Experimental and Numerical Study of Effects of the Application of Hydrofoil on Catamaran Ship Resistance

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Keywords: Catamaran, CFD, Hydrofoil, Resistance, Towing-tank Test.

Abstract: The use of hydrofoil on a catamaran can reduce the ship's resistance at a certain speed. The reduction of ship resistance occurs because of the lifting force that lifts the ship's hull above the waterline to reduce the wet surface area. This research aims to study the effect of adding hydrofoil in the hull of a catamaran on the ship's total resistance using experimental and numerical CFD methods. A 44m passenger catamaran was considered with two variations of hydrofoil: one hydrofoil on the bow section and two hydrofoils (one on the bow section and one on the stern section). The hydrofoil is rectangular NACA 641-212 section and aspect ratio of 16,34. The results indicate increasing ship resistance instead of decreasing on the catamaran with the hydrofoil. At service speed (Fr=0,7), the Total resistance value occurs in case 1 (catamaran without hydrofoil) is 114.59 kN, case 2 (catamaran with added one foil on the bow section), and case 3 (catamaran with added foil on both bow and stern section) are respectively 31% and 59% higher than the catamaran without hydrofoil. These data show that not all existing catamaran vessels can be added hydrofoil between the demihulls.

1 INTRODUCTION

Abbreviation Hysucat stands for Hydrofoil Supported Catamaran and describes a new High-Speed Small Craft, a seagoing catamaran with a hydrofoil arrangement the two demi-hulls which carries a part of the craft's weight at speed. Vessels of this type have greater efficiency than fast boats or varieties of a catamaran with a gastric form V. "Hysucat" shows a reduction in propulsion power and has good seakeeping characteristics in rough water (Hoppe, 1995).

Based on research on variations in the type of hydrofoil on catamaran vessels, catamaran vessels' performance, especially on ship resistance, has increased efficiency, as evidenced by resistance improvement of up to 40% based on the output from several research projects (Hoppe, 2001).

Research and development related to Hysucat ships (hydrofoil supported catamaran) and Hysuwac (hydrofoil supported watercraft) began in the late 1970s or early 1980s at Stellenbosch University, South Africa, led by Prof. Karl Gunter Hoppe (Hoppe, 1987). Aside from Hoppe, the research results related to the use of foil on catamarans were also reported in (Calkins, 1984) and (Suastika et al., 2018) conduct numerical simulations of hysucat mono foil vessels using CFD. The simulation results show that the position of hydrofoil placement in the longitudinal direction dramatically affects the size of the ship's resistance. The most optimum position is the position just below the Center of Gravity (CoG) of the ship.

The latest technology in ships has been developed in a variety of conventional forms, including one with Hydrofoils, Surface Effect Ships (SES), Air Cushion Vehicles (ACV), and Smal Waterplane Area Twin Hulls (SWATH). The difference between various concepts is the method to help the weight of the ship. Three basic methods, namely, (1) static lift (Buoyancy), (2) supported static lift (lift fans), and (3) dynamic lift force (hydrofoils planing hull). The results of ship technology development with this method. 95-100% of the ship's weight is assisted by one of the three methods above (Hoppe, 1989).

NACA (National Advisory Committee for Aeronautics) Aerofoil is an aerodynamic body shape that functions to give a certain lift force to a body. An aerofoil is an aerodynamic form that aims to produce a large lift force with the smallest drag force possible. When an aerofoil is passed by fluid flow, because of the influence of the interaction between fluid flow and the surface, variations in velocity and pressure will occur along the top and bottom surfaces as well

Firdhaus, A. and Suastika, I.
Experimental and Numerical Study of Effects of the Application of Hydrofoil on Catamaran Ship Resistance.
DOI: 10.5220/0010854400003261
In *Proceedings of the 4th International Conference on Marine Technology (senta 2019) - Transforming Maritime Technology for Fair and Sustainable Development in the Era of Industrial Revolution 4.0*, pages 104-110
ISBN: 978-989-758-557-9; ISSN: 2795-4579

as the front and rear. The pressure difference between the upper and lower surfaces gives rise to a resultant force whose direction is perpendicular to the direction of the flow of fluid, and this force is called lift force. The difference in pressure between the front and back will result in a resultant force in the direction that is in line with the direction of the flow of fluid, and this force is called a drag force (Hoppe, 1991).

Catamarans tend to have low water draught so that the ship can be operated in shallow water. Slender hull shape can reduce the occurrence of wave wash compared to monohull vessels. The components of the catamaran ship resistance have a more complex phenomenon than a monohull because there is an interaction effect between the two hulls of the ship, which causes ship resistance interference. The empirical formula used is based on the equation from the study in (Jamaluddin et al., 2013), which is a modification of the method (Molland et al., 1996).
The purpose of this study is to investigate the effects on the ship resistance of the positioning of the hydrofoil arrangement between the two demi-hulls. Studies on the hydrofoil positioning in the longitudinal directions were reported in (Suastika et al., 2018). This study pursues that reported in (Suastika et al., 2018) but utilizing different arrangement as case 1 (catamaran without hydrofoil), case 2 (catamaran with added one foil on the bow section), and case 3 (catamaran with added foil on both bow and stern section). The results can enrich the literature on the applications of hydrofoil catamaran.

2 METHOD

The ship particulars are summarised in Table 1. The study utilizes CFD simulations and towing test experiments.

Table 1: Ship Particular.

Principal Dimension	Catamaran	Demihull
LWL	44.00 m	44.00 m
B	20.6 m	3.00 m
T	1.40 m	1.40 m
H	3.80 m	3.80 m
V	28 knot	28 knot
Cb	0.491	0.491
Displacement	185.50 ton	92.75 ton

Furthermore, the ship's resistance analyses with the variation of the number of foil placed on between the catamaran demi-hull

2.1 Modeling with CAD Software

From the main dimension data of the ship model, the ship body modeling was made with the help of a CAD modeler, as shown in figure 1 below. Figure 1 shown the 3D geometry of the ferry catamaran with one foil on the bow section of the ship as a wireframe view. 3D geometry should be similar to a real ferry catamaran so it can be used for numerical simulation and represents the real condition. In this research, there are three variations from the original condition is catamaran without foil. Variation 1 is a catamaran with one foil on the bow section of the ship, and variation 2 is a catamaran with two foils (1 on the bow section and one on the stern section). NACA 641-212 is used for added foil. Places 1m below draught (1.4m) with 1m cord and 17.3m span.

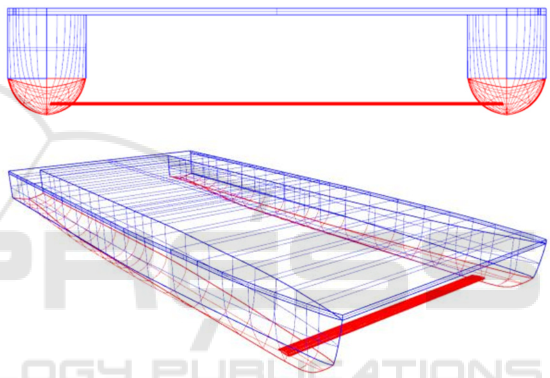

Figure 1: Front view (upper) and diagonal view (below) of Geometry of catamaran vessel model (Case 1 - 1 foil at bow section) using CAD modeler.

2.2 CFD Simulation of the Foil NACA 64_1-212

Simulations of the foil alone were undertaken to measure lift force produced by foil NACA 641-212 with 1m cord and 17.6m span on different speed based on catamaran service speed for preliminary measurement to get information about how much lift force from foil before it is assembled on between demihull catamaran, from this, we can estimate WSA reduction because of the lifted hull, trim that will happen to the ship, and total ship resistance.

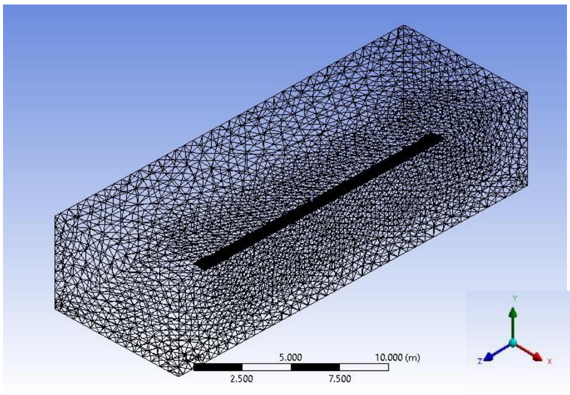

Figure 2: Preview Mesh of the NACA 641-212 foil on boundary domain from pre-processing of CFD simulation with hybrid mesh consists of the unstructured element on the domain and structured element on boundary layer and foil.

The boundary conditions of the computational domain are as follows (Versteeg & Malalasekera, 2007). The inlet boundary, located at 1-c upstream from the leading edge (where c is the chord length), is defined as a uniform flow with velocity equaling the ship/foil's velocity. (In the simulations, the foil is at rest, but the water flows.) In the outlet boundary, at a location 4-c downstream from the trailing edge, the pressure equals the undisturbed (hydrostatic) pressure, ensuring no upstream propagation of disturbances (Mitchel et al., 2008). The boundary condition on the foil's surface is defined as a no-slip condition. The boundary conditions on the top and bottom walls (at a distance of 2-c above and below the foil, respectively) and on the side walls (approximately 7-c away from the side of the model) are defined as free-slip condition. Furthermore, because the foil is fully submerged at a relatively deep submergence elevation (the foil's thickness is much smaller than the submerged depth), and in order to reduce the time of convergence, free surface effects (generation of waves) were not modeled in this case.

2.3 CFD Simulation of the Catamaran with and without Foil

The process of numerical simulation on Computational Fluid Dynamic starts from making a hull model. Modeling using the CAD software, then the file is exported in the form of a file .igs. The model used must be solid. After the model is finished, the work continues using numerical simulations. The numerical simulation software used is software based on Computational Fluid Dynamic. These simulation steps are divided into several stages, including Geometry, Mesh, Setup, Solution, and Result.

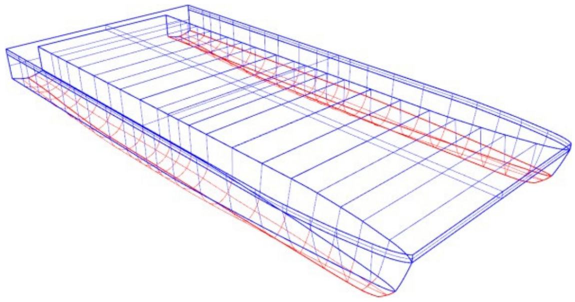

Figure 3: Imported Geometry solid modeling of catamaran without foil on CFD pre-processor phase from CAD modeler.

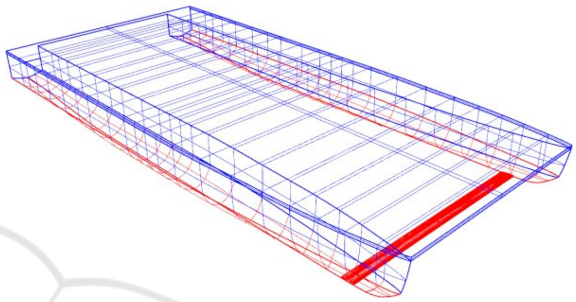

Figure 4: Imported Geometry solid modeling of a catamaran with one foil on CFD pre-processor phase from CAD modeler.

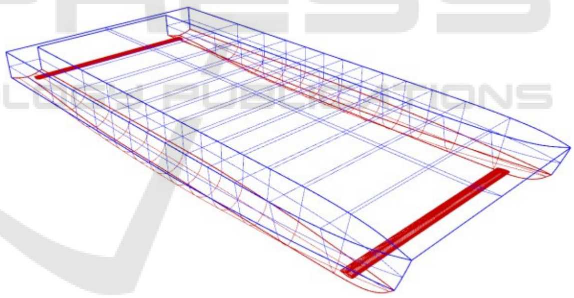

Figure 5: Imported Geometry solid modeling of a catamaran with one foil on CFD pre-processor phase from CAD modeler.

Figures 3 to 5 show the geometry model after imported to CFD software from CAD software. It must be solid so CFD software can read the geometry fully correct and ready to simulate. After the running or simulation process is complete, the results can be seen in the result stage. The results obtained are the resistance value of the ship, the model, and visualization of the flow on the free surface and station behind the hull.

2.4 Towing-tank Experiments

Towing tank experiments were held in the Hydrodynamic Laboratory of the Faculty of Marine Technology, ITS Surabaya, Indonesia, to verify the results from CFD simulations. The dimensions of the towing tank are 50m in length, 3m in width, and 2m in depth.

1:40 geometrical scaled Ship Model were designed and manufactured for the ship hull and the foil. Fiberglass-reinforced plastic was used to make the ship model, and the foil was made from copper. The model's resistance was measured by using a load cell. The load cell was connected to a voltage amplifier, which was in turn connected to a computer network in the control room. Before carrying out a measurement, the load cell was calibrated by using a mass of 0.5kg. Five ship speeds were tested: 0.87, 1.16, 1.46, 1.74, and 2.037 m/s (full-scale speeds: 12, 16, 20, 24, 28 knots). Figure 7 shows a photograph of the model being towed at a speed of 1.16 m/s (full-scale speed: 16 knots; Fr = 0.4).

Figure 6: Model 2 of a catamaran with one foil on the bow section of the demihull catamaran before tested on towing tank on 16-knot speed (1.16m/s).

3 RESULTS AND DISCUSSION

3.1 Foil Characteristic

Table 2 summarizes the effect of different foil angels of attack on the lift-to-drag ratio as obtained from simulations of the foil alone with an angle of attack from -8º to 24. The results show that, for the same foil size (aspect ratio), the lift-to-drag ratio of NACA 641-212 is increasing along with the rise of the angle of attack until 4º and then decreasing. Furthermore, the vane characteristics were obtained from CFD simulations of foil alone. To verify the CFD results, these are compared with the theoretical results.

The shifts in lift and drag coefficients due to finite span are given as follows (White, 2011). For a given C_L, the horizontal shift in α due to the finite span as compared with the infinite span case is given as:

$$\Delta a = \frac{C_L}{\pi A} \quad (1)$$

Furthermore, for a given α, the increase in C_D due to the finite span as compared with the infinite span case is given as:

$$\Delta C_D = \frac{C_L^2}{\pi A} \quad (2)$$

In Equations (1) and (2), the C_D is the drag coefficient, C_L is the lift coefficient, α is the angle of attack and A is the aspect ratio. Then the results of C_L from CFD are compared with C_L from experimental calculations that have been carried out by others to ensure that calculations using CFD can be trusted by plotting the graphic of C_L from CFD and experiment such in Figure 7.

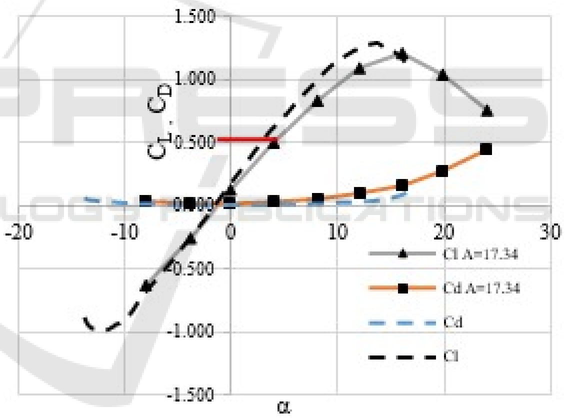

Figure 7: Lift and drag coefficients for NACA 641-212 section (theoretical results with infinite aspect ratio A) compared with NACA 641-212 vane with an aspect ratio of 17.3 obtained from CFD simulations (Re_c = 5.0 x 106).

Table 2: Foil NACA 641-212 Characteristic.

α	Drag(kN)	Lift(kN)	Cd	Cl	L/D
-8	32.35	-590.27	0.03	-0.62	-18.25
-4	16.79	-239.12	0.01	-0.25	-14.24
0	13.67	116.74	0.01	0.12	8.54
4	28.15	470.71	0.03	0.50	16.72
8	47.48	782.32	0.05	0.83	16.48
12	93.89	1028.04	0.10	1.09	10.95
16	148.51	1138.18	0.15	1.20	7.66
20	258.75	979.08	0.27	1.04	3.78
24	419.03	712.66	0.44	0.75	1.70

Figure 7 shows the lift and drag coefficients for NACA 641-212 section with infinite span compared with NACA 641-212 section and aspect ratio A = 17.34. The lift curve slope for α between -8° and 12° for the infinite span case is approximately 0.1 per degree and stall takes place at α approximately 14° according to the theoretical prediction (Abbot & Von Doenhoff, 1959).

Table 3 summarizes the lift forces that occur on the foil when it is simulated under several ship speed conditions as obtained from foil simulations only without catamaran, with the angle of attack α = 2º, chord 1m length and span 17.3m. The results show that, for the same foil size (aspect ratio), the higher the speed of the ship, the higher the lift force produced by the foil. NACA 641-212 foil has a greater lift when it's simulated on service speed (Fr=0.7).

Table 3: Lift force of foil NACA 64_1-212.

Fr	V (Knots)	V (m/s)	L (kN)	D (kN)
0.3	12	6.17	67.83	11.61
0.4	16	8.23	119.71	20.72
0.5	20	10.29	184.53	32.75
0.6	24	12.35	249.25	50.48
0.7	28	14.40	327.88	70.32

Table 4 summarizes the lift force that occurs on the foil when it is simulated under some conditions of ship speed obtained from the simulation when the foil is on a catamaran, with the angle of attack α = 2º, chord 1m length, and span 17.3m. The results show that, for the same foil size (aspect ratio), the higher the speed of the ship, the higher the lift force produced by the foil. The value of this condition is greater than the lift and drag on foil-only condition because when the foil is attached to the catamaran hull, the foil condition seems to have a wingtip because both ends of the foil are covered by demihull.

Table 4: Lift force of foil NACA 641-212 on the catamaran.

Fr	Vs. (knot)	Vs (m/s)	Lift (kN)	
			1 Foil	2 Foil
0.3	12	6.17	69.57	124.86
0.4	16	8.23	149.62	233.42
0.5	20	10.29	246.97	425.51
0.6	24	12.35	352.14	612.88
0.7	28	14.40	451.14	707.15

3.2 Ship Resistance with and without Foil

Results of resistance for the ship with vane are presented in this section. A comparison between the CFD and towing test results are shown in Figure 9.

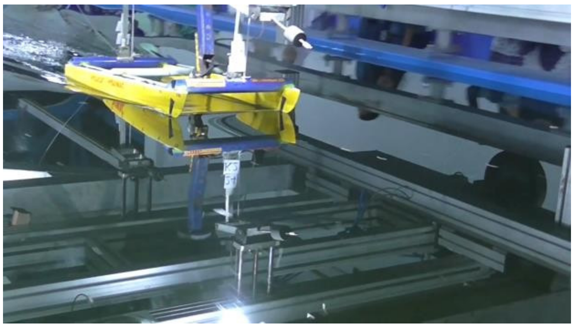

Figure 8: Model 2 of a catamaran with one foil on the bow section of the demihull catamaran being tested on towing tank at 16-knot speed (1.16m/s).

It can be shown in Figure 9 below that trim occurred on the model because of the effect of bow foil. The result of the Ship resistance analysis using CFD and Experiment was gathered and then process to get the final data. In figure 8 above is Case 2 of a catamaran with one foil on the bow section of the demihull catamaran being tested on towing tank at a 16-knot speed (1.16m/s). It can be shown in Figure 9 below that trim occurred on the model because of the effect of bow foil. The percent relative error between Ship resistance value from each model with various speeds from CFD calculation and towing tank experiment can be seen on the table below.

Table 5: Percent relative error between the CFD results and experiment.

Fr	Case 1	Case 2	Case 3
0.3	4.80	0.88	4.84
0.4	3.48	3.16	2.64
0.5	1.10	4.12	1.96
0.6	1.40	3.30	1.22
0.7	3.40	4.08	2.00

Table 6: Percent increase of total resistance compared between case without foil (Case 1) and case with foil (Case 2) and (Case 3) based on CFD result.

Fr	Case 2	Case 3
0.3	41.11	98.94
0.4	39.27	87.49
0.5	36.05	82.21
0.6	34.09	77.42
0.7	31.04	59.32

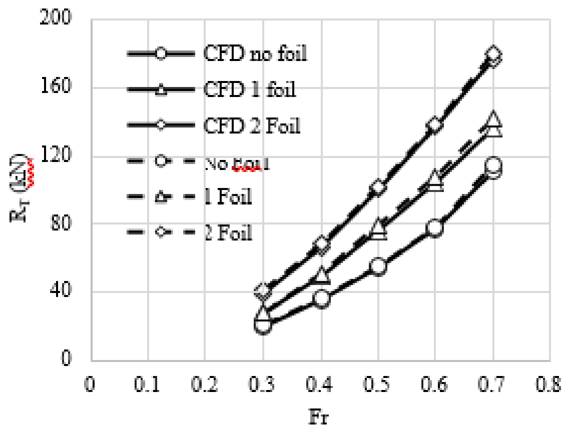

Figure 9: Total ship resistance from 3 various models of a catamaran with and without foil with different speeds (Fr=0.3-0.7).

Line with black dash is resistance for catamaran without foil, dash dots line is Resistance for a catamaran with one foil on bow section, the straight line is a catamaran with two foil (1 on the bow and quarter span on the stern section of each demihull), and node without line results from the experiment. The calculation results and the graph image above show the difference in the resistance value of each ship model according to the Froude number and the speed of each ship model. As table 5 show that there is no reduction in ship resistance because of added foil, a catamaran with two foil is higher than a catamaran without foil. Based on the literature (Calkins, 1984; Hoppe, 1982, 1989, 1991, 2001), the effect of added foil on the ship hull will reduce the total resistance at a certain speed. In this study, the effect of adding foil has not reached a state where the addition of lift force is greater than the addition of drag force due to the addition of foil, so a higher speed is needed to achieve this condition. But as the speed going higher, it will consume much power, so the efficiency will not be optimum.

4 RESULTS AND DISCUSSION

Based on CFD Simulation and Towing tank experiment that has been done on 3 different cases. (K1) catamaran without foil, (K2), 1 catamaran with 1 foil on the bow section, (K3), a catamaran with 1 in the bow section, and 1 in the stern section show that the added foil significantly affect the catamaran’s total resistance. Generally, hydrofoil on a ferry catamaran increases the total resistance produced by the ship at service speed. The highest resistance value occurs in the case catamaran with foil on the ship's bow and stern section (K3). Total resistance value happens in case 1 as the existing catamaran without foil is 114.59 kN at service speed, case 2 (1 foil) design of catamaran with added 1 foil on the bow section, and case 3 (2 foil) with added foil on both bow and stern section is respectively 31% and 59% higher than the catamaran without foil **T**hese data show that not all existing catamaran vessels can be added hydrofoil between the demihulls. To get optimal hydrofoil-supported catamaran performance, designing a catamaran ship with hydrofoil from the preliminary design is necessary**.** For further research, a more sophisticated hydrofoil technology is needed to change the hydrofoil conditions at each ship's speed. The resulting lift remains stable in providing a lift to the hull and the least possible drag force.

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