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EXPERIMENTAL STUDY OF HARD-CHINE CREW-BOAT RESISTANCE IN HIGH FROUDE-NUMBER RANGE UTILIZING A STERN-FOIL WITH VARYING POSITION IN THE VERTICAL AND LONGITUDINAL DIRECTIONS

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ABSTRACT

Effects of the application of a stern foil and its placement relative to the ship hull in the vertical and longitudinal directions are studied experimentally focusing on the high Froude number range (0.61 <~ Fr <~ 0.92). The hard-chine Orela crew-boat with target top speed of 28 knots (Fr = 0.86) is considered as a case study. Three variations of foil position in the longitudinal direction are investigated: (i) the leading edge precisely below the transom, (ii) the leading edge one chord-length behind the transom and (iii) the leading edge two chord-lengths behind the transom. Furthermore, four variations of foil's submerged elevations are studied: h/T = 0.75, 1.0, 1.25 and 1.50, where h is the foil's submerged elevation and T the boat's draft. Generally, the application of a stern foil in the high Froude-number range results in an increase of ship resistance. Considering the vertical variation of foil's placement, the shallowest foil's submerged elevation (h/T = 0.75) results in the smallest resistance. Considering the longitudinal variation, the foil placement with the leading edge 2 chord lengths behind the transom results in the smallest resistance. The Froude number range recommended for an application of a stern foil is 0.5 <~ Fr <~ 0.7.

Keywords: *Crew boat, high Froude-number range, ship resistance, stern foil, towing-tank experiments*

1.0 INTRODUCTION

Many innovations with the purpose to reduce the resistance of an existing boat utilize appendages. The most successful application of an appendage was that of a stern hydrofoil, called Hull Vane®, which was invented by van Oossanen in 1992 and patented in 2002. The mechanism of the Hull Vane® is described in [1]. The Hull Vane®, when applied to a boat, can generate an additional thrust, thereby affecting the trim and the wetted surface area positively, leading to saving of fuel consumption [2]. It has been successfully applied on a 55 meter fast vessel *MV Karina* and a 42 meter superyacht *Alive* [3].

The performances of the Hull Vane®, interceptors, trim wedges and ballasting have been compared each other and it was found that the Hull Vane® was the most efficient device in reducing the ship resistance and in improving the seakeeping performance [4]. Commonly, the Hull Vane is applicable to high-speed non-planing boat in moderate waves with Froude number up to approximately 0.7 [5].

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Considering the application of a stern foil (Hull Vane®), the question regarding the most optimum foil's placement relative to the ship hull, both in the longitudinal and vertical directions, has not sufficiently been explored [6]. The purpose of the present study is to systematically investigate the effects of foil's placement on the ship resistance.

2.0 METHODOLOGY

As a case study, the Orela hard-chine crew boat is considered in the present study. The boat is one of PT. Orela shipyard proven designs and products, which has a target top speed of 27 knots (Froude Number Fr = 0.86). The ship particulars are summarized in Table 1.

Table 1: Principal particulars of the hard-chine crew boat.

Length Overall (L_{OA})	31.20 m
Length Between Perpendicular (L_{BP})	28.80 m
Breadth (B)	6.80 m
Depth (H)	2.75 m
Draft (T)	1.40 m
Maximum Speed (V_{max})	27 kn
Displacement (Δ)	104.68 t

Table 2: Variation of foil's placement in the vertical and longitudinal directions.

Case	***h/T***	**Position of foil's leading edge**
T0.75/0C	0.75	Precisely below the transom
T1.00/0C	1.00	Precisely below the transom
T1.25/0C	1.25	Precisely below the transom
T1.50/0C	1.50	Precisely below the transom
T0.75/1C	0.75	1 chord length behind the transom
T0.75/2C	0.75	2 chord lengths behind the transom
h = foil's submerged elevation T = boat's draft		

To obtain the most optimum foil type and dimension, CFD simulations were done of foil alone. Three foil types from the NACA series are investigated, namely, NACA 64(1)212, NACA 4412 and NACA 21021 [7]. In addition, CFD simulations of ship with and without foil are planned to be carried out (have not finished yet at present) to verify the experimental results of foil's placement on the ship resistance. In the present study, the towing-tank test result for the case of ship without foil is verified using the Savitsky planing formula [8].

