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RESEARCH ARTICLE

Evaluation of the Hydrodynamic Performance of Planing Boat with Trim Tab and Interceptor and Its Optimization Using Genetic Algorithm

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Abstract
Nowadays, several stern devices are attracting a great deal of attention. The control surface is an effective apparatus for improving the hydrodynamic performance of planing hulls and is considered an important element in the design of planing hulls. Control surfaces produce forces and a pitching moment due to the pressure distribution that they cause, which can be used to change the running state of high-speed marine boats. This work elaborates a new study to evaluate the hydrodynamic performance of a planing boat with a trim tab and an interceptor, and optimizes them by using an optimization algorithm. The trim tab and the interceptor have been used to optimize the running trim and motion control of semi-planing and planing boats at various speeds and sea conditions for many years. In this paper, the usage of trim tab is mathematically verified and experimental equations are utilized to optimize the performance of a planing boat at a specificd trim angle by using an optimization algorithm. The genetic algorithm (GA) is one of the most useful optimizing methods and is used in this study. The planing boat equations were programmed according to Savitsky's equations and then analyzed in the framework of the GA-based optimization for performance improvement of theplaning hull. The optimal design of trim tab and interceptor for planing boat can be considered a multi-objective problem. The input data of GA include different parameters, such as speed, longitudinal center of gravity, and deadrise angle. We can extract the best range of forecasting the planing boat longitudinal center of gravity, the angle of the trim, and the least drag force at the best trim angle of the boat.

Keywords Trim tab · Interceptor · Drag force · Genetic algorithm · Optimization algorithm

1 Introduction

The concept of planing boat was introduced in the late nineteenth century. The planing hull form remains one of the most effective designs for high-speed marine vehicles that are employed in military, commercial, and recreational activities. Prediction of the forces acting on a planing hull is required for hull form design, and knowing the performance of high-speed vessels in different conditions is of great importance. At the direct motion of a vessel, a pressure distribution is created at the bottom of the vessel, thereby causing vessel trim and resistance.

Hydrostatic pressure is generated at low speed (length Froude number, $Fn < 0.5$), and hydrodynamic pressure is produced at high speed ($Fn > 0.7$) (Blount and Codega 1992). A vessel is planing when the Fn is greater than 1.2 ($Fn > 1.2$) (Benford 1991). We cannot set a clear line of demarcation between planing and non-planing conditions simply by referring to the Froude number. During planing, the weight of the vessel is mainly supported by hydrodynamic pressure loads. The hydrodynamic pressure both lifts the vessel and affects the trim angle.

The vessel motion changes dynamic pressure distribution, trim, and draft of a planing boat. Trim variations may cause additional resistance in the planing boat and create instabilities such as porpoising instability in the planing boat (Ikeda and Katayama 2000). Therefore, the trim needs to be controlled in high-speed boats.

The study of planing surfaces was initiated by Sottorf. Hydrodynamic experiments were conducted to obtain the most favorable forms for planing boats, flying boats, and seaplane floats with respect to water resistance and seaworthiness (Sottorf 1934). An important study on planing boats was conducted at the Davison Laboratory at the Steven Institute of Technology in 1947.

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The hydrodynamic characteristics of prismatic planing surfaces were discussed and empirical planing equations were given, which describe the planing-surface lift, drag, wetted area, pressure distribution, impact factor, wake shape, spray formation, dynamic stability, and parallel planing surface (Savitsky 1964). Subsequently, several other studies were conducted, such as the experimental and theoretical study of Brown on planing surfaces with trim tabs. His experiments were conducted on a 10° deadrise prismatic planing surface over a range of speed both with and without full-span and half-span trim flaps fitted at the transom. The lift, drag, and pitching moment characteristics are summarized in a planing formula that accounts for the effect of transom flaps and includes the flap hinge moments (Brown 1971).

A few years later, another paper was published by Savitsky and Brown on the effects of controlling the trim tabs. Other subsequent studies are related to the pre-planing resistance of transom stern hulls, the effectiveness of trim control flaps, the effect of bottom warp on planing efficiency, the influence of reentrant transom forms, and the seakeeping of planing hulls (Savitsky and Brown 1976). Since then, the study of trim control system became popular, and their usage in controlling the additional trim of planing hulls became the focal point of other studies. The most well-known trim control device of the high-speed planing boats might be the trim tab.

In addition to empirical works for predicting the performance of planing hulls, several other studies investigated the performance of planing hulls through mathematical models. The most famous and usable method for predicting the performance of the planing hull is the model suggested by Savitsky (Savitsky 1964; Savitsky and Brown 1976). As mentioned earlier, Savitsky's original method was further developed by Savitsky and Brown, and a comprehensive study was conducted to extract a mathematical model for predicting the performance of planing hulls with trim tabs in different situations, such as smooth and rough water (Savitsky and Brown 1976); Savander et al. (2002); (Matveev and Ockfen 2009; Ferrando and Gaggero 2015; Veysi et al. 2015; Brizzolara and Vernengo 2016).

Resistance tests of a systematic series of US Coast Guard planing hulls were performed by Metcalf. They presented trim angle and resistance of four models in various conditions including different displacements and various centers of gravity (CGs). One finding is related to the effect of longitudinal center of gravity (LCG) location on the resistance per pound of displacement. A favorable result was obtained with aft LCG location at higher speeds and forward LCG location at lower speeds. In addition, dynamic wetted surface area data revealed an interesting trend with regard to high speed and the variation of displacement. The dynamic wetted surface area of a particular hull form and LCG location for all displacements converge to the same value once the hull form is planing. Moreover, for the same hull form, a forward LCG location increases the dynamic wetted surface area to which all the displacements converge (Metcalf et al. 2005).

Begovic and Bertorello attempted 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 the boat. Their observation indicated the complex behavior of the wetted area and the stagnation line angle. The reported results can be a useful reference when dealing with pre-planing and planing hull form. They highlighted a speed range where the warping of hull bottom and the increased deadrise angles of the forward part of the hull do not significantly affect the hydrodynamic resistance and identify a relative speed range where they can be comparable to medium-deadrise monohedral. This conclusion encourages the scheduled research on seakeeping and dynamic instability evaluation of non-monohedral forms aimed at providing a complete reference for planing hull form design. They also showed that keel wetted length increases with an increase in the speed of the warped hulls, whereas it decreases in the prismatic body (Begovic and Bertorello 2012).

Three different planing hulls were introduced by Kim for improving performance and seakeeping. The third model has favorable resistance and seakeeping performance among the three model ships. Its hull form will be optimized to improve its hydrodynamic performance in the near future. Moreover, stern appendages may be effective for reducing its required power. For good seakeeping performance, the bow shape is to be designed as a wave-piercing type (Kim et al. 2013).

A parametric study on the effects of trim tabs on the running trim and resistance of planing hulls was conducted by Ghadimi 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 (Ghadimi et al. 2014).

The evolution of stern appendages in later years has led to new contributions. The increase in the size and performance of some large yachts has been accompanied by the development of innovative trimming systems (Deakin and Scarponi 2009). Another study, which involved a series of model tests to compare and determine the roles of the interceptor and the trim tab, was suggested by MDI company using interceptors of different heights but the same span size. Test results clearly show the hydrodynamic advantages of interceptors over trim tabs at different heights (Maritime-Dynamics Inc. 2011).

A preliminary study of a new stern device to improve the efficiency of a fishing vessel was performed in 2010. The project focused on the study of hydrodynamics at the stern to achieve advantages, such as consumption reduction and other improvements in some navigation parameters. A particular type of experimental device with a combination of depth and position was designed and tested in a fishing vessel. Sea experiences have proven the validity of such a device in a transom stern fishing boat. These results show the benefits in the performance of the boat obtained by using the device with a combination of angle and depth (Peláez et al. 2010).

Brizzolara used an interceptor at the maximum height of 200 mm on the steering interceptor of STENA HSS-1500 vessel with 127 m overall length and 40 knot speed (Brizzolara 2003). Molini and Brizzolara introduced a potential flow model to predict pressure and lift force in front of the interceptors (Brizzolara and Molini 2005). Hydrodynamics of the interceptor on a 2D flat plate was studied by using computational fluid dynamics (CFD) and experiments by Mansoori and Fernandes at the Federal University of Rio de Janeiro. Results show that the increase in pressure at the end of the flat plate was proportional to the interceptor height. In addition, the existence of interceptors can significantly increase the lift force coefficient at high angles of attack proportional to the interceptor height (Mansoori and Fernandes 2015).

Mansoori and Fernandes analyzed the hydrodynamics of the interceptor analysis by conducting ultra-reduced model test and dynamic CFD simulation. Results show that the interceptor causes an intense pressure gradient, decreasing the wet surface of the vessel and, quite surprisingly, the resistance. This paper shows that, within a range, a better trim control is possible. The height of the interceptor has an important effect on interceptor efficiency, and it should be especially selected according to the length of the vessel and boundary layer thickness at the transom (Mansoori and Fernandes 2017a).

Another study on the interceptor was conducted in 2016 by Mansoori in cooperation with Fernandes and presented an interceptor hydrodynamic analysis for controlling the porpoising instability in high-speed boats. Findings show that the interceptor causes intense pressure at the stern bottom. It also decreases the trim and resistance of the vessel and increases the lift force coefficient, which directly affects the porpoising instabilities. Results indicate that the interceptor can completely control the porpoising phenomenon (Mansoori and Fernandes 2016).

The latest research in this area was performed by Mansoori and Fernandes to 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 (Mansoori and Fernandes 2017b).

Hydrodynamic performance can be evaluated by using stern appendages. We focused on trim tab and interceptor in this study, and investigated the evaluation of hydrodynamic performance of a planing boat with a trim tab control system. For this purpose, the mathematical formulation of Savitsky's method and the effects of trim tab on forces and center of pressure are explained. The procedure of Savitsky's modified method for planing hulls equipped with trim tabs is then introduced in a code. After presenting the code and validating the code, with the use of the genetic algorithm (GA), the hull is optimized to diminish the drag force of the trim tab at a specific trim angle. The proposed method is used to examine the performance of a planing hull, as analyzed by Savitsky and Brown (Savitsky and Brown 1976). Finally, the improvement of the hydrodynamic performance of a planing boat with a trim control system by using GA is studied.

2 Hydrodynamic of Planing Boat

Planing hulls operate at different speed ranges, namely, displacement, cruising, and planing ranges of speed. However, different optimum trim angles exist for each operating speed. Improving the planing hull performance at different operating speeds requires continuous control of the trim angle during operation. Trim tabs and interceptors were considered in this research as controlling devices of boat trim angles. These devices can be continuously adjustable to provide suitable trim angles at any operating speed and loading condition.

To fully understand the effects of trim tabs and interceptors, a short introduction about the mechanics of ships and planing boats is given. Trim tabs are well-known appendages with a relatively small size and are constructed in the form of a protruding aft plane at an angle as an extension of the lower surface of the hull. The most significant geometric parameters of a trim tab shown in Fig. 1 are

- chord length (chord),
- size through the aft beam (span), and
- trim tab angle (angle).

Other aspects of the design of a trim tab are profile, variations in the thickness, and agreement with the hull. Trim tabs are used to

- reduce operating costs and life cycle,
- save fuel,
- increase the speed of the boat, and
- decrease the amount of pollutants emitted into the atmosphere.

The evolution of the stern apparatus has led to new contributions in recent years. The increase in size and performance of some large yachts has been accompanied by the development of innovative trimming systems (Deakin and Scarponi 2009).

Its schematic representation is of a metal plate embedded vertically in the stern, covering a portion of the aft beam and with its lower edge protruding vertically below the transom (Fig. 2). The interceptor is used to improve the hydrodynamics performance of planing and semi-planing boats. Interceptors are vertical blades installed symmetrically aft of the boat.

The interceptors cause changes in pressure magnitudes around the vessel bottom and especially at the end of the hull where they are located. The pressure variations have an effect on resistance, draft height, and lifting forces, which may result in improved control of the trim. On the basis of the latest scientific achievements, the interceptor height should not be higher than 60% of the boundary layer thickness at the transom. For optimum efficiency, when the interceptor height equals 60% of the boundary layer thickness, the interceptor span length should be seven times the interceptor height (Mansoori et al. 2017). The magnitude of the lift created by the trim tab and the interceptor normally depends on their dimension and flow velocity. However, other parameters may influence the effectiveness of the trim tab and interceptor. Figure 3 shows the effect of the arrangement of the trim tabs and interceptors on the modification of the added lift of the boat whereby the resistance of the boat can be reduced and the attitude of the vessel can be controlled.

This case is defined by a few variables that are related to the geometry of the planing body and the trim tab. Moreover, the design speed and mass of the planing body are included. With these variables, the output will be the trim angle and total resistance. Computer programs have been specially designed to perform an optimization process and develop design contours for the best operating trim and optimum resistance.

2.1 Governing Equilibrium Equation

Planing boat theory was explained in the introduction, but a better look on how the forces react on a planing hull is essential. Figure 4 shows the main forces that act on planing boats with a trim tab and an interceptor.

Vertical equilibrium is given by

$$\varDelta_0 = N\cos\tau + T\sin(\tau+\varepsilon) - R\sin\tau \tag{1}$$

Horizontal equilibrium is

$$T\cos(\tau+\varepsilon) = R\cos\tau + N\sin\tau \tag{2}$$

The pitching moment equilibrium around the CG equals

$$Nc + Ra - Tf = 0 \tag{3}$$

The vertical equilibrium of a planing boat with a trim tab or an interceptor is given by

$$\varDelta_0 = N\cos\tau + T\sin(\tau+\varepsilon) - R\sin\tau + L_{\text{Trim-tab}}\cos(\tau+\delta) - D_{\text{Trim-tab}}\sin(\tau+\delta) \tag{4}$$

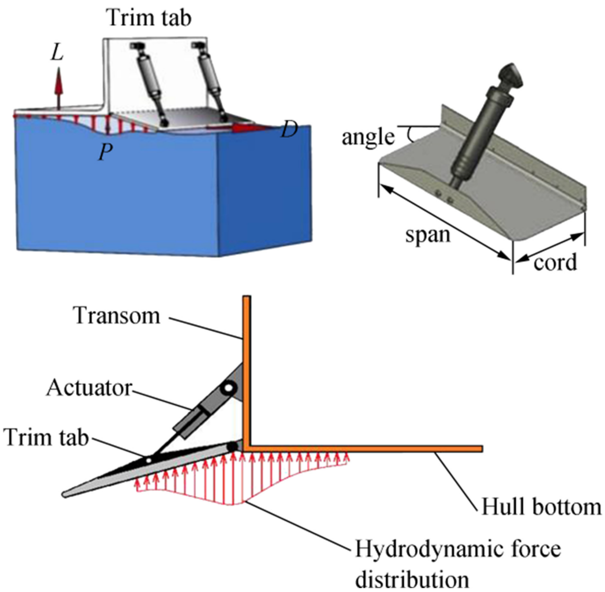

Fig. 1 Trim tab features

The horizontal equilibrium of a planing boat with a trim tab and an interceptor is

$$T\cos(\tau+\varepsilon) = R\cos\tau + N\sin\tau + L_{\text{Trim-tab}}\sin(\tau+\delta) + D_{\text{Trim-tab}}\cos(\tau+\delta) \tag{5}$$

The pitching moment equilibrium of a planing boat with a trim tab and an interceptor around the CG is calculated by

