IJEAST

INTERNATIONAL JOURNAL OF ENGINEERING APPLIED SCIENCE AND TECHNOLOGY

VOLUME : 7 ISSUE : 04 Print / Issue Publication Date: 30-Sep-2022

ISSN : 2455-2143

DOI : 10.33564/IJEAST.2022.v07i04.001

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International Journal of Engineering Applied Sciences and Technology, 2022
Vol. 7, Issue 4, ISSN No. 2455-2143, Pages 01-05

SOLUTION TO REDUCE TOTAL RESISTANCE OF PLANING VESSELS THROUGH RETROFITTING OF STERN APPENDAGES

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***Abstract* - During operation, there is a variation in total drag and trim angle in planingvesselsin accordance with the increasing in speed when they change from nonplaning regime to planing regime. The article presents some solutions to reduce total drag through controlling and optimizingthe trim angle during the operation of planing vessels, the theoretical basis of those solutions as well as presentssomeappendages currently being used on the planing vessels over the world**.

Keywords -**Resistance, trim angle, planing hulls, interceptor, stern flap, hull vane.**

I. INTRODUCTION

Compared to the history of ship design, the concept of planing hull appeared also relatively early, from about the 1960s of the last century. Planing vessels are used in many fields, especially in the military with patrol boats, missile boats, torpedo boats. Nowadays, with the development of major types of propulsion equipment such as gas turbines engines and internal combustion engines, the speed of ships is increased day by day. Even so, the number of reseaches on planing hull is still relatively small.

Planing vessels are characterized by the appearance of hydrodynamic lift, which plays an important role in maintaining the steady motion of the vessels in the planingregime. In essence, the vessels' motion state is a function of the trim moment, the vertical forces and the longitudinal forcescorresponding to the parameters of trim angle, draft and vessels' speed [1].Reseaches as well as experiments show the change of drag curve and trim angle curve with speed, respectively. In semi-displacement regime, the trim angle curve and drag curve will be convex, showing that the drag of the vessel is significantly higher than that in the nonplaningregime. This has a relatively large impact on the economy and navigation of the vessel because it requires a large loss of engine power and a short-term change in the position, rolling, and pitching of the vessel. Drag reducing and propulsion efficiency increasing will help minimize unnecessary fuel consumption,contribute to improving economic efficiency for vessels as well as reduce environmental pollution. Especially with warships, the requirement for high speed is very important, reducing drag and increasing thruster efficiency also helps the ship to achieve more optimal speed with the exist propulsion system. Therefore, not only planing vessels in particular but also surface vessels in general, resistance reducing and propulsion efficiency increasing is a basic and very important requirement of the ship design and operation process.

As stated above, it is possible to reduce thedrag of planing vessels through controlling the variation of the trim angle, while still increasing the lift on the hull. The solution is to use stern appendages like stern wedges, stern flaps, interceptors or hull vanes. In the world, there have been many researches on these solutions such as **Cusanelli and Karafiath**[2] [3] on stern wedgeand stern flaps that have been successfully applied to a number of US Navy ships with results as reducing power consumption from 6.2% ÷ 11.6%, the research of **Tsai et al.**[4] on interceptors which are installed on high-speed vehicle, the research of **Uithof et al.**[5]on the hull vane also gives relatively good results with a reduction in drag from 5% ÷ 10%.

In this paper, the author presents the general theoretical bases, operating principles of the above-mentioned appendage devices in reducing the drag of planing vessels and analyzes the application of these devices in the world.

II. THEORETICAL BASE

To be able to properly and fully understand the theoretical basis of applying the solutions given for reducing drag through controlling and adjusting the trim angle of the planing vessels, we first need to understand the influence of the trim angle with respect to drag, lift when the vessel is in operation.

In order to facilitate research with acceptable deviation of results, researchers often assume that the planing vessels has a prismatic hull. Here it is necessary to determine the trim angle and drag of vessels with the known speed, displacement and center of gravitylocation.

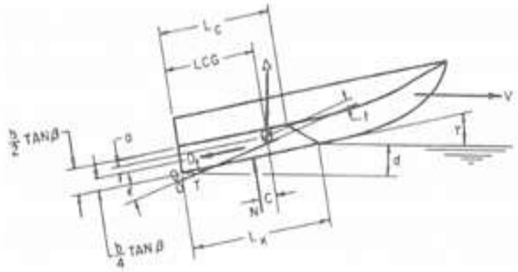


Fig. 1. Forces and moments acting on the hull

Then the equations to balance the ship in all directions are written as follows[6]:
The equilibrium of vertical forces:

$$\Delta = N\cos\tau + T\sin\left(\tau+\varepsilon\right) - D_f\sin\tau \quad (1)$$

The equilibrium ofhorizontal forces:

$$T\cos\left(\tau+\varepsilon\right) = D_f\cos\tau + N\sin\tau \quad (2)$$

The equilibrium ofpitching moments:

$$N_c + D_f a - Tf = 0 \quad (3)$$

where:T -Propeller thrust,Δ-Weight of vessel; D_f-Viscous component of drag, τ-Trim angle, LCG -Longitudinal distance of center of gravity, CG -Center of gravity, ε-Inclination of thrust line, N -Resultant of pressure forces, a -Distance between $D_f$and CG, f - Distance between T and CG, c - Distance between N and CG, β-Deadrise angle, b - Beam, L_k-Wetted keel length, L_c - Wetted chine length, V -Planing speed, d -Draft of keel at transom.
From the above equations, it can be reduced to the following simple equation[6]:

$$\Delta\left\{\frac{\left[1-\sin\tau\sin\left(\tau+\varepsilon\right)\right]c}{\cos\tau} - f\sin\tau\right\} + D_f\left(a-f\right) = 0 \quad (4)$$

For a exist vessel, the values Δ, a, b, ε, LCG, f and β are all defined values. The unknown values here are the lift, drag and pressure center location.
The research of **Daniel Savitky**[6] has given the calculation formulas for the lift coefficients:

$$C_L = \tau^{1.1}\left[0.0120\lambda^{1/2} + \frac{0.0055\lambda^{5/2}}{C_v^2}\right] \quad (5)$$

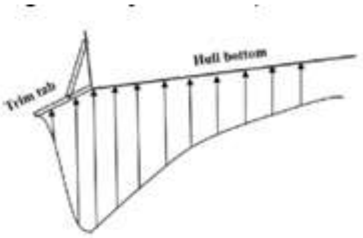
and hydrodynamic drag

$$D = \Delta\tan\tau + \lambda\frac{\rho}{2}\frac{V_1^2 C_f \lambda b^2}{\cos\beta\cos\tau} \quad (6)$$

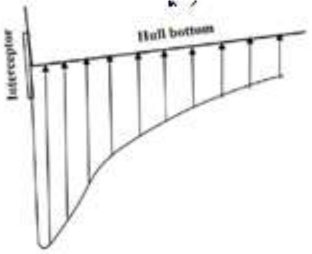
These formulas show the proportional dependence of lift and drag on the vessel's trim angle. Therefore, the goal here is to reduce the trim angle of the vessels, thereby reducing the drag of the vessel but still creating a compensating lift. The proposed solution is by sternappendagesretrofitting to adjust the flow direction and reduce the flow velocity through the stern, thereby creating an increase in hydrodynamic pressure at the bottom of the stern. This increase in pressure leads to a lifton the stern, creating a pitching moment that still generates lift, and at the same time reduces the trim angle of the ship.

III.WORKING PRINCIPLE OF APPENDAGES

The basic structure of the appendages such as the stern wedge, stern flaps and interceptor are all flat plates mounted on the transom, especially the hull vane has an asymmetrical profile, arranged in behind the transom and submerged in the water. The common principle of operation of these devices is to create a change in the flow and pressure distribution in the stern of the vessel. The degree of change depends greatly on the design parameters of such devices, including position, length, width (height), working angle of the device.
Structural arrangement and diagram of the lifting force acting on the hull at this appendage devices position (Fig. 2) shows the effect in creating effective hydrodynamic lift at the stern of the ship[7]. At the same time, it also slows down the flow under the hull where these appendages are installed.
The decrease in flow velocity through the hull at the stern leads to an increase in the pressure under the hull, which in turn contributes to the reduction in drag by reducing the suction force of the stern (reducing residuary resistance).



(a)



(b)

Fig. 2. (a) Lifting force acting on trim tab (b) Lifting force acting on Interceptor

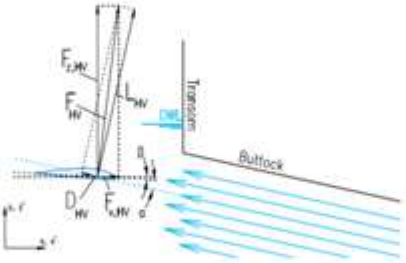


Fig.3. Forces actingon the hull vane

Given the characteristics of planing vessels, which are usually not very long (under 30m), the additional lifting forces at the stern change the trim of the ship significantly, which can be achieved from $4^0 \div 5^0$. In large ships, this effect is smaller.

The reseaches of **Shiju John, MD Kareem Khan, PC Praveen, Manu Korulla and PK Panigrahi**[8] conducted a test of a vessel model with appendages retrofitting compared to that without appendages. Relatively positive results are shown in Table 1.

Table-1 Maximum speed (knots) ofvessel with and without appendages retrofitting

Configuration	**Without appendages**	**With appendages**
Wedge 1%, 10^0	32.0	32.10
Wedge 1%, 10^0, Flap2 10^0	32.0	32.41
Wedge 1%, 10^0, Interceptor 1mm	32.0	32.60
Interceptor 1mm	32.0	32.34

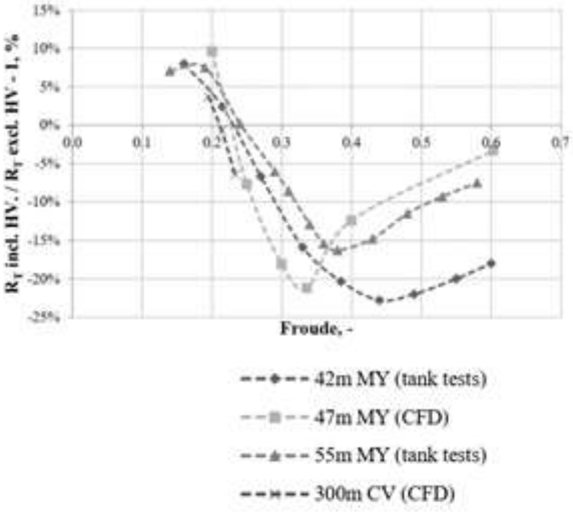


Fig.4. Comparison of vessels' drag with and without hull vane according to the change of Froude number in yachts (MY) and container vessels (CV).

The reseaches of **K. Uithof, P. van Oossanen, N. Moerke, P.G. van Oossanen and K.S. Zaaijer** [9] applies hull vanes in some container vessels and yachts. The comparison results between the CFD calculation and the tank tests are shown in Figure 4.

From the theoretical basis and a number of reseaches, it shows the effectiveness and high applicability of the use of stern appendages to control the trim angle, thereby reducing the drag of the planing vessels in the wateroperating process[9], [10], [11].

The problem here is to calculate the design parameters of the stern wedge, stern flap, interceptor, hull vane. These parameters will contribute to calculate the optimal trim angle of the vessel to achieve the minimum drag.

Of course, these extra devices are not without their downsides. The graph in Figure 4 shows that the appendages helps to increase speed and reduce drag at high speed, but at low speed it causes an increase in drag to a certain extent. However, this number is not large and in terms of operating conditions of planing vessels, high speed mode is still the main priority[12].

IV. SOME DEVICES IN USE IN THE WORLD

Stern appendages are now widely available commercially as assemblies, mainly stern flaps and interceptors. Stern wedge and hull vane are substructures, which are calculated, fabricated and welded to the stern of the ship. These appendages are fixed and not controllable.

4.1. SternFlap

A system of stern flaps (also known as trim tabs), consisting of sensors, control unit, hydraulic power unit, hydraulic cylinders and flap mechanisms (consisting of 02 plates symmetrical about the center plane of vessel)[13].

(a) (b)

Fig.5.(a) System diagram of Trim taps (b) Typical layout of Trim tabs

In this system, the Tabs are sized according to the specific vessel. However, manufacturers often have certain sizes for customers to choose from. The main objective is to ensure longitudinal equilibrium of the vessels at different speeds. The system of sensors provides the signal, combined with the speed signal from the vessels' tachometers, all transmitted to the central control unit, which will automatically control the

Tabs. These tabs can be raised and lowered simultaneously or independently, so that the vesselsare stable and has better rolling and pitching characteristics.

A typical example is the application of the M80 and M120 stern flaps on a high speedboat resulting in a 30% increase in lift compared to the boat which does not have stern flaps[14].

The advantage of this type of device is that it can control and optimize relatively well the flow through the stern, adjust the roll, trim angle as well as the hull lifting force (through adjusting the working angle and independent operation of Tabs). The device is also manufactured, ready-made, easy to install on vessels and boats, thereby shortening the necessary construction time.

Its main disadvantage is that it is not possible to achieve an optimal value for a particular vessel because the device is prefabricated to a number of predetermined dimensions. The shipowners must choose the device that the manufacturer has available.

Some manufacturers can mention here such as Lenco Marine, Bennett Marine, Livorsi,…

4.2. Interceptor

Similar to the stern flaps, the Interceptors also includes sensors, a central control unit and mechanisms to lift-up and lower the plates[15].

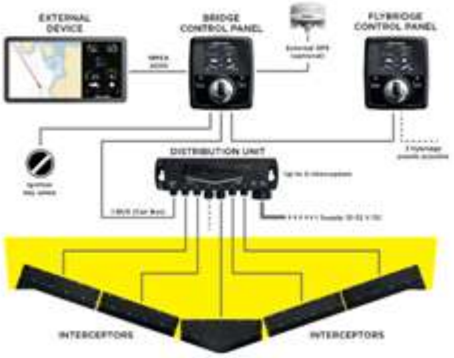


Fig.6.Interceptor control system layout

The central control unit also receives incoming signals, processes and controls automatically (or can be manipulated manually) the interceptors to control the ship's trim and roll angle. As a result, the ship has better navigational performance, stability and speed. The application of Humphree's Interceptor system on the Sunseeker Predator showed an increase of 3.5 knots in top speed (34.5 knots compared to 31.0 knots which is without Interceptors) and time to reach the top speed is also shortened much[16].

The advantages and disadvantages of the Interceptors are the same as those of the Trim tabs. However, compared with the flaps that can adjust the lift through the change of the inclination angle of the flaps, the lift force generated by the interceptors has a relatively constant value because, in terms of structure, the retracting stroke of the Interceptor plates is relatively constant. This is also a significant drawback of the Interceptor device.

Some of the manufacturers mentioned here are Humphree, Zipwake,….

4.3. Stern wedge

Stern wedge are usually calculated by the designer according to the specifications of the vessel to be installed. This structure is usually welded to a fixed angle, without the ability to control or change the effective working angle. Therefore, it is only to control the trim angle, reduce drag and increase ship speed, but does not have the ability to control the rolling of vessels like Trim Tabs or Interceptors.

These structures are usually designed and built directly by the shipyardrather than as a commercially available devices.

Fig.7. Typical Stern Wedge layout

The advantage of this structure is that it is simple, easy to process and fabricate. The working angle of the wedge is calculated, optimized for the vessel.

The disadvantage is that it requires the designer to make specific calculations to choose the dimensions and working parameters suitable for the vessel. At the same time, since the operation angle is fixed, it is only optimal for a certain speed range of vessel. This type of structure cannot help the vessel to control the roll angle of the vessel when circling like the Stern flaps and Interceptors.

4.4. Hull Vane

Similar to the Stern Wedge, the Hull Vane are also calculated and designed to suit the requirements of the vessel. But there are also some manufacturers that outsource and make it available as a commercially product. Example Hull Vane Company - Netherlands.

These structures will be welded or bolted to the transom.

Fig.8. Place Hull Vane in the transom

The hull vane construction has exactly the same advantages and disadvantages as the stern wedge. But because it can be prefabricated, it shortens construction time and installation time compared to stern wedge.

However, the effect achieved when using hull vane structures is also relatively good. Using hull vane construction on Heesen Yacht's Alive showed a reduction in drag of 20.4% at 12 knots and 23.2% at 14.5 knots[17].

V. DISCUSSION

The article presents the problem and general theory about the coefficient of lift and the drag of the vessels depends on the trim angle. From there, combinate solutions which can be used to reduce thedrag, increase speed and still create the necessary additional lift for the vessel as well as the theoretical basis of these solutions. The article also statistics the use of equipment and structures corresponding to the proposed solutions currently available in the world, evaluates the advantages and disadvantages of each device and structure given. On that basis, it is possible to continue researching to widely apply the above solutions.

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