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An Experimental Study of Hydrodynamic Performance of a Planing Hull Due to the Improvement of Stern Flap: The Effects of Form and Angle

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Abstract

The stern flap and stepped hull are widely applied for high speed vessels to reduce resistance by adjusting the performance attitude. In this present study, a form design of stern flap has been improved on the high speed ferry as a planing hull, namely I and 2V. The stern flap was attached on the transom stern of the planing hull installed at several angles of 10, 20, 30 degrees. The free running model test and resistance analysis of the planing hull were carried out to determine the effects of the improved stern flaps on the parameters of trim by stern, resistance, and speed. The planing attitude of planing hull captured in the model test were analyzed using the application of Maxsurf Resistance. The study results revealed that both the stern flaps I and 2V on the planing hull afford to reduce the trim by stern, resistance, and to improve speed. The average value of the difference of the increase of trim by stern between the stern flap 2V and stern flap I is 1.79%. With the constant FnV, the planing's resistance can be reduced by the increase of the stern flap angles. The average value of the reduction of planing's resistance due to the increase of the stern flap angles is 6.27% for the stern flap I, and 5.05% for the stern flap 2V. Regarding the effect of the stern flap form with its angle on the planing's resistance, the planing's resistance due to the stern flap 2V is lower compared with the stern flap I wherein overall the average difference is 4.73%. The reductions of the trim by stern and planing's resistance due to the stern flap form and angle are caused by the vertical lift force and pressure distribution acting on the transom of the aft planing hull.

Keywords: Planing hull; Porpoising phenomenon; Resistance reduction; Stern flap; Trim by stern

1. Introduction

Energy efficiency plays an essential role in accelerating the clean energy, decarbonizing the economies, securing the energy supplies, and increasing the productivity. This has drawn global attention including the marine engineering field as well. Therefore, the International Maritime Organization (IMO) has urged the Marine Environment Protection Committee (MEPC) to identify and develop mechanisms to achieve a reduction of ships' greenhouse gas emissions [1]. Also, the MEPC has introduced regulations focused on the limitation of CO2 production of newly built ships [2]. To scale up action on energy efficiency and GHG emissions reduction, a ship's geometry and an attachment device (appendage) should be optimized appropriately due to its significant relation to ship performance.

For the optimization of the ship's hull, the effect of hull form parameters on the hydrodynamic performance of a bulk carrier was studied by analyzing the joint optimization process, fast principal-dimension optimization of the origin parent ship considering the integrated performance of ship resistance, seakeeping, and maneuverability [3]. Beside the optimization of overall hull geometry, the bow shape or stern shape has been studied widely to obtain the reduction of ship resistance. The bow and stern hull of KRISO Container Ship was optimized to reduce its resistance through an innovative methodology of synchronous local optimization with the consideration of the whole ship speed range [4]. Numerical method for optimizing the stern shape of a container ship based on the Sequential Quadratic Programming (SQP) method and Reynold Averaged Navier-Stokes (RANS) equation to minimize the pressure resistance was proposed [5]. The improvements of stern part and additional part on the transom affected an increase on the heave and pitch amplitudes, and the effects were dependent on the improvement of the form [6].

Most of high speed ferries have transom stern to consider an improvement of flow around the stern and hydrodynamic performance. Besides the consideration of the optimization of stern shape, the appendages fitted on the stern also have been designed such as stern flap, interceptor, and wedge stern in order to improve the hydrodynamic performance. One of stern appendages is applied to a high speed ship is a stern flap. Then, this application is to be an important concern on a hydrodynamic design in improving a performance of high speed ship. Related to the hydrodynamic performance due to the effect of a stern flap, the followings are some studies that have been carried out. The reductions of resistance due to stern flap were compared based on the variations of chord length and angle as investigated by using the computational fluid dynamics (CFD) wherein the stern flap 1%Lpp with angle 4 degrees is most optimal resistance reduction [7]. Two stern flaps active ride control were designed for the wave piercing catamarans (WPC) to reduce the heave, roll and pitch motions in beam waves wherein the ride control system based on linear quadratic regulator and genetic algorithm [8]. Experimental and numerical simulation methods were carried out to explore the influence of the flap mounting angle coupled with the steps wherein the low speed resistance performance was improved in increasing the mounting angle [9]. The influence of stern flaps was investigated by numerical simulations and model towing test wherein the proper length and optimal angle of stern flaps could be greatly reduced the resistance [10]. The parameter optimization of the stern flaps of the series displacement ships was studied through the model test wherein the result revealed that the ship with stern flaps has lower resistance and could save 3% and 5% of energy [11], the stern flap reduces the ship resistance with the energy savings between 30% and 50%, however it affects the ship model flow field to a certain extent with a consequence in affecting the propulsion performance of the ship [12]. CFD simulations and experimental model testing of a typical high speed displacement vessel equipped a stern flap design in 12 different configurations were conducted for determining most favorable flap design in for reducing the energy efficiency design index [13]. The model experiment and CFD analysis of the stern flap were conducted to examine the effect of stern flap on the running attitudes and wave making at the after portion of the hull on resistance reduction [14].

