of planing surface lift, wetted area, pressure distribution, wake shape and etc. Subsequent to these studies, several other studies were conducted like experimental and theoretical study of Brown [7] on planing surfaces with trim tabs. Few years later, another paper was published by Savitsky and Brown [8] in which effects of controlling the trim tabs was studied. From that time on, the study of trim tabs became more popular and their usage in controlling the additional trim of planing hulls became the focal point of other studies. Humphree [9] studied effect of trim tab on planning hulls and suggested that "The basic principle of the interceptor trim tab is to create pressure underneath the hull, at the stern of the boat. The pressure is created when the blade is deployed into the water flow underneath the hull."

In addition to experimental works for predicting the performance of planing hulls, there were several other studies that investigated the performance of planing hulls through mathematical models. The most famous and yet usable method to predict the performance of planing hull is the model suggested by Savitsky [6]. This method, which is also used in this paper, is now the basis of many new studies and its effectiveness is very well known to everyone. As mentioned earlier, Savitsky's original method has been further developed by Savitsky and Brown in 1976 [8]and a comprehensive study was done to extract a mathematical model for predicting the performance of planing hulls with trim tabs in different situations such as smooth and rough water. This helped improving the design process of planing hull further. Metcalf et al [10] conducted an experimental research for analysing the U.S. Coast Guard planing hulls. They presented trim angle and resistance of four models in various conditions including different displacements, various centres of gravity and etc. Taunton et al [11] 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 [12] tried to study the effect of variation of deadrise angle and introduced four hulls. In three models, deadrise angle varied from the stern to the bow of craft. Their observation indicated the complex behaviour 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 hulls were introduced by Kim et al. [13] for improving the performance and seakeeping of the planing boats. Performance of the planing trimarans was also considered as a subject of research by Ma et al. [14] 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 trimarans. Step is another parameter which affects the performance of planing hulls experimentally studied by Lee et al [15] and the best height of the step for decreasing the resistance was achieved.

In the present paper, prediction of the performance of planing crafts with trim tabs is undertaken as a field of study and effect of the trim tabs on running trim and resistance is investigated. For this purpose, mathematical formulation of Savitsky's method and effects of trim tab on forces and centre of pressure are explained. Later, procedure of Savitsky's modified method for planing hulls equipped with trim tabs is introduced in an algorithm. After presenting the algorithm, the proposed method is used to examine the performance of two different planing hulls. The first case involves a speedboat analysed by Harris [16] that has difficulties with trim angle and is examined by a trim tab and the effect of trim tab is studied. The second case is related to a planing hull which was studied by Savitsky and Brown [8]. Finally, optimized deflection angles for the both hulls are determined and variation of 'trim angle vs. speed' and 'EHP vs. speed' with optimized deflection angle is studied.

II. TECHNICAL DESCRIPTION OF PROBLEM

As pointed out earlier, the best option for modelling a planing hull with trim tab is the modified Savitsky's method. The process is the same as in original Savitsky's method [6] with a few add-ons. This case is defined by a few variables that are related to geometry of planing body and the trim tab. Moreover, the design speed and mass of planing body are included. With these variables, the output will be trim angle and total resistance as well as effective horse power (EHP). The required inputs are:

1. Mass [kg]
2. Beam [m]
3. Longitudinal distance of centre of Gravity from transom [m]
4. Distance of centre of gravity from above keel line [m]
5. Angle of deadrise of planing surface [degree]
6. Inclination of thrust line relative to keel line [degree]
7. Velocity [m/s]
8. Flap chord [m]
9. Flap span-beam ratio
10. Flap deflection [degree]

The last three parameters related to the trim tab are described in the next paragraphs. With these results, a preferable case study can be conducted to predict the best situations where a trim tab can be used in a planing body.

First assumption is the fact that the planing body is in a steady state condition which implies there is no acceleration in any direction. Here, a trim tab is added to the planing body. Two parameters of total mass of planing body and length of centre of gravity (LCG) are different from the original Savitsky's method [6]. In order to implement these two parameters, it is important to understand the geometry of a trim tab. As shown in Fig. 1, a trim tab must be identified by the following parameters:

Δ_F Flap lift increment

D_F Flap drag increment

M_F Flap moment about flap trailing edge

H_F Flap hinge moment

L_F Flap chord

Σ_F Flap span-beam ratio

Δ Flap deflection

τ Trim of planing surface

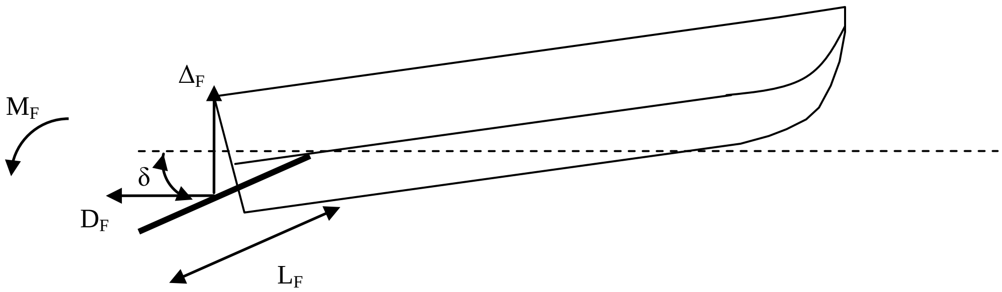

Fig. 1 Trim tab geometry

III. GOVERNING EQUATIONS

Calculation begins with determination of flap lift increment. This parameter is added to the total displacement of the planing body which is used to calculate the displacement.

$$\Delta_F = 0.14025 L_F \delta\sigma b(\frac{\rho}{2}\mathrm{V}^2) \tag{1}$$

Here, L_F (m) is the flap chord, b (m) is the beam of planing craft, σ is the flap span-beam ratio, ρ (Kg/m^3) is the density of the water and V is the velocity of the craft (m/s). By having Δ_F, it is easy to take into consideration the usage of trim tab for a planing hull. This basically means that it is now possible to calculate the new displacement and new LCG of the planing body, as follows:

$$\Delta_e = \Delta - \Delta_F \tag{2}$$

$$LCG_e = \frac{(\Delta \times LCG - 0.6 \times \Delta_F \times \mathrm{b})}{\Delta_e} \tag{3}$$

Where Δ_e and LCG_e are called the Effective Displacement and Effective LCG, respectively. It is then possible to start the calculations of the original Savitsky's method [6] in which the mass and LCG in the governing equations should be replaced by the new Mass and LCG which considers the inclusion of trim tab in the planing body.

As shown in Fig. 2, the main goal of Savitsky's method is to find the equilibrium of the planing body. By finding momentum equilibrium, the best trim angle, total resistance, and best EHP can easily be found.

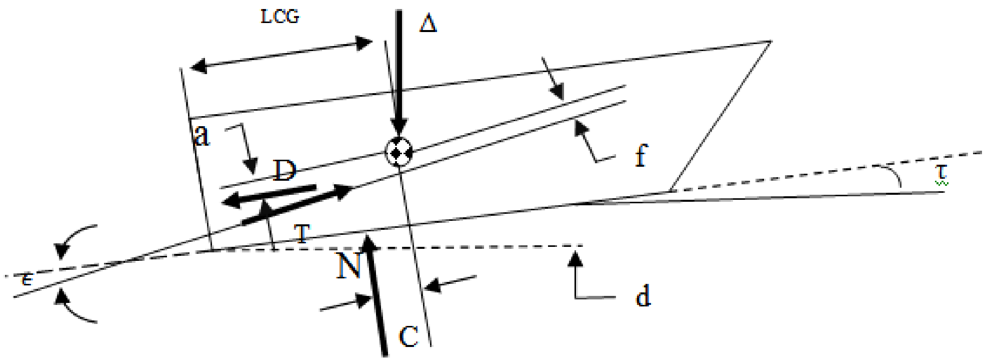

Fig. 2 Forces acting on a planing body

The Original Savitsky's method [6] includes 30 steps which will be studied and executed. For getting the calculations started, first a trim angle must be guessed for the planing body, and for terminating the calculations, the suitability of this guess should be assessed.

Subsequently, it is necessary to find the involved constants. These constants include the beam Froude number, C_V, and the lift coefficient $C_{L\beta}$. Lift coefficient is the parameter which gives enough force to lift the planing body. These two constants are calculated by Eqs. (4) and (5).

$$C_V = V / \sqrt{gB} \tag{4}$$

$$C_{L\beta} = \frac{mg}{0.5\rho V^2 B^2} \tag{5}$$

Here, g is the gravity acceleration, C_v is the speed coefficient, and m is the mass of the craft. By having the lift coefficient and utilizing Eqs. (6) and (7), it is possible to calculate the length-beam ratio , λ, as in

$$C_{L\beta} = C_{L0} - 0.0065\beta C_{L0} \tag{6}$$

$$C_{L0} = \tau^{1.1}(0.012\lambda^{0.5} + \frac{0.0055\lambda^{2.5}}{C_V^2}) \tag{7}$$

Where C_{L0} is the lift coefficient of planing plate, β is the deadrise angle of the craft (degrees), τ is the trim angle (degrees) of the planing surface, and λ is the non-dimensional mean wetted length of the planing boat. Next step is to find frictional Drag, D_f, but before hand, a mean velocity (V_m) ought to be calculated for substituting in the equation of frictional drag. The mean velocity can be calculated from Eq. (8) as in

$$V_m = V[1 - \frac{0.012\lambda^{0.5}\tau^{1.1} - 0.0065\beta(0.012\lambda^{0.5}\tau^{1.1})^{0.6}}{\lambda\cos\tau}]^{0.5} \tag{8}$$