Towing-tank experiments were performed at the Hydrodynamic Laboratory, Faculty of Marine Technology, ITS Surabaya, Indonesia. To investigate the effects of foil's placement on ship resistance (particularly in high Froude-number range, Fr = 0.61 to 0.92), four variations in the vertical direction (T0.75/0C, T1.00/0C, T1.25/0C and T1.50/0C) and three variations in the longitudinal direction (T0.75/0C, T0.75/1C and T0.75/2C) are considered as shown in Table 2.

2.1 NACA-Foil Simulations with CFD

The foil-alone simulations were done to obtain the most optimum foil type and size by calculating the lift-to-drag ratio for varying foil's aspect ratio. The foil's aspect-ratio was kept within the recommended range [9]. For the chosen aspect ratio, the lift-to-drag ratio was also calculated for varying angle of attack (α) to obtain the optimum angle of attack. In the calculations, the foil's span was kept constant (the same as the boat's breadth) but the chord length was varied.

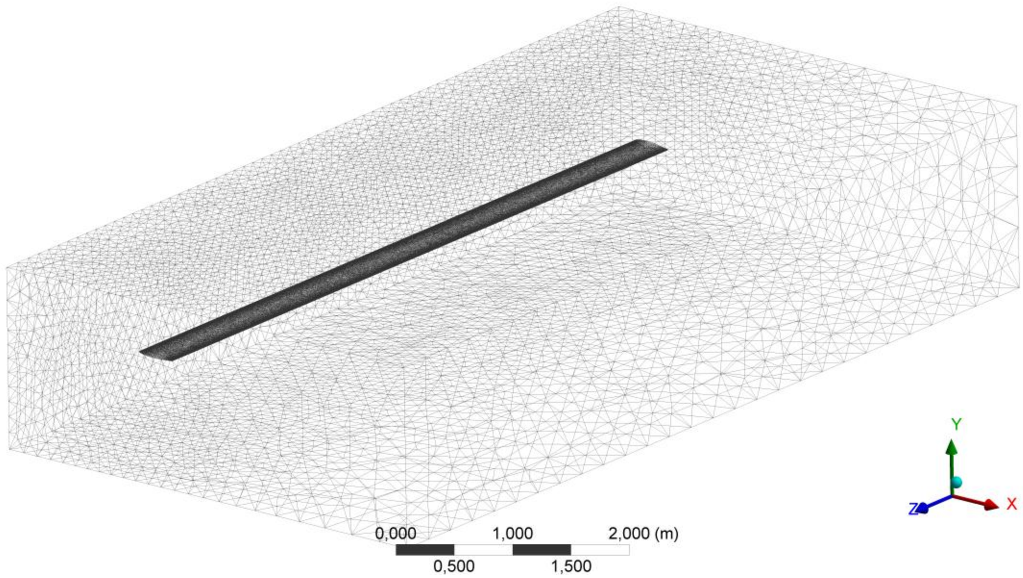

Figure 1: Mesh of the NACA 64(1)212 foil and its position in the computational domain.

The boundary conditions of the computational domain are as follows [10]. The inlet boundary located at 1-*c* upstream from the leading edge (*c* is the chord length) is defined as a uniform flow with velocity equaling the ship speed (in the simulations the foil is at rest but the water flows). The outlet boundary, at a location 4-*c* downstream from the trailing edge, is given as that the pressure equals the undisturbed pressure, ensuring no upstream propagation of disturbances. The boundary condition on the foil's surface is defined as no-slip condition. The boundary conditions on the top and bottom walls, at a distance 2-*c* above and below the foil, respectively, and on the side walls (approximately 7-*c* aside the model) are defined as free-slip condition.

To obtain the most optimum grid size (number of elements), tests were performed so as the numerical solution fulfills the grid-independence criterion [11]. The turbulence model used is the shear stress transport (SST) model. RANS method for incompressible flow is used to solve the viscous flow field. The root mean square (rms) error criterion with a residual target value of 10^{-5} is used as the criterion for the convergence of the numerical solution.

2.2 Towing-Tank Experiments

The towing tank of the Hydrodynamic Laboratory of the Faculty of Marine Technology, ITS Surabaya, Indonesia has the dimensions as follows: length = 50.0 m, width = 3.0 m, and water depth = 2.0 m. For the towing-tank tests, it is necessary to model the vessel in accordance to the size and capacity of the towing tank. The Froude scaling was applied (with a geometrical scale of 1:40). The model consists of boat's hull, struts and a lift foil. The boat's model was made from fiberglass-reinforced plastic (FRP) coated with paint and resin. The stern foil (NACA 64(1)212) and the struts (NACA 0010) were made from brass (see Fig. 2 for the ship model).

The total resistance of the boat (with or without stern foil) was measured by using a load cell. The load cell was connected to a voltage amplifier, which was connected to a computer network in the control room. The load cell was calibrated by using a mass of 0.5 kg before performing a measurement. Six boat speeds were tested:1.62, 1.79, 1.95, 2.12, 2.28, and 2.44 m/s (full-scaled speeds: 20, 22, 24, 26, 28 and 30 knots). Figure 3 shows the ship model towed at a speed of 1.62 m/s (full scale speed of 20 knots; Froude number *Fr*=0.61).

(a). Side view.

(b) Aft View.

Figure 2: Ship model with stern foil attached to the boat hull using two struts (scale 1:40).

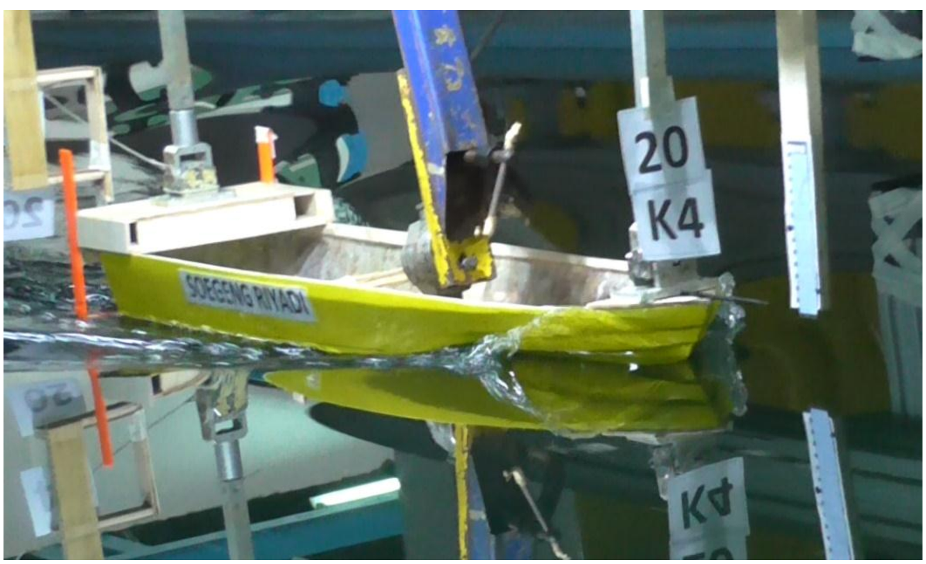

Figure 3: Ship model towed at speed of 1.62 m/s (full-scale speed 20 knot; *Fr* = 0.61).

3.0 RESULTS AND DISCUSSION

Results of lift-to-drag ratio C_L/C_D obtained from the simulations of foil alone with angle of attack $\alpha = 2^o$ [12] and different foil's aspect ratios are shown in Table 3. Table 3 shows that, for the same foil size (aspect ratio), the NACA 64(1)212 foil has the largest lift-to-drag ratio among the three foil types under consideration. Furthermore, for all foil types, the lift-to-drag ratio increases with increasing aspect ratio. From all foils under consideration, the NACA 64(1)212 foil with aspect ratio of 8.50 has the largest lift-to-drag ratio. Therefore, it is chosen as the stern foil of the hard-chine crew boat.

Table 3: Lift-to-drag ratio of NACA 4412, NACA 21021 and NACA 64(1)212 foils for varying aspect ratio.

Chord length [m]	Span [m]	Aspect Ratio	C_L/C_D		
			NACA 4412	NACA 64(1)212	NACA21021
0.80	6.80	8.50	40.08	41.25	29.77
1.00	6.80	6.80	34.90	39.83	26.67
1.20	6.80	5.67	31.20	36.54	24.10

Figure 4 shows the lift-to-drag ratio for the NACA 4412, NACA 21021 and NACA 64(1)212 foils with aspect ratio of 8.50 as function of angle of attack (α). For the NACA 64(1)212 and NACA 21021, the value of C_L/C_D first increases, takes a maximum value and then decreases monotonically with increasing angle of attack (α). For the NACA 4412 the increase in the first segment ($0 < \alpha < 2^o$) is rather small. The NACA 64(1)212 gives the largest C_L/C_D value, which is 41.25 at $\alpha \approx 2^o$. Therefore, in the towing-tank experiments, the foil's angle of attack is fixed at $\alpha = 2^o$.

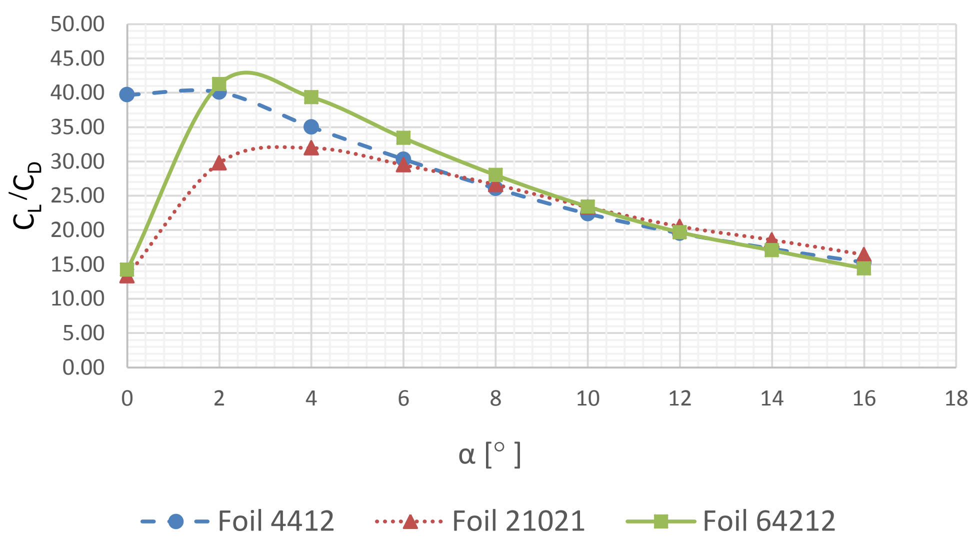

Figure 4: Lift-to-drag ratio of NACA 4412, NACA 21021 and NACA 64(1)212 foils with aspect ratio of 8.50 as function of angle of attack (α).

Figure 5 shows the total ship-resistance R_T as function of the Froude number Fr obtained from experiments with vertical variation of stern foil's placement, together with the case without foil and the Savitsky model [8]. Figure 5 shows that for the case with high speed as considered in the present study (Froude number Fr = 0.61 Fr 0.92) the application of a stern foil generally results in an increase of the total ship-resistance. The increase can reach 33.78% at Fr = 0.92 (the case T1.00/0C). Among the foil's placement variations in the vertical direction, the position h/T = 0.75 (T0.75/0C) gives the smallest resistance (h is the foil's submerged elevation and T is the boat's draft). Furthermore, the Savitsky model gives a good prediction of ship resistance for the case without foil with an averaged percentage error of 1.27%.