By referring to numerous studies above, the effects of stern flap on hydrodynamic performance of a ship remain to be investigated extensively. The form and placement of the stern flap also have been the considerations for the improvement of hydrodynamic performance. Regarding the use of methods, the accuracy of the research results has showed the satisfaction. Regardless, the improvement of design of a stern flap remains challenging to be conducted and proposed in order to extend the studies of the hydrodynamic performance due to the effect of the stern flap through using the numerical method, experimental method or computational fluid dynamics (CFD). By the miscellaneous of the studies of the hydrodynamics design regarding the stern flap will enhance the complex considerations to obtain the favorable design.

This paper presents the experimental study of hydrodynamic performance of a planing hull caused by improving the form of stern flap in calm water condition. The aims of this study are to propose the stern flap design and to investigate the effect of the proposed design of stern flap on the resistance reduction and improvement speed. The free running test of the planing hull model with the proposed stern flap was conducted, and then the attitude (trim by stern) of the planing hull model with the angle of stern flap at the constant speed was captured. In addition, various stern flap angles and Froude numbers were considered. The attitude of the planing hull model is used for the resistance prediction using the Maxsurf application.

2. Methods

In this present study, the experimental investigation of the influence of the proposed stern flap with various angles and Froude numbers on the ship's attitude in calm water has been conducted. Also, the prediction of ship resistance due to due to the ship's attitude effected by stern flap with various angles and Froude numbers has been carried out. The methods that used for the investigation of the ship's attitude and resistance of the planing due to the effect of stern flap with various angles and Froude numbers are then accordingly discussed.

2.1. Ship Model

The ship type is general high speed passenger ferry, and the main dimensions of the ship and the body lines plan are shown in Table 1 and Fig. 1 respectively. For the geometry, the scale of the ship model is 1:15, which was considered in relation to the towing tank size to avoid some disturbances due to high speed. The ship model was made of fiberglass combined with thin wood material.

Table 1. The main dimensions of high speed passenger ferry.

Description	Actual
Length Over All (LOA)	19.06 m
Length Between Perpendicular (LBP)	17.72 m
Length Water Line (LWL)	17.77 m
Breadth (B)	4.51 m
Height (H)	1.80 m
Draft (T)	0.45 m

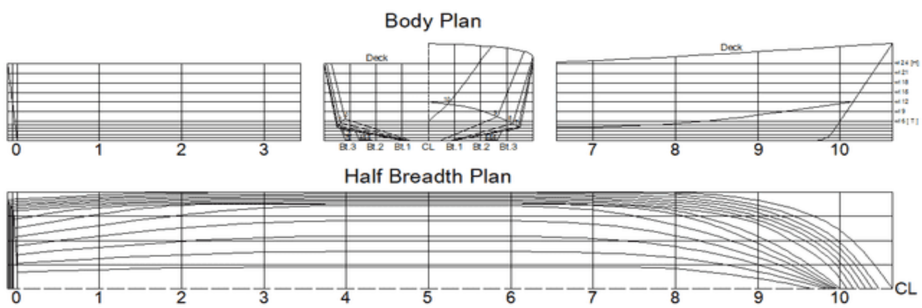


Figure 1. The lines plan of high speed passenger ferry.