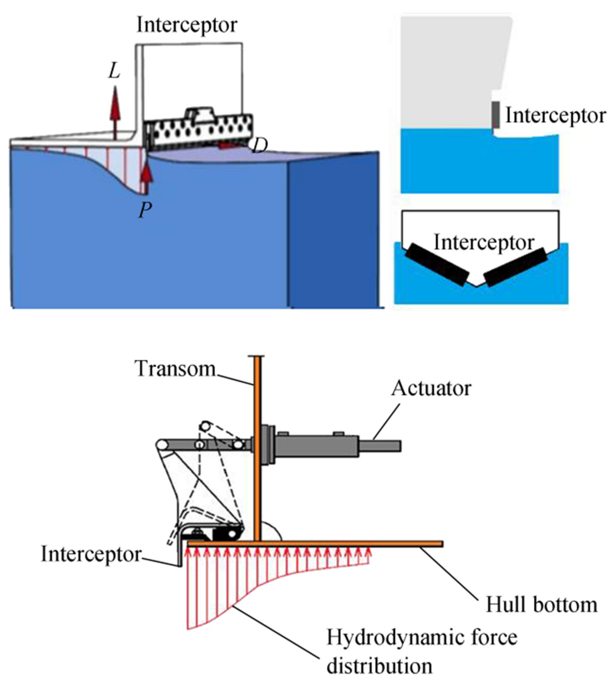

Fig. 2 Interceptor features

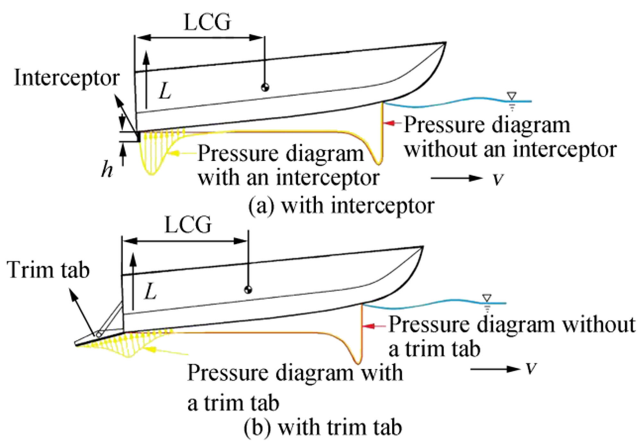

Fig. 3 Illustration of physical phenomena associated with interceptor (**a**) and trim tab (**b**)

$$Nc + Ra - Tf + L_{\text{Trim-tab}}(LCG + b) + D_{\text{Trim-tab}}(VCG + d) = 0 \quad (6)$$

where b is the horizontal distance from the trim tab lift force center to the transom, and d is the vertical distance from the trim tab drag force center to the keel.

The vertical equilibrium of a planing boat with an interceptor is given by

$$\Delta_0 = N\cos\tau + T\sin(\tau + \varepsilon) - R\sin\tau + L_{\text{Interceptor}}\cos\tau - D_{\text{Interceptor}}\sin\tau \quad (7)$$

The horizontal equilibrium of a planing boat with a trim tab and an interceptor is

$$T\cos(\tau + \varepsilon) = R\cos\tau + N\sin\tau + L_{\text{Interceptor}}\sin\tau + \text{D}_{\text{Interceptor}}\cos\tau \quad (8)$$

The pitching moment equilibrium of a planing boat with a trim tab and an interceptor around the CG is calculated by

$$Nc + Ra - Tf + L_{\text{Interceptor}} \times (\text{LCG}) + D_{\text{Trim-tab}} \times (\text{VCG} + \text{k}) = 0 \quad (9)$$

where k is the vertical distance from the interceptor drag force center to the keel (Fig. 5).

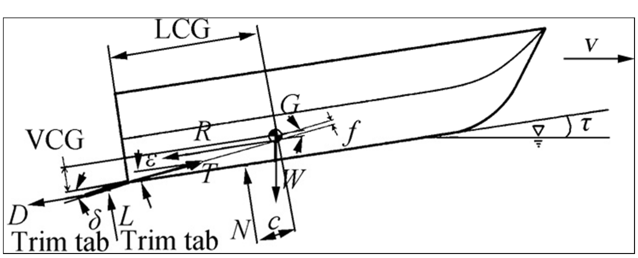

Fig. 4 Equilibrium of forces acting on a planing boat with a trim tab

2.2 Governing Lift and Drag Equation

The lift force in the planing surface can consist of two separate effects: dynamic reaction against the moving surface and buoyant lift associated with the static pressure corresponding to a given draft and trim. The total hydrodynamic drag of a planing surface consists of pressure drag force developed by dynamic pressure acting normal to the bottom and viscous drag acting tangential to the bottom in both pressure and spray areas. If side wetting occurs, then this additional component of viscous drag must be added to the hydrodynamic drag acting on the bottom of the planing surface.

Therefore, the lift coefficient is the parameter that gives enough force to lift the planing body and is presented as follows:

$$F_{L\beta} = Mg \rightarrow C_{L\beta} = \frac{Mg}{0.5\rho V^2 B^2} \quad (10)$$

The planing boat method of Savitsky is used to calculate all the parameters that affect the running state of a planing boat. Although some assumptions are made in the computation, this method is the most common tool that is used to analytically describe a planing hull. First, the lift coefficient of a planing boat with a deadrise angle β is given by

$$C_{L\beta} = \frac{\Delta}{0.5\rho V^2 B^2} \quad (11)$$

where Δ is the boat's mass, ρ is the density of water, V is the velocity, and B is the beam. The lift coefficient for the planing hull when modeled as a flat plate, C_{L0}, is

$$C_{L0} = C_{L\beta} + 0.0065\beta C_{L0}^{0.6} \quad (12)$$

where λ is the running mean wetted length-beam ratio (L_m/B) and is calculated through an iteration of the following equation:

$$C_{L0} = \tau^{1.1}\left(0.012\lambda^{0.5} + 0.0055\left(\frac{\lambda^{2.5}}{{Fn_B}^2}\right)\right) \quad (13)$$

where τ is the trim of the planing boat and Fn_B is the

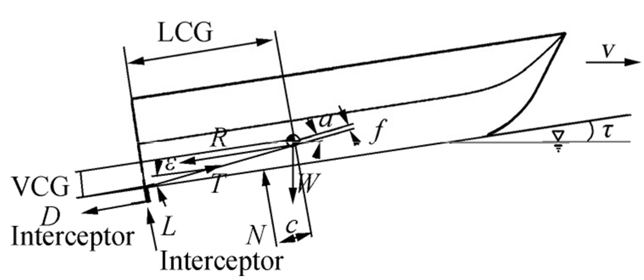

Fig. 5 Equilibrium of forces acting on a planing boat with an interceptor

beam Froude number. The total hydrodynamic drag (D_{Total}), consists of both pressure drag resistance (D_p) and friction drag resistance (D_f), which is

$$D_{\text{Total}} = D_P + D_f \tag{14}$$

$$D_P = F_{L\beta}\tau = \Delta\tan\tau \tag{15}$$

In this study, the skin friction coefficient (C_F) is calculated by using the ITTC-57 formula.

$$D_f = 0.5\rho V_m^2 S C_F \tag{16}$$

Where:

$$C_F = C_{F,\text{ITTC}} + \Delta C_F \tag{17}$$

$$C_{F,\text{ITTC}} = \frac{0.075}{(\log\text{Re}-2)^2}$$

$$\Delta C_F = \left[111(\text{AHR}, V)^{0.21} - 404\right] C_{F,\text{ITTC}}^2 \tag{18}$$

$$\text{Re} = \frac{VL_k}{\upsilon} \rightarrow \upsilon = 1.19\times10^{-6}\,\frac{m^2}{s}, \text{AHR} = 150\times10^{-6}$$

where the Reynolds number is Re and the kinematic viscosity of the water is υ. After obtaining the Reynolds number and S, the frictional drag can be calculated.

$$S = S_1 + S_2 \tag{19}$$

$$S_1 = \frac{\tan^2\beta}{\sin\beta}\left(\frac{B^2}{4\left(\frac{1+z_{\max}}{Vt}\right)\tau}\right) \tag{20}$$

$$S_2 = \frac{B}{\cos\beta} L_C \tag{21}$$

Here, β and τ are in radian. In the calculation, the wetted length L_K and L_C can be obtained as follows

$$\frac{0.5(L_K + L_C)}{B} = \lambda \qquad L_K - L_C = x_S \tag{22}$$

Thus,

$$L_K = \frac{1}{2}(2\lambda B + x_S) \tag{23}$$

$$L_C = \frac{1}{2}(2\lambda B - x_S) \tag{24}$$

From $\frac{B}{2} = \frac{\pi}{2\tan\beta} x_S\tau$, we know

$$x_S = \frac{B\tan\beta}{\pi\tau} \tag{25}$$

Thus,

$$L_K = \frac{1}{2}\left(2\lambda B + \frac{B\tan\beta}{\pi\tau}\right), L_C = \frac{1}{2}\left(2\lambda B - \frac{B\tan\beta}{\pi\tau}\right) \tag{26}$$

Now the friction drag resistance, pressure drag resistance, and total drag resistance can be calculated. The mean velocity over the bottom of the planing surface, V_m, is

$$V_m = V\left(\sqrt{\frac{C_{L\beta}}{\lambda\cos\tau}}\right) \tag{27}$$

The distance between CG and the center of pressure where the hydrodynamic lift force acts is

$$c = \text{LCG} - l_P = \text{LCG} - C_P\lambda B \tag{28}$$

$$l_P = \lambda B\left(0.75 - \frac{1}{5.21\left(\frac{Fn_B^2}{\lambda^2}\right) + 2.39}\right) \tag{29}$$

To decrease the complexity of the planing hull shape and the fluid flow, the following assumptions are used in the Savitsky method: the running trim is in a steady state, the spray root line is considered straight, the deadrise angle is constant over the entire wetted area, and a hard-chine form is observed.

Some restrictions exist with the use of the Savitsky method for the planing hull, i.e., $\lambda \le 4$, $\tau \le 15^{\circ}$. To prevent porpoising, the trim angle should be less than the critical trim angle ($\tau < \tau_{\text{crit}}$). Critical trim angle is found by using Celano's critical trim angle formula (Faison 2014)

$$\tau_{\text{crit}} = 0.1197\beta^{0.7651}\exp\left(15.7132\sqrt{\frac{C_{L\beta}}{2}}\beta^{-0.2629}\right) \tag{30}$$

When $l_P \neq LCG$ the hydrodynamic force will cause a trim moment about CG, and the trim moment must be generated by the lift force on trim tabs. According to the equilibrium of moment about the CG

$$M_{\text{Trim-tab}} + F_{L\beta}(l_P - \text{LCG}) = 0 \tag{31}$$

The lift force due to the trim tab is

$$L_{\text{Trim-tab}} = 0.5\rho V^2 L_{C_{\text{Trim-tab}}} B C_{L_{\text{Trim-tab}}} \tag{32}$$

where $L_{C\text{Trim}-\text{tab}}$ is the chord length of the trim tab and is calculated by

$$C_{L_{\text{Trim-tab}}} = 2\pi\sin\alpha_{\text{Trim-tab}} \tag{33}$$

If we assumed the center of the lift force of trim tab locates $x_{C_P\text{Trim-tab}} = 0.75L_{C\text{Trim-tab}}$ from the trailing edge, then the positive $\alpha_{\text{Trim - tab}}$ is used to acquire the downward lift force on the trim tab. Thus, the distance from the center of the lift to the CG is

$$x_l = (L_{C_{\text{Trim-tab}}} - 0.75 L_{C_{\text{Trim-tab}}}) + \text{LCG} \tag{34}$$

Thus, the trim tab moment is

$$M_{\text{Trim-tab}} = F_{L\beta_{\text{Trim-tab}}} \times x_l \tag{35}$$

Therefore, we obtained the equations

$$0.5\rho V^2 L_{C_{\text{Trim-tab}}} B C_{L_{\text{Trim-tab}}} \times (0.25 L_{C_{\text{Trim-tab}}} + \text{LCG}) = M_{\text{Trim-tab}} \tag{36}$$

We can prove that these two equations are equivalent. Thus, we can use one of them to obtain the possible combination of chord of the trim tab $L_{C\ TB}$ and the trim tab angle.