Figure 6 shows the total ship-resistance R_T as function of the Froude number Fr obtained from experiments with variation of foil's placement in the longitudinal direction, together with the case without foil and the Savitsky model [8]. The application of stern foil for the cases T0.75/0C and T0.75/1C results in an increase of total resistance (compared to the case without foil). The increase can reach 31.76% at Fr = 0.92 (the case T0.75/1C). The foil position with leading edge 2 chord lengths behind the transom (T0.75/2C) gives the smallest resistance among all the longitudinal foil's placement variations. At Fr < 0.70 the foil position T0.75/2C results in a decrease but at Fr > 0.75 it results in an increase of ship resistance. For example, at Fr = 0.61 the decrease of ship resistance is approximately 14.74% and at Fr = 0.92 the increase of resistance is approximately 31.76% (compared to the case without foil).

From the observations presented above, there are Froude-number range (Fr < ~ 0.70) and appropriate foil's placement in the vertical and longitudinal directions which can reduce the total ship resistance. For Fr >~ 0.75 all foil's placements result in an increase of ship resistance. Suastika *et al.* [12] reported an increase of ship resistance when a stern foil is applied for Fr <~ 0. 45. The Froude number range recommended for an application of a stern foil is therefore 0.5 <~ Fr <~ 0.7.

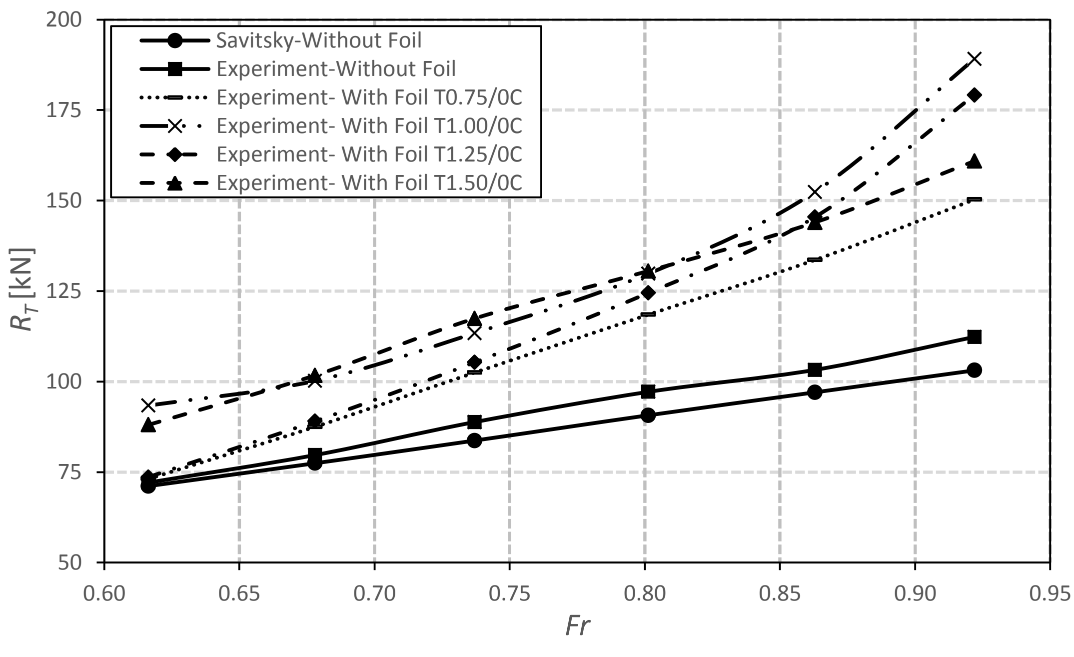

Figure 5: Total ship-resistance R_T as function of Froude number Fr with vertical variaton of foil position.

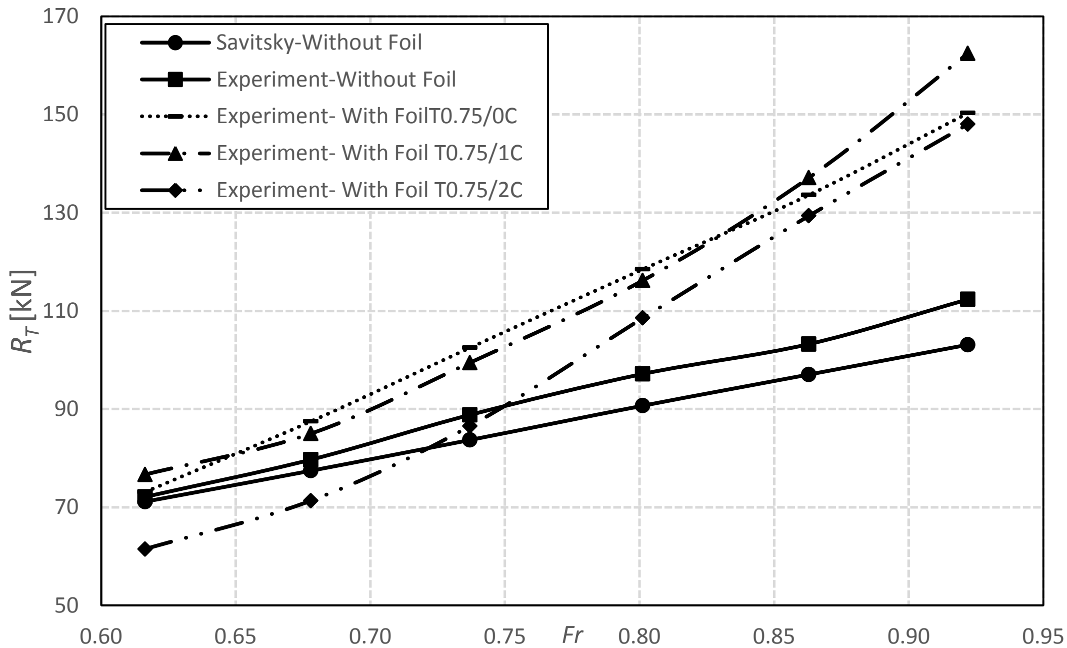

Figure 6: Total ship-resistance R_T as function of Froude number *Fr* with longitudinal variation of foil position.

For the cases considered in the present study, considering the vertical variation of foil's placement, the shallowest foil's submerged elevation (h/T = 0.75, h is the foil's submerged elevation and T is the draft) results in the smallest resistance. Furthermore, considering the longitudinal variation, the foil placement with the leading edge 2 chord lengths behind the transom results in the smallest resistance.

4.0 CONCLUSIONS

Towing-tank experiments were performed to study the effects of an application of a stern foil and its placement relative to the ship hull in the vertical and longitudinal directions on the ship resistance focusing on the high Froude number range (0.61 <~ *Fr* <~ 0.92). The planing-hull hard-chine Orela crew-boat was considered as a case study. Four variations of foil's placement in the vertical direction and three variations in the longitudinal directions were investigated. For *Fr* >~ 0.75 all foil's placements result in an increase of ship resistance. A previous study [12] reported also an increase of ship resistance for *Fr* <~ 0. 45. Therefore, the Froude number range recommended for an application of a stern foil is 0.5 <~ *Fr* <~ 0.7.

From the cases considered in the present study, considering the vertical variation of foil's placement, the shallowest foil's submerged elevation (h/T = 0.75, h is the foil's submerged elevation and T is the draft) results in the smallest resistance. Furthermore, considering the longitudinal variation, the foil placement with the leading edge 2 chord lengths behind the transom results in the smallest resistance.

Finally, for the case without foil, the Savitsky model [8] gives a good prediction of the ship resistance with an averaged percentage error of 1.27%.

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