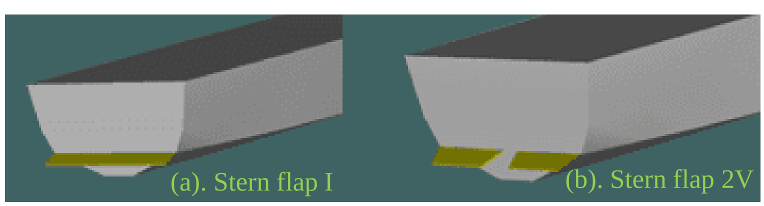


Figure 2. The design of the stern flap.

(a). Ship model with the stern flap I

(b). Ship model with the stern flap 2V

Figure 3. The ship model with the attachment of stern flap.

The illustration of two forms of stern flap (I and 2V) is shown in Fig. 2. Two forms of stern flap (I and 2V) with various angles that attached in the stern's model were employed in the experiment as shown in Fig. 3, and the models of stern flap was made of fiberglass combined with thin wood material. The chord and span of stern flap even the difference of form I and 2V were considered in the same length of 0.0236 m and 0.27 m, respectively. The stern flap is placed vertically in the same height with water draft level. Also, various angles of the stern flap which is side adjacent to angle (water surface) were considered 10 degrees, 20 degrees, and 30 degrees.

2.2. Experimental Set-up

Free running model test was conducted at towing tank, Ship Hydrodynamic Laboratory, Naval Architecture Department, Faculty Engineering, Hasanuddin University. The towing tank sizes are 60 m in length, 4 m in width, and 4 m in depth. For the free running test, the ship model was equipped by the fixed pitch propeller (FPP) with three blades, and the propeller diameter (Dp) is 36 mm (0.036 m). Also, for experimental set-up, some tools and devices were provided such as electric motor brushless (244 – 5400 KV), servo motor (Torque 15 kg.cm), electronic speed control (ESC) 120 Amp., rudder, universal joint (diameter of in 3.17 mm and out 4 mm), radio control remote of 6 channel (2.4 GHz), receiver of 6 channel (2.4 GHz), shaft (diameter 3 mm), universal joint (diameter 4 mm), rudder, stopwatch, tachometer, battery (5200 mAh, 11.1 Volt., and 25 C^o). The tools and devices are shown in Fig. 4.

(a). ESC

(b). Receiver

(c). Remote control

(d). Battery

(e). Motor DC

(f). FPP 3 blades

(g). Universal joint

(f). Shaft

Figure 4. Tools and devices used in free running model test.

2.3. Resistance Prediction Using Maxsurf Resistance Application

Ship resistance were predicted using the application of Maxsurf Resistance [15]. The planing hull with the stern flap was modelled using the application of the Maxsurf Modeler [15] as shown in Fig. 5. In the computational simulation of ship resistance, the model ship was fixed related to the planing attitude (trim by stern) as captured in the free running model test. Then, ship resistance was predicted in the same speed or Fn. Since a planing hull is to be analyzed, select the methods pertinent to such a design, and the Wyman method was selected. In this resistance prediction, the propulsive coefficient was set 0.75 [16].

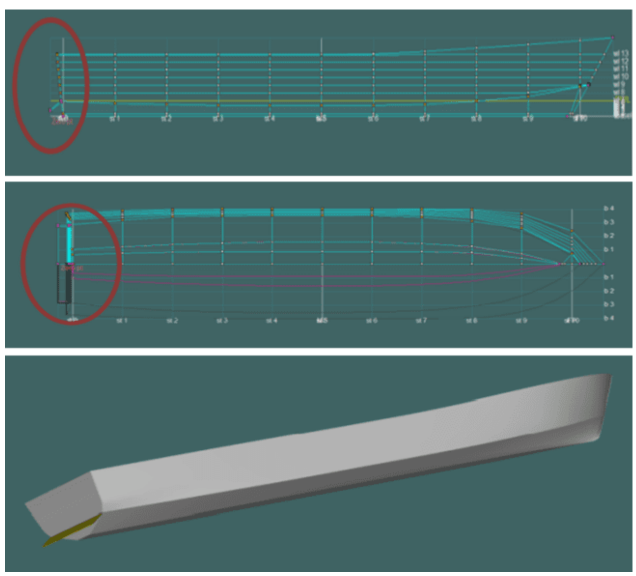


Figure 5. Computational model of the planing hull with the stern flap using Maxsurf Modeler.

In the Maxsurf Resistance application [15], the Correlation Allowance value uses ITTC'57 friction line, but Reynolds number R_e is based on a shorter length: 0.7Lpp. The wetted area of the appendages $A_{appendage}$ (m^2) is the total wetted surface of appendages, while the appendage factor is an indication of the resistance of the appendages. Value for the appendage factor $f_{appendage}$ is typically vary from 1.0 to 3.0. The appendage resistance (N) is calculated as follows:

$$R_{appendage} = \frac{1}{2} C_f \rho A_{appendage} V^2 f_{appendage} \tag{1}$$

where ρ is the water density (kg/m^3), and V is the ship speed (m/s), and C_f is the skin friction calculated from the ITTC'57 formula using the nominal appendage length to calculate the Reynolds number as follows:

$$C_f = \frac{0.075}{[\log_{10}(R_e) - 2]^2} \tag{2}$$

A nominal length for the appendages is used to calculate the Reynolds number R_e at which the appendages are operating. This Reynolds number is used to calculate the skin friction drag of the appendages using the ITTC'57 formulation. The following resistance formula which components are calculated by the Wyman method.

$$R_T = R_R + R_F + R_{appendage} \tag{3}$$

where R_R is the residuary resistance (N) that is total hydrodynamic resistance less skin friction resistance. R_F is the friction resistance (N); skin friction of equivalent flat plate area, typically uses the ITTC'57 ship-model correlation line or Schoenherr friction line.

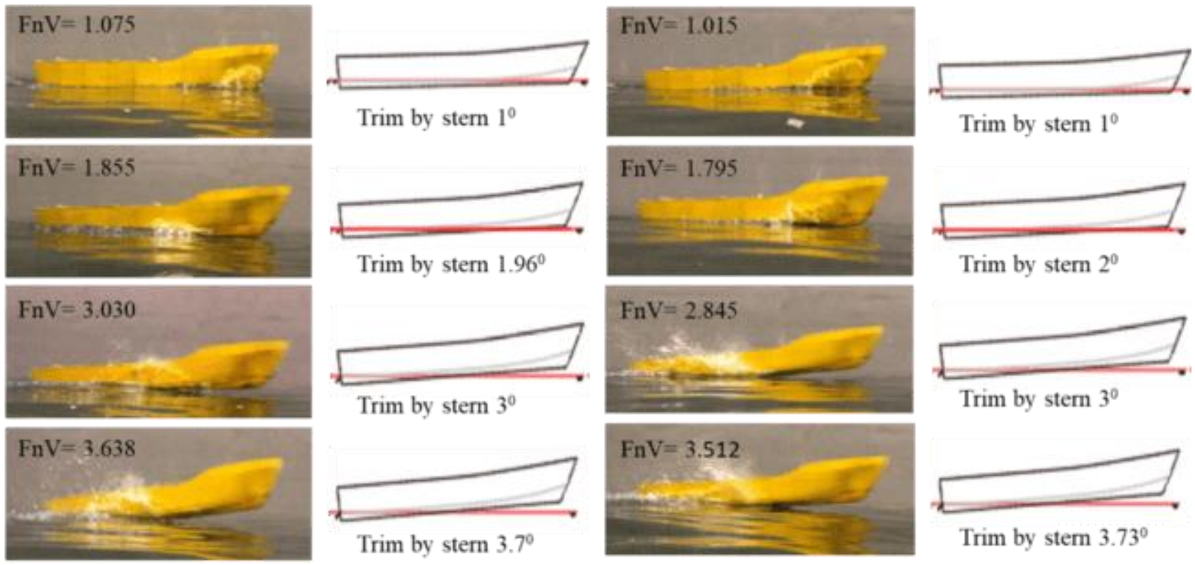
3. Results and Discussion

3.1. Planing Attitude of the Planing Hull in Free Running Model Test

The free running model test was conducted successfully. The planing attitude of the planing hull equipped with the stern flap in calm water was captured at constant speed as shown in Figs. 6 to 8. Based on Figs. 6 to 8, the increase of the speed or FnV of the planing hull with the stern flap affects proportionally in increasing the trim by stern. For the high FnV > 3.0, the trim by stern was reached more than 3.0 degrees, and this planing attitude is characterized as high trim by stern. In addition, the stern flap also affects the planing attitude of the planing hull.

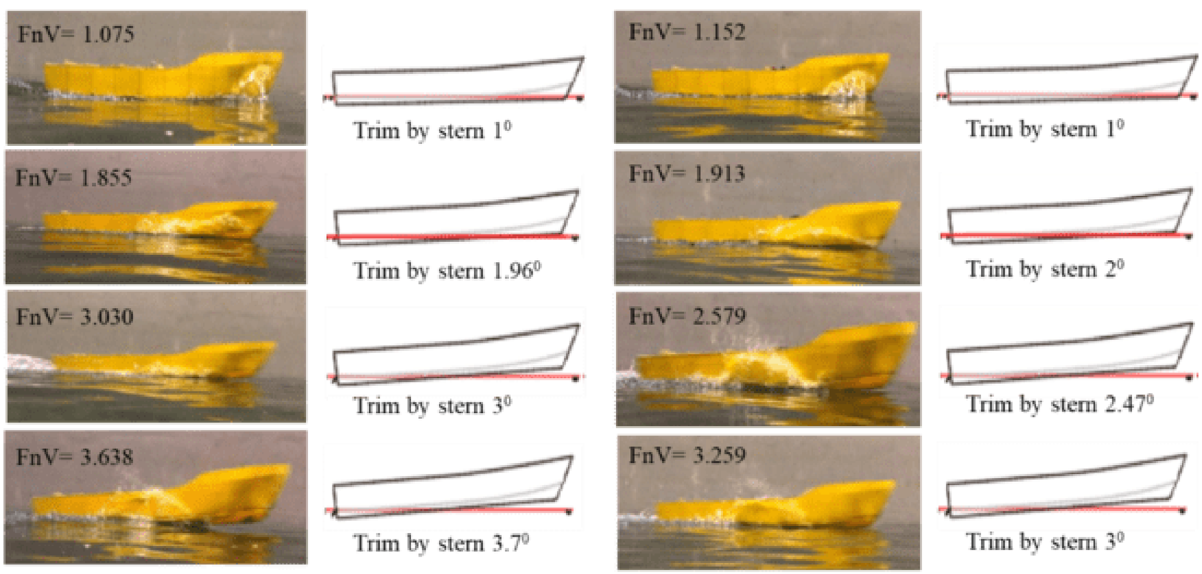
As the interpretation that has been stated in the previous paragraph, to characterize the effect of the peed and stern flap on the planing attitude, Figs. 9 and 10 show the tendency of the trim by stern in increasing the FnV. The trim by stern increases significantly in the FnV range of 1.0 to 2.0 for all stern flap angles and both stern flaps I and 2V, and it remains to increase gradually in the FnV > 2.0. However, the trim by stern remains to increase significantly due to the angle of stern flap of 10 degrees for both stern flaps I and 2V. Based on Fig. 9, for the stern flap I, the average increase of the trim by stern in increasing the FnV is 22.26% for the stern flap angle of 10 degrees, 21.93% for 20 degrees, and 20.94% for 30 degrees. For the stern flap 2V, the average increase of the trim by stern in increasing the FnV is 22.57% for 10 degrees, 22.37% for 20 degrees, and 21.37% for 30 degrees. For the comparison, the increase of the trim by stern due to the stern flap 2V is higher than the stern flap I. The average value of the difference of the increase of trim by stern between the stern flap 2V and stern flap I is 1.79%.

For the comparison of the trim by stern due to the angle of stern flap, the trim by stern due to the angle of 10 degrees is higher than 20 degrees, and it due to the angle of 20 degrees is higher than 30 degrees. This characteristic of the difference of trim by stern due to the angle of the stern flap I is similar to the stern flap 2V. The average value of the difference of the increase of the trim by stern between the stern flap angle I of 10 degrees and 20 degrees is 1.50%, and it is 4.51% between the angle of 20 degrees and 30 degrees. Moreover, for the stern flap 2V, the average value of the difference between the angle of 10 degrees and 20 degrees is 0.81%, and it is 4.54% degrees between 20 degrees and 30 degrees.



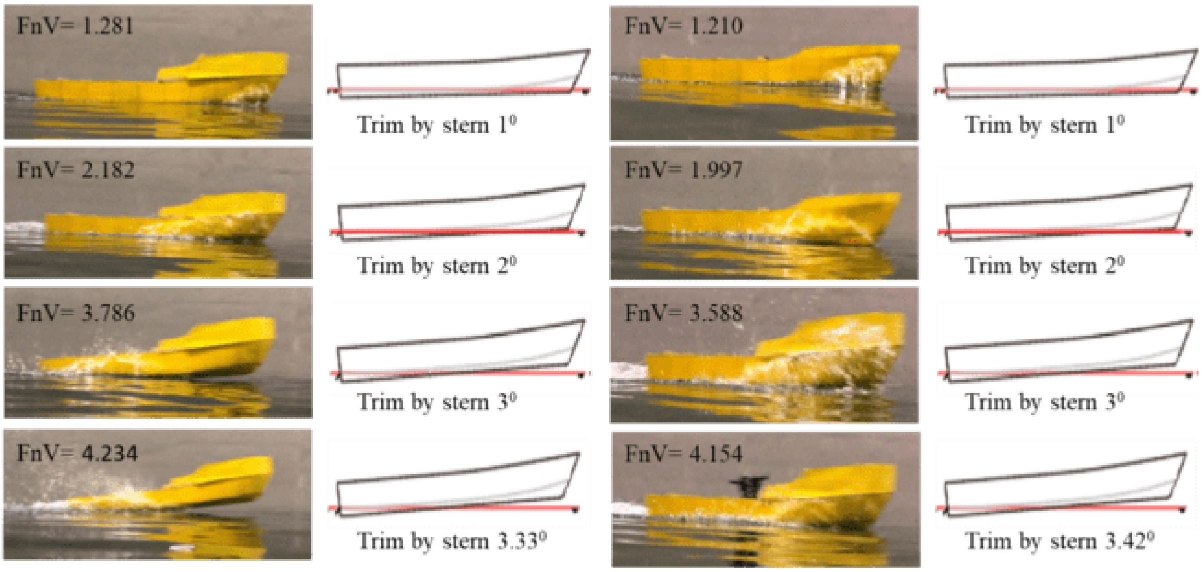
(a). Stern flap I (b). Stern flap 2V

Figure 6. The planing attitude of planing hull with stern flap for the angle of 10 degrees.



(a). Stern flap I (b). Stern flap 2V

Figure 7. The planing attitude of planing hull with stern flap for the angle of 20 degrees.



(a). Stern flap I (b). Stern flap 2V

Figure 8. The planing attitude of planing hull with stern flap I for the angle of 30 degrees.

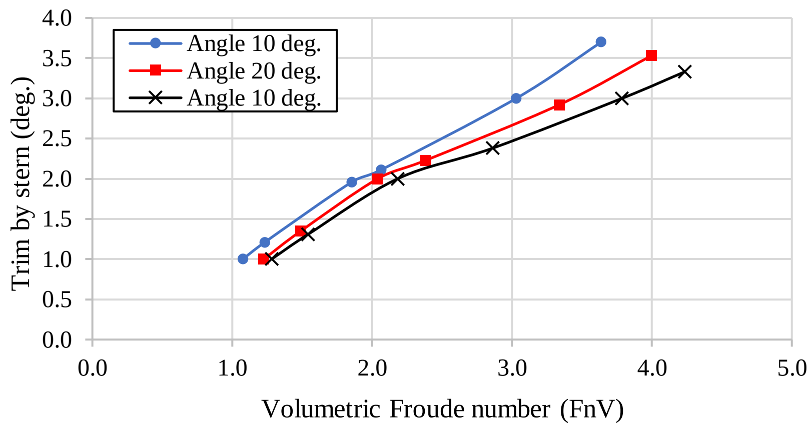


Figure 9. The tendency of trim by stern of planing hull with stern flap I in increasing the FnV.

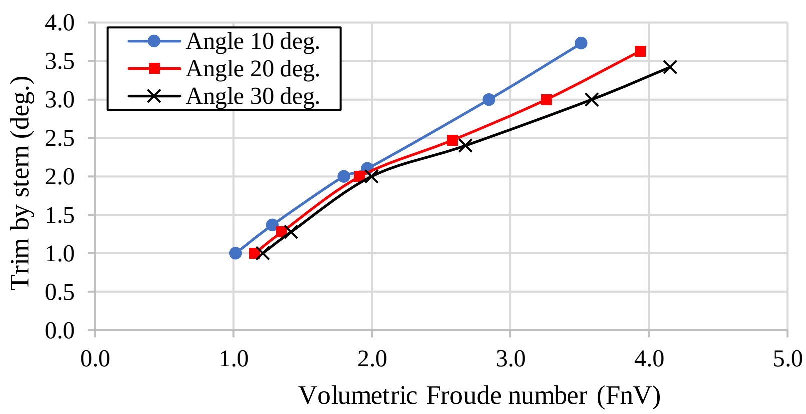


Figure 10. The tendency of trim by stern of planing hull with stern flap 2V in increasing the FnV.

Based on the characteristic of the trim by stern incorporated with the speed, the trim by stern is reduced significantly due to the angle of stern flap from 20 degrees to 30 degrees. This means that the reduction of the trim by stern due to stern flap is caused by the vertical lift force at the transom and pressure distribution the aft planing hull. Therefore, the increase of the angle of stern flap increases the vertical lift acting on the planing transom.

3.2. Ship Resistance Prediction Due to Planing Attitude

The planing's resistance was predicted using the Maxsurf Resistance. Before predicting the planing's resistance, the planing attitude of the planing hull due to the stern flap form and the angle of stern by trim was initially set with fixed condition in Maxsurf Modeler. The planing's resistance was determined based on the similar speed or FnV to the planing model in the free running test model. Accordingly, the planing's resistance due to the stern flap form with the angle of stern flap incorporated with the planing's FnV is discussed.

Figs. 10 and 11 show the tendency of the resistance of planing hull in increasing the FnV due to the angle of stern flap for both stern flap I and 2V, respectively. The tendency of the planing's resistance for the stern flap I with various angles shows similar to the stern flap 2V. The planing's resistance tends to increase significantly in the FnV from 1.0 to 2.0, and then it decreases in the FnV more than 2.8. In the same FnV, the planing's resistance due to the stern flap with the angle of 10 degrees is highest. Based on Fig. 10, the average weight of difference of the planing's resistance due to the stern flap I between the angle of 10 degrees and 20 degrees is 6.09%, and 6.44% for the comparison between the angle of 20 degrees and 30 degrees. Meanwhile, for the comparison due to the stern flap 2V, the average weight of difference of the planing's resistance between the angle of 10 degrees and 20 degrees is 6.25%, and 3.84% for the comparison between the angle of 20 degrees and 30 degrees.

Furthermore, the planing's resistance due to the stern flap 2V is lower compared with the stern flap I. For the comparison of the planing's resistance between the stern flap 2V and I, the average difference due to the angle of 10 degrees in the increase of the FnV is 5.43%, 5.68% for the angle of 20 degrees, and 3.07% for the angle of 30 degrees. The differences are contributed by the effect of the stern flap form with its angle on the wave resistance and pressure distribution on the planing hull's transom and appendage (stern flap). Even though the differences show small, these can be a consideration on the improvement of the stern flap form as well as the angle. In addition, the stern flap can reduce the resistance on the planing hull, therefore, it can reduce the propulsion power required to achieve a given speed.

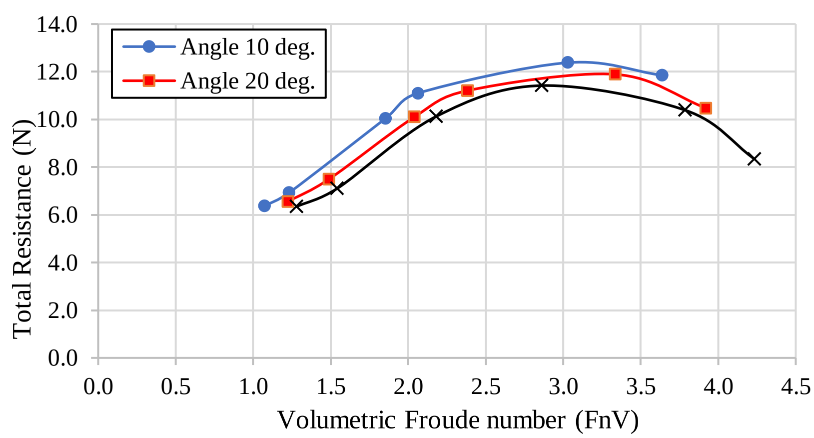


Figure 11. The tendency of total resistance of planing hull with stern flap I in increasing the FnV.

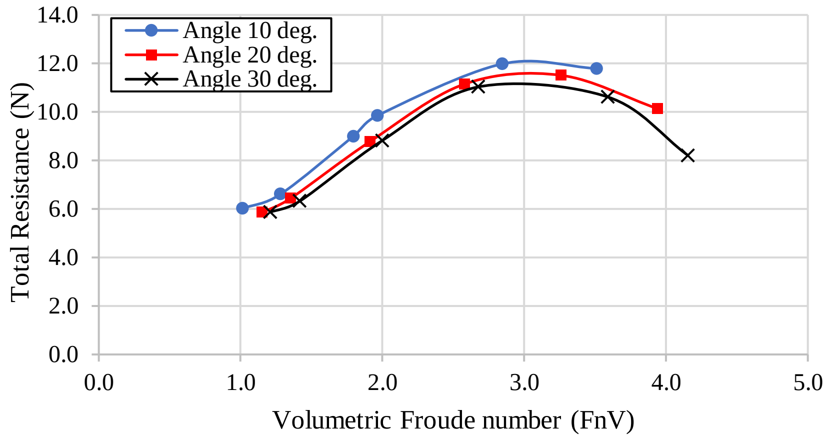


Figure 12. The tendency of total resistance of planing hull with stern flap 2V in increasing the FnV

4. Conclusions

The free running model test in calm water and the analysis of the planing's resistance using Maxsurf Resistance were carried out successfully. The effects of the stern flap form with its angle on the planing attitude and planing's resistance have been discussed. In this present study, the notable contributions are concluded accordingly.

The increase of the angles of stern flap at constant speed affects on the reduction of the trim by stern. For each angle of the stern flap, the trim by stern increases significantly in the FnV range of 1.0 to 2.0 for both stern flaps I and 2V, and it remains to increase gradually in the FnV > 2.0. Regarding the form of stern flap, the increase of the trim by stern due to the stern flap 2V is higher than the stern flap I. The average value of the difference of the increase of trim by stern between the stern flap 2V and stern flap I is 1.79%. The reduction of the trim by stern due to the stern flap form and angle is caused by the vertical lift force and pressure distribution acting on the transom of the aft planing hull.

With the constant FnV, the planing's resistance can be reduced by the increase of the stern flap angles. The average value of the reduction of planing's resistance due to the increase of the stern flap angles is 6.27% for the stern flap I, and 5.05% for the stern flap 2V. Regarding the effect of the stern flap form with its angle on the planing's resistance, even though the trim by stern due to the stern flap 2V at the same FnV is higher than stern flap I, the planing's resistance due to the stern flap 2V is lower compared with the stern flap I. Overall the average difference is 4.73%. The stern flap form with its angle affects on the wave resistance and pressure distribution on the planing hull's transom and appendage (stern flap).

Even though the differences show small, these can be a consideration on the improvement of the stern flap form as well as the angle. In addition, the stern flap can reduce the resistance on the planing hull, therefore, it can reduce the propulsion power required to achieve a given speed. Therefore, this study of the improvement of the stern flap form will be extended in our future work.

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