Dawson and Blount presented a way to find the equivalent interceptor dimensions if the interceptor and the trim tabs are assumed to have the same width (Dawson and Blount 2002; Brizzolara and Villa 2009). First, the interceptor angle is given by (Fig. 6)

$$\alpha_{\text{Interceptor}} = 0.175\alpha_{\text{Trim-tab}} + 0.0154\alpha^2{}_{\text{Trim-tab}} \tag{37}$$

The chord length of the interceptor is equal to the height of the interceptor (h_{Int}) and is calculated by Eq. (38)

$$L_{C_{\text{Interceptor}}} = \frac{h_{\text{Interceptor}}}{\sin\alpha_{\text{Interceptor}}} \rightarrow \alpha_{\text{Interceptor}} = 90^{\text{o}} \rightarrow L_{C_{\text{Interceptor}}} = h_{\text{Interceptor}} \tag{38}$$

According to Brown formulas, while using the equivalent angle for the interceptor, the interceptor-added lift coefficient is equal to (Brown 1971)

$$C_{L_{\text{Interceptor}}} = 0.046 \frac{L_{C_{\text{Interceptor}}}}{B} \alpha_{\text{Interceptor}} \rightarrow L_{\text{Interceptor}} = 0.5 C_{L_{\text{Interceptor}}} \rho B^2 V^2 \tag{39}$$

Furthermore, the added drag is calculated by

$$D_{\text{Interceptor}} = 0.0052 L_{\text{Interceptor}} \left(\alpha_{\text{Interceptor}} + \tau\right) \tag{40}$$

According to the moment equilibrium of the planing boat with interceptor about the CG

$$M_{\text{Interceptor}} + F_{L\beta}(\text{l}_P - \text{LCG}) = 0 \rightarrow M_{\text{Interceptor}} = L_{\text{Interceptor}} \times \text{LCG} \tag{41}$$

3 Computational Procedure and Validation Case

3.1 Computer-Aided Program for Equilibrium Trim

A computer program has been specially created to determine the optimal resistance and the equilibrium trim angle. Through an iterative process, the developed program is designed to use planing hull data to determine all forces and moments acting on that hull for a range of a boat's velocities. This computer-aided program is also equipped to improve the Savitsky prediction of the planing boat resistance at a cruising speed range. To illustrate the process clearly, a flowchart is provided in Fig. 7.

3.2 Verification of Computer-Aided Program with Experimental Data

The results of the written computer-aided program are compared with the results obtained by Savitsky and Brown (Savitsky and Brown 1976). This case is pertinent to a planing boat with a trim tab whose characteristics are described in Table 1. After computer program verification, the program might be developed to add the process of controlling the trim angle by using different controlling devices such as a trim tab and an interceptor. Also, the program can be developed to achieve the optimum trim angle through a proposed optimization process, to attain the best regimes of the operating trim.

As seen in Table 1, the span of the trim tab is exactly equal to the beam of the planing hull, thereby implying that the trim tab uses the whole beam. This type of trim tab is called full-span trim tab, and the cord of the trim tab is equal to 1. Results of this case study are shown in Table 2 and compared against the original results of Savitsky.

Table 2 shows that the results are fairly close. The trim angle has a 2.41% error, while the total resistance has a 1.51% error. These errors are attributed to the number of used decimals and can be natural.

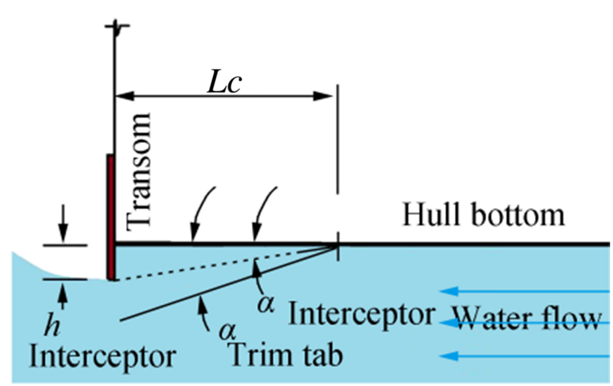

Fig. 6 Configuration of the transom and equivalent angle for the interceptor

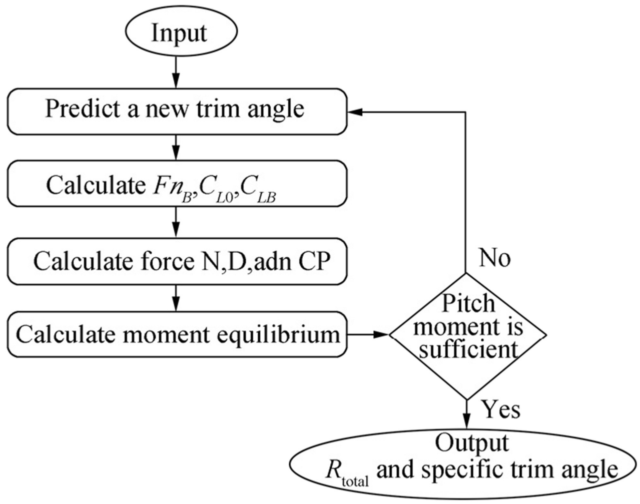

Fig. 7 Flowchart of the computational process of the computer-aided program

3.3 Optimization of Hydrodynamic Performance of Planing Boat Using Trim Tab and Interceptor

The basic theories used in this paper are the analytical evaluation of a planing boat with a trim tab and an interceptor and multi-objective genetic algorithm (MOGA) for the optimization process. To achieve an optimum planing boat, some constraints could be considered objective functions that are used in MOGA. In this study, optimization is conducted to optimize the resistance at a specific trim angle. The optimization is performed to achieve the minimum resistance and trim angle at a specific speed. Therefore, no limitation in trim angle exists.

GA is a heuristic search and optimization technique inspired by natural evolution. It has been successfully applied to a wide range of real-world problems of significant complexity. GA is a stochastic optimization technique inspired by the evolution process of natural life. In GA, selection is performed in the population of a certain generation so that an individual with high fitness to the objective function in the optimization problem survives with high probability. Furthermore, the population of the next generation is formed by crossover and mutation. As alternation of generations proceeds, individuals with higher fitness increase, and the most suitable solution is provided. The above is a basic concept of GA.

Table 2 Comparison of Savitsky's results and the computer-aided program's results

	Savitsky's results	Calculated (paper results)
Trim angle/(°)	2.9	2.97
Total resistance/N	72 061	73 151

In general, an individual is expressed by a binary string of 0 or 1 of the suitable number per one design variable in GA, and this binary string is transformed to the design variable, which is a real number. The chromosome of each individual is expressed by binary strings of the same number as the number of the design variables. Spaces expressed by binary strings and real numbers are called genotype and phenotype spaces, respectively. The mapping from phenotype to genotype is called coding.

Shape optimization in ship hydrodynamics using CFD was performed by Campana and Peri. In this paper, the optimization was performed by using GA (Campana et al. 2006). Gaggero and Gonzalez attempted to design contracted and tip-loaded propellers by using boundary element methods and to perform optimization by using GA (Gaggero et al. 2016). The drag force optimization of a planing craft with a trim control system by using GA was conducted by Sakaki et al. (2017). The fully automatic optimization chain was implemented by adopting the *modefrontier* optimization environment to interface the Friendship-Framework (parametric definition of the hull shape), the CFD codes developed by CETENA S.P.A. (to predict the steady wave resistance and unsteady seakeeping performances of each design candidate), and MOGA (Biliotti et al. 2011).

Table 1 Case of Savitsky and Brown

Model of Savitsky and Brown features	
Mass/kg	84 444
Beam/m	7.32
LCG from stern/m	10.675
VCG/m	0.5
Deadrise angle β/(°)	15
f/m	0.6
ε /(°)	0
Design speed/kn	25.4
Flap chord/m	0.305
Span/m	7.32
Flap deflection δ/(°)	5

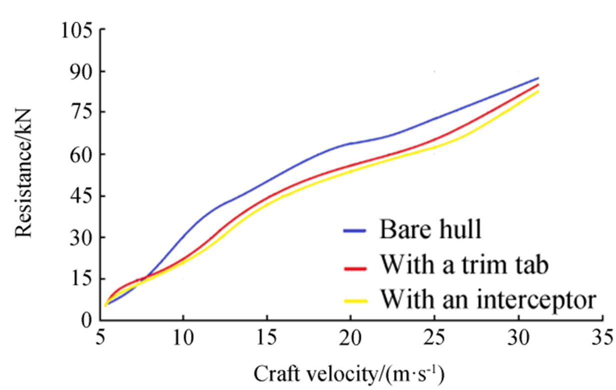

Fig. 8 Total resistance force of a planing hull in terms of velocity (bare hull, with a trim tab and an interceptor)

Table 3 General information about MOGA

MOGA settings	
Type of parameter	Rate or type of consideration
Population size	50
Iteration	750
Type of mutations	Random number generation
Percentage of crossover/%	50
Type of crossover	Two-point crossing over
Percentage of recombination/%	15
Type of selection	Random selection

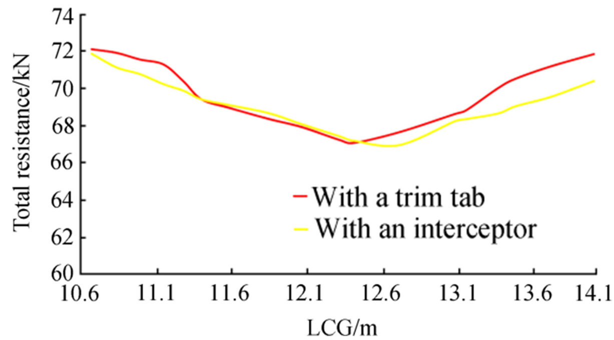

Fig. 9 Total resistance force of a planing hull in terms of LCG (with trim tab and an interceptor)

In this study, the input variables (lcg, β, and V) are assumed as the genotype and output variables (resistance and trim angle) as the phenotype on both of which the genetic operations are applied. In each generation, selection functions pick the most significant genes as the parents of the next generation and then the crossing-over procedure is performed on them. Random genes are added to the population as mutation functions, and this procedure is repeated until the ultimate criteria are established. Different conditions can be set to stop the problem. In this paper, the condition was to reach the number of iterations, which is set to a maximum of 750. The flowchart of the optimization process approach is shown in Fig. 8. Any evolutionary optimization algorithm needs to be configured by settings. The parameters for this paper are shown in Table 3.

4 Results

The results for the planing hull with a trim tab and an interceptor are summarized in Table 4. The total resistance force of the planing hull with a trim tab and an interceptor in terms of velocity and LCG are shown in Figs. 8 and 9, respectively. The hydrodynamic performance of a planing boat with a trim tab and an interceptor were optimized by MOGA, which was described in the beginning of Section 3.3. Some important parameters that can affect the performance of a planing boat with a trim tab and an interceptor are boat velocity, LCG, and deadrise angle. After optimizing the planing boat with a trim tab via GA, the optimum resistance at a specific trim angle for the model of Savitsky and Brown (Savitsky and Brown 1976) is $R = 67\,072.69$ at a specific trim angle of 1.924°.

Table 4 Results of GA for the case of Savitsky and Brown (Savitsky and Brown 1976)

	Savitsky's results	GA optimization with trim tab	GA optimization with interceptor
Total resistance/N	72 061	67 072.69	66 823.51
Trim angle/(°)	2.9	1.924	1.98
Velocity/(m·s^{-1})	25.4	25.4	25.4
LCG/m	10.675	12.42	12.57
Deadrise angle/(°)	15	15	15

After optimization with the use of GA, the total resistance of the planing boat with a trim tab is decreased to 6.9% at a trim angle of 1.924° and LCG is 12.42 m from the transom. The optimization of the total resistance of a planing boat with an interceptor caused a 7.26% decrease in the trim angle to 1.98° and LCG of 12.57 m from the transom. The results of GA optimization of resistance force variation are presented in Figs. 10 and 11 with a trim tab and an interceptor, respectively.

5 Conclusions

The major goal of this paper was to evaluate and optimize a planing boat with an interceptor and a trim tab. The effects of the trim tab and the interceptor in the same situations were studied separately. Overall, the planing boat with an interceptor exhibits better reduction in resistance force than the planing boat with a trim tab. The trim installation mechanism, such as an interceptor or a trim tab, increases the lift forces and consequently leads to trim control, lower draft height, and less drag forces.

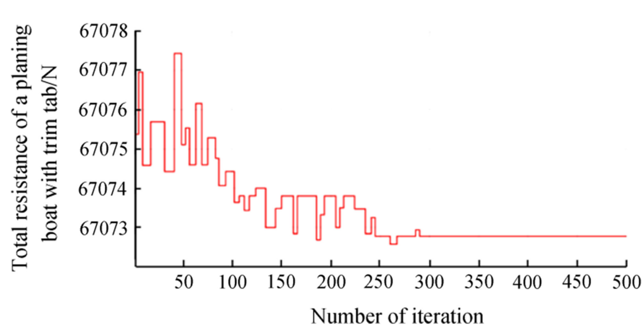

Fig. 10 Total resistance variation for a planing hull with a trim tab during optimization by GA

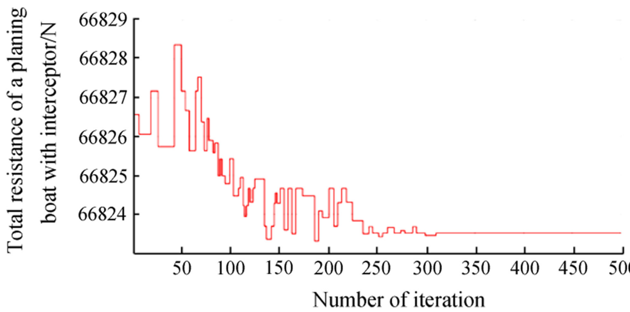

Fig. 11 Total resistance variation for a planing hull with an interceptor during optimization by GA

This work optimized planing boats with a trim tab and an interceptor by using Savitsky's equations with GA. After validating the calculated results using Savitsky's results (Savitsky and Brown 1976), optimization was performed.

The GA method uses three variables, V_n. LCG. β, which affect the total resistance of the boat. In this study, the model of Savitsky and Brown (Savitsky and Brown 1976) was optimized by only changing the LCG variables. Results show a decrease in the total resistance of the boat with an interceptor and a trim tab at a specific trim angle. Therefore, changing the LCG variables results in a change in the trim angle, thereby lessening the total resistance.

GA is able to optimize all the variables. The performance of planing boats with variable deadrise angles was considered. Optimization by changing the deadrise angle showed that the total resistance decreased at different deadrise angles. The proposed method can be used as a proper optimization tool for designing planing boats.

Nomenclature

M	Displacement of boat
$F_{L\beta}$	Hydrodynamic force
β	Deadrise angle
ρ	Density of water
C_{L0}, $C_{L\beta}$	at zero deadrise angle
$C_{L\beta}$	Lift coefficient
C_P	Pressure coefficient
C_F	Frictional drag coefficient
$C_{L\ TB}$	Lift coefficient of trim tab
$C_{L\ Int}$	Lift coefficient of interceptor
λ	Mean wetted length-to-beam ratio
l_p	Longitudinal center of pressure
L_K	Keel wetted length
L_C	Chine wetted length
L_{TB}	Lift of trim tab
D_{TB}	Drag of trim tab
M_{TB}	Moment of trim tab
$L_{c\ TB}$	Chord length of trim tab
α_{TB}	Trim tab deflection
L_{Int}	Lift of interceptor
D_{Int}	Drag of interceptor
M_{Int}	Moment of interceptor
$L_{c\ Int}$	Chord length of interceptor
α_{Int}	Interceptor deflection
τ	Trim angle
Fn_B	Beam Froude number
Rn	Reynolds number
B	Breadth of the boat
V	Boat velocity
g	Gravitational acceleration
D_f	Frictional resistance
S	Wetted surface of the boat
v	Kinematic viscosity of the water
α	Trim tab angle
x_{cp}	Center of lift force of trim tab
x_l	Distance from the center of lift force of trim tab to center of gravity
LCG	Longitudinal center of gravity
VCG	Vertical center of gravity

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