Friction drag coefficient (C_f) can be determined by ITTC-57 equation given in Eq. (9). After finding the Reynolds number, the frictional drag can be calculated. It is important to note that due to the ITTC standard, a quantity ΔC_f=0.0004 should be taken into consideration for calculating the frictional drag in Eq. (11).

$$C_f = \frac{0.075}{(\log_{10}\mathrm{Re} - 2)^2} \tag{9}$$

$$\mathrm{Re} = V_m \lambda \frac{B}{\upsilon} \tag{10}$$

$$D_f = 0.5\frac{\rho V_m^2 \lambda B^2}{\cos\beta}(C_f + \Delta C_f) \tag{11}$$

Where Re is the Reynolds number and ν is the kinematic viscosity of the water. Later, forces that have to be calculated are hydrodynamic force normal to the bottom, i.e. *N*, and total drag, i.e. *D*, which are presented in Eqns. (12) and (13).

$$mg = N\cos\tau \rightarrow N = \frac{mg}{\cos\tau} \tag{12}$$

$$D = mg\tan\tau + \frac{D_f}{\cos\tau} + 0.0052\Delta_f\tan(\tau + \delta) \tag{13}$$

Here, the first term is induced drag of the craft, second term is frictional drag, and the last term is the drag of the flap. Moreover, the distance of frictional drag from VCG, i.e. a, and the distance of normal force from LCG, i.e. *c*, have to be determined. For this purpose, finding the center of pressure, *C*p, is imperative. These parameters are presented in Eqs. (14) through (16).

$$c_p = 0.75 - \frac{1}{\frac{5.21C_V^2}{\lambda^2} + 2.39} \tag{14}$$

$$c = LCG - l_p = LCG - C_p\lambda b \tag{15}$$

$$a = VCG - \frac{b}{4}\tan\beta \tag{16}$$

With all the stated forces calculated, it is now possible to calculate the pitch moment of the planing body from the following equation:

$$M_{tot} = mg\left[\frac{c}{\cos\tau}(1-\sin\tau\sin(\tau+\varepsilon) - f\sin\tau)\right] + D_f(a-f) \tag{17}$$

Where ε is the inclination of thrust line relative to the keel (degree). As shown in Fig.2, parameter f is the vertical distance of the thrust from center of gravity. For reaching the equilibrium, Eq. (17) should be set equal to zero. Normally, this cannot be done by guessing and it has to be calculated by an interpolation scheme. In Eq. (17), if M_{tot} is negative, it implies that the guessed trim angle at the first step is too low. Therefore, trim angle should be increased and all the calculations must be repeated again. This process continues until M_{tot} becomes a positive value. At this point, it is possible to find the right trim by using the interpolation of the last two results.

IV. COMPUTATIONAL PROCEDURE AND VALIDATION CASE

The process of using these equations for the purpose of intended analyses has been automated by different MATLAB programs. In order to illustrate the process clearly, a flowchart is provided in Fig. 3.

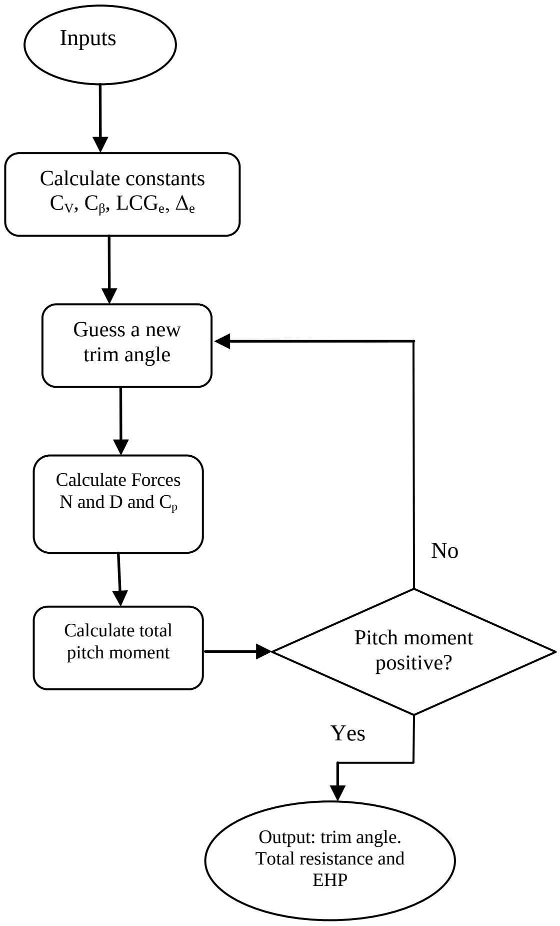

Fig. 3 Flowchart of the computational process

For validating the results of the written program, the case in Savitsky and Brown's paper [8] is studied in this section. This case is pertinent to a planing body possessing a trim tab whose characteristics are described in Table 1. This case is revisited again as the second case being parametrically studied in the current paper.

TABLE 1 FONT SIZES FOR PAPERS

Mass (kg)	84444
Beam (m)	7.32
LCG from stern (m)	10.675
VCG (m)	0.5
Deadrise angle β (degree)	15
f (m)	0.6
ε (degree)	0

Design speed (knots)	25.4
Flap chord (m)	0.305
Span (m)	7.32
Flap Deflection δ (degree)	5

As seen in Table I, the span of trim tab is exactly equal to the beam of planing hull which implies that trim tab uses the whole beam. This type of trim tab is called full span trim tab. Results of this case study are shown in Table 2 and compared against the original results of Savitsky's paper.

TABLE 2 FONT SIZES FOR PAPERS

	Savitsky's Results	Calculated (our) results
Trim Angle	2.9°	2.95°
Total Resistance	72061N	73253N

By looking at Table 2, it can be understood that results are quite close. The trim angle has a 1.7% error, while the total resistance has a 1.6% error. These errors are attributed to the number of used decimals and can be quite natural.

V. CASE STUDIES, RESULTS AND DISCUSSIONS

As mentioned earlier, two cases are being studied in different situations. The first case is a speedboat called Water Imp and is manufactured by Multi marine Composites Ltd. This planing craft is equipped by a trim tab whose characteristics are presented in Table 3.

TABLE 3 CHARACTERISTICS OF THE PLANING HULL IN CASE 1

Mass (kg)	215
Beam (m)	1.22
LCG from stern (m)	0.87
VCG (m)	0.03
Deadrise angle β (degree)	15
f (m)	0.45
ε (degree)	3
Design speed (knots)	23
Flap chord (m)	0.3
Span (m)	0.4
Flap Deflection δ (degree)	2

A. Case 1 - Effects of Span Length

Another important parameter which has been studied in this paper is the span of trim tab. Span is actually the beam of trim tab and is parallel to the beam of planing body. Figure 4 illustrates the span parameter in a trim tab.

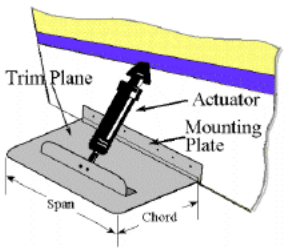

Fig. 4 Span and chord definitions of a trim tab

In this part of the study, like the previous part, the effects of different span lengths on the trim angle and the EHP are studied at various speeds. Figs. 5 and 6 display the results. There are three span lengths which are 0.3, 0.6 and 0.9 meters.

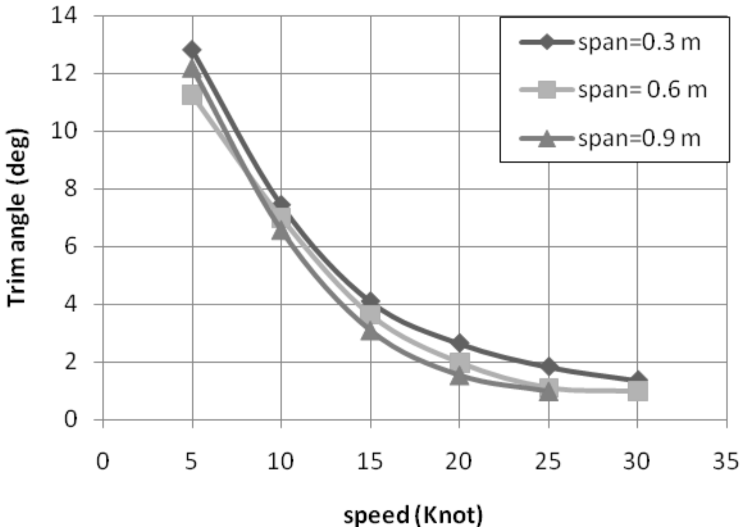

Fig. 5 Effects of different span lengths on the trim angle

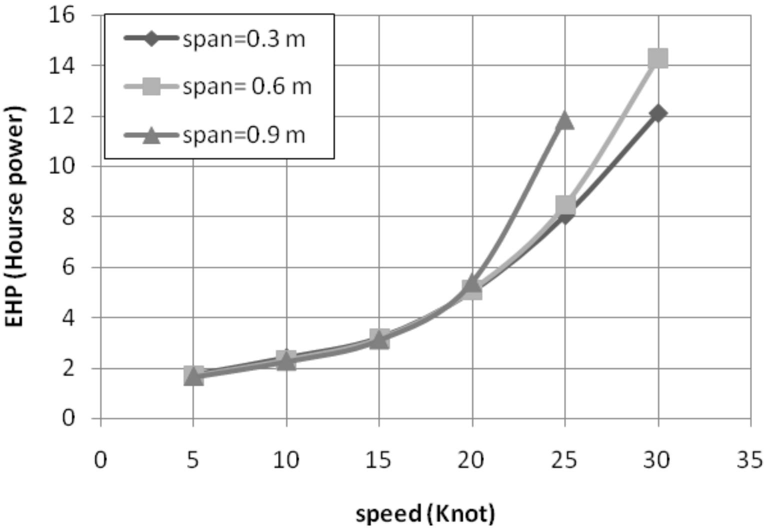

Fig. 6 Effects of different span lengths on EHP

Figs. 5 and 6 imply that by increasing the span length, the trim angle still decreases, though it is not crucial. On the other hand, an increase in the span length results in an increase in EHP. It is obvious in Fig.8 that at the speed of 25 knots, with a span of 0.3 meters, the EHP would be less than 10 horse powers, but it rapidly increases about10 horse powers by increasing the span length to 0.9 meters. The main reason behind this fact is the lift that is produced by an increase in the span length. This increase in the lift multiplied by tangent of the sum of trim and deflection angles causes a larger span resistance. Therefore, it is now understood that span length should be minimized in order to obtain the minimum EHP for a planing hull.

B. Case 1 - Investigations of the Effects of Deflection Angle for Optimization of Deflection Angle

One of the most important parameters that can affect the performance of a planing craft with a trim tab is the deflection angle, δ, of the trim tab. In the next case study, different deflection angles are investigated at different speeds to find the optimized deflection angle of the trim tab for a planing boat. For this purpose, Figs. 7 and 8 illustrate the effects of four deflection angles on the trim and EHP of a planing boat at various speeds.

From Figs.7 and 8, two important conclusions can be drawn. Firstly, by increasing the deflection angle of a planing craft, the trim angle decreases. This reduction in the trim angle is indeed the desirable target of using trim tab. However, the rate reduction intensifies by increasing the speed (as shown in Fig. 7). On the other hand, increasing the deflection angle causes an increase in the EHP. These results are indicative of the fact that determination of an optimized deflection angle at which trim angle and EHP has the most appropriate values is imperative. If change in the trim angle for a vessel without the trim tab (τ_0) from the trim angle for the vessel with the trim tab (τ) is defined as τ' and change in EHP for a vessel without the trim tab (EHP_0) from EHP for the vessel with trim tab (EHP) is defined as EHP', then it seems more suitable to plot distribution of τ' and EHP' versus the deflection angles. Values of these parameters can be obtained from

$$\tau' = \tau / \tau_0 \qquad (18)$$

$$EHP' = 1 - EHP / EHP_0 \qquad (19)$$

By having these quantities, two curves can be plotted. Intersection of these two curves can be considered as the optimized deflection angle. For the planing hull in case 1, the design speed is taken to be 23 knots. Variation in τ' and EHP' at different deflection angles for this speed are determined and displayed in Fig. 9. As expected, τ' decreases while EHP' increases and the intersection of these curves is at 5.2 degrees. This angle is found to be the optimized deflection angle.

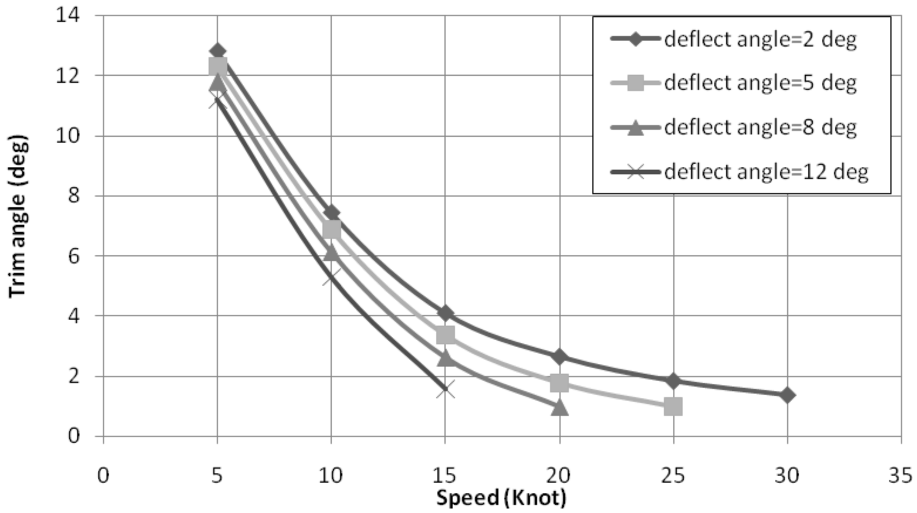

Fig. 7 Trim angle of the boat with different deflections

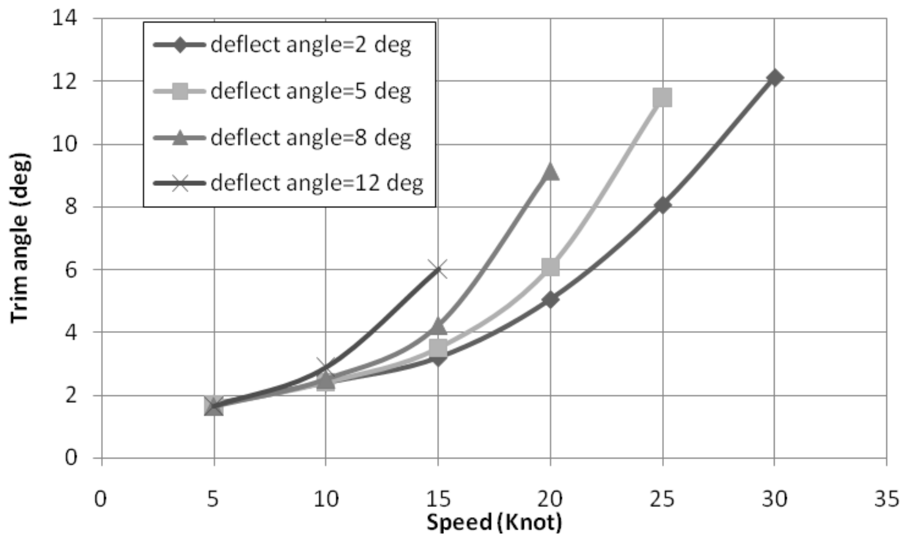

Fig. 8 EHP of the boat with different deflections

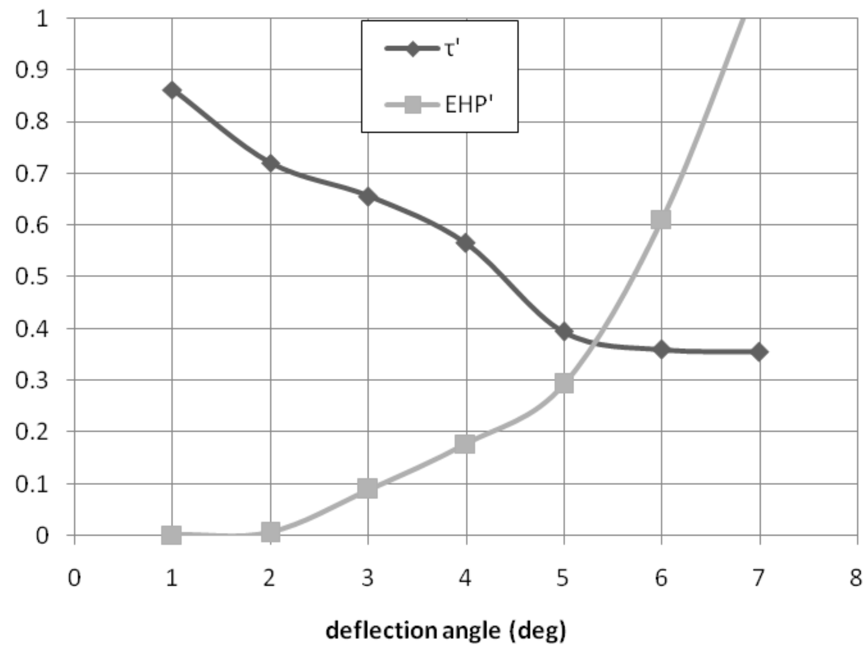

Fig. 9 Plots of τ' and EHP' for determining the optimized deflection angle

After determining the optimized deflection angle, trim angle, and EHP of the craft are computed and illustrated in Figs. 10 and 11.

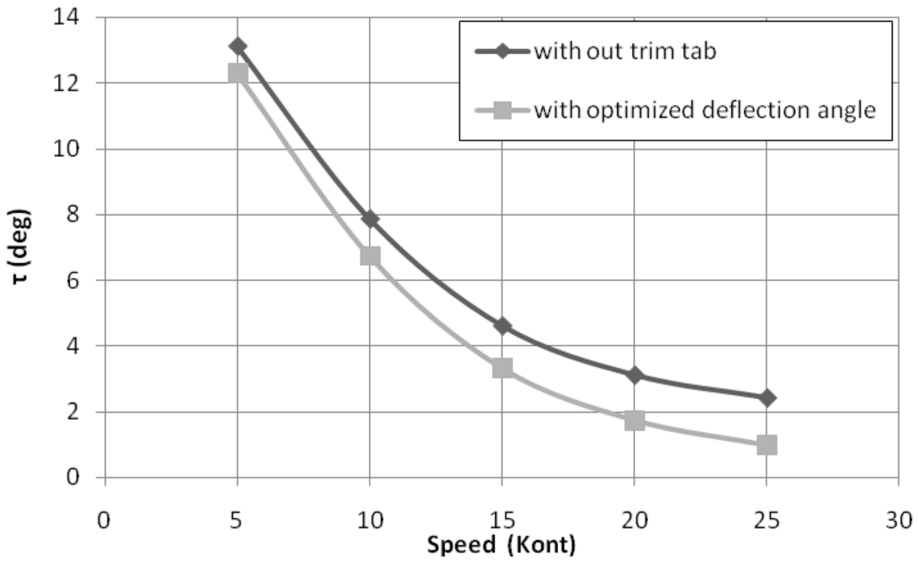

Fig. 10 Variation of trim angle of the planing hull in case 1 without trim tab and with optimized deflection angle

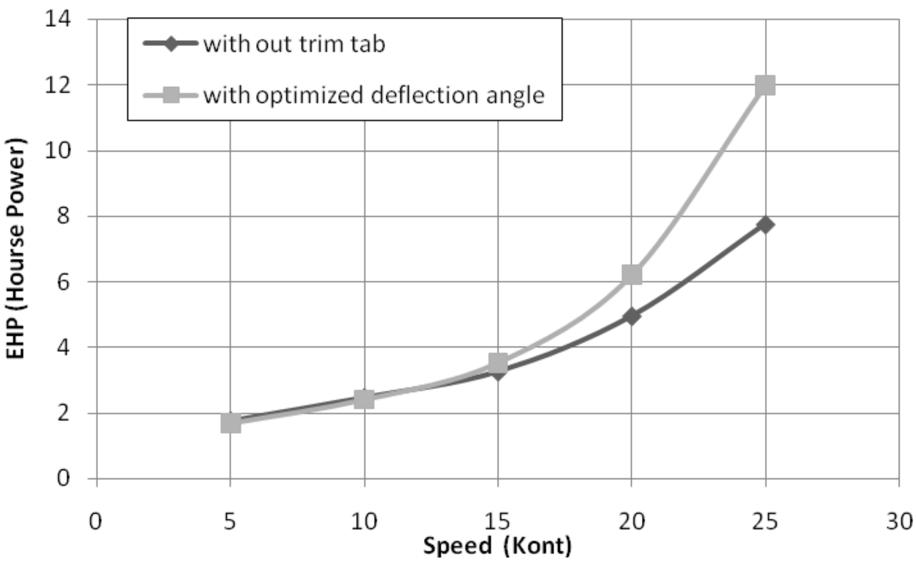

Fig. 11 Variation of EHP of the planing hull in case 1 without trim tab and with optimized deflection angle

C. Case 2 - Finding an Optimized Deflection Angle

At this point, the optimized deflection angle of the second planing hull (case 2) is studied. Mass of this craft is approximately 400 times as large as the mass of case 1, for producing a sufficient lift for the craft in case 2, a much larger area for the flap is needed. Therefore, a flap with chord length L_F=5.9 m and span length=5.9 m is adopted. Area of this span is about 392 times as large as of case 1. For case 2, the values of τ' and EHP' are also calculated and displayed in Fig. 12. Based on this figure, the optimized deflection angle is found to be 3.5 degrees at the design speed of 25 knots.

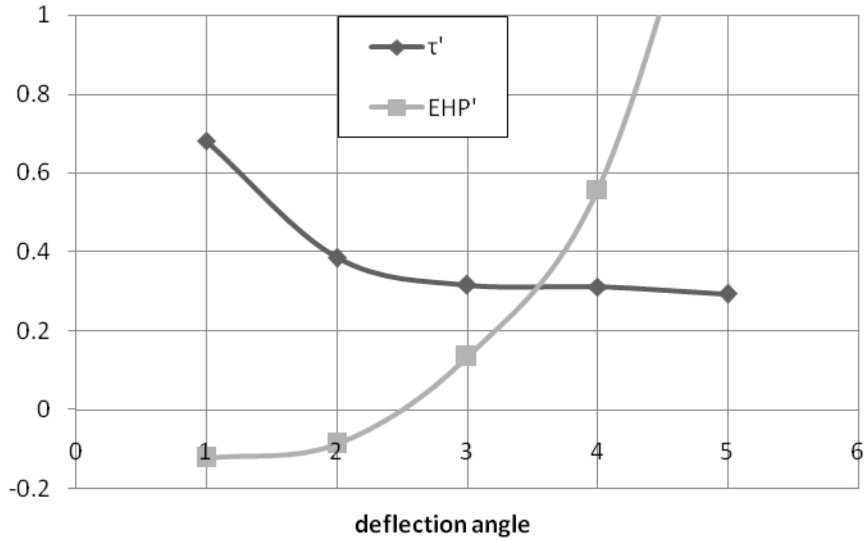

Fig. 12 Variation of trim angle of the planing hull in case 1 without trim tab and with optimized deflection angle

The predicted trim angle and EHP for case 2 with optimized deflection angle and without the trim tab are shown in Figs. 13 and 14.

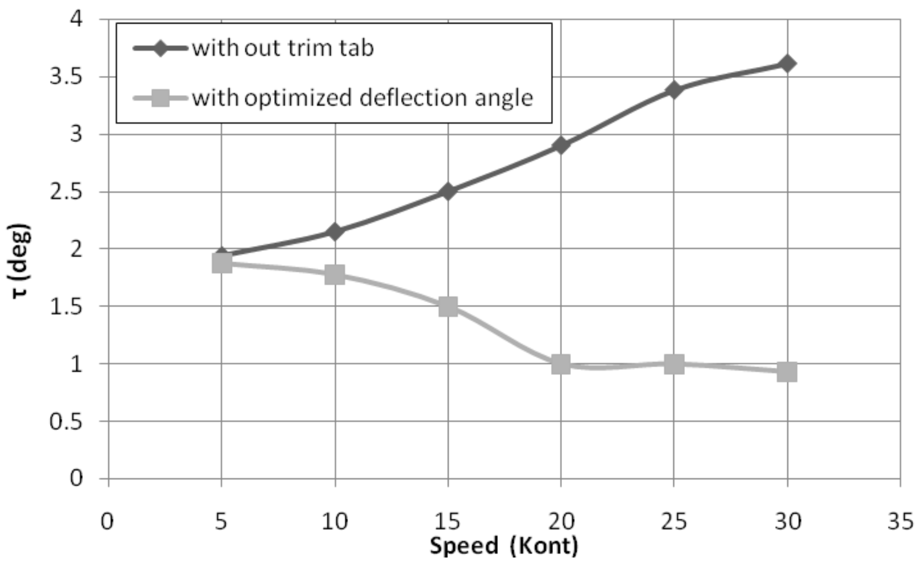

Fig. 13 Variation of trim angle of the planing hull in case 2 without trim tab and with optimized deflection angle

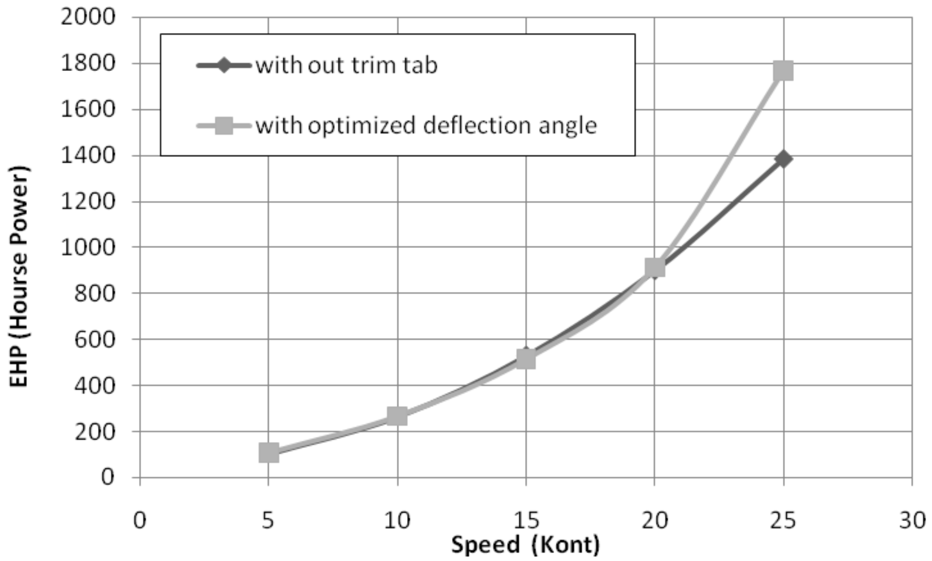

Fig. 14 Variation of EHP of the planing hull in case 2 without trim tab and with optimized deflection angle

As observed in Fig. 13, the trim angle of the considered craft decreases by the use of an optimized trim tab, while it increases, when no trim tab is utilized. Moreover, these plots prove that trim tab has the ability to control the trim angle, while avoiding an increase in the trim angle and before it grows to a very large value. However, avoiding an increase in the trim angle produces a larger value of EHP.

VI. CONCLUSION

A In this paper, effects of trim tab in two different practical situations have been studied, separately. Overall, it is concluded that, with a planing craft that has a trim tab, it is better to reduce the span length to a possible minimum extent, because the former leads to a lower trim angle, while the latter leads to a lower EHP. Subsequently, it is concluded that behaviour of trim tab is different at various deflection angles and it is necessary to find an optimum deflection angle. Accordingly, ratio of trim angle with trim tab to trim angle without the existence of the trim tab (τ') and ratio of EHP with trim tab to EHP without trim tab (EHP') was determined at various deflection angles and consequently an optimized deflection angle is found. This optimization is performed for two different planing crafts. For the first planing craft, where LCG/B =0.71, the optimized deflection angle is determined to be 5.2 degrees. However, for the second hull, where LCG/B =1.87, the optimized deflections found to be3.5 degrees. Furthermore, based on the obtained results, it is quite evident that in the case of a planing craft with a larger value of LCG/B, the effects of an optimized deflection angle is greater.

The results for both high speed crafts with an optimized deflection angle show that if the planing hull is constructed and there are difficulties with the trim angles, the best way for saving the hull is using either a fixed or a controllable trim tab, however, it can bring about an increase in the resistance.

Developing a mathematical model for predicting the performance of planing hulls with variable deadrise angles can be considered an important future study. This result can then be used to find an optimized hull in which the variation of the deadrise angle causes the least resistance.

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