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A New Approach to Analysis and Evaluation Planing Hull Design

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Abstract – *Analyzing and evaluating hull design is always an essential need in practice to ensure safety and economic-techno efficiency for seagoing ships, save production costs, shape well-suited hull models for series production, etc., especially in the absence of the conditions to test the model. This problem is usually resolved by the model test method. However, many actual hulls have been unable to achieve the desired seakeeping performances even after model testing. For planning hulls, this problem is much more difficult due to the complex nature of the hydrodynamics interactions that occur when the planning hulls move at high speeds. Therefore, in this paper, an analysis of the parameters that greatly affect planing hull performance by our modified Savitsky method is performed and based on that to establish a methodology to evaluate existing planing hull designs. The results of this study have also been applied to analyze and evaluate the design of a Vietnamese high-speed vessel, denoted SESCO K88, which was tested in the towing tank but has not achieved the desired speed and performances, and pointed out solutions to overcome these disadvantages.*

Keywords — *high-speed vessel, hydrodynamic, performance, planing hull, Savitsky method.*

I. INTRODUCTION

The planing hull design is always a difficult problem due to the complexity of hydrodynamic interactions at high speeds [1]. This problem is solved by model testing in the towing tank, but this method is expensive and takes a lot of time, effort. Also, in some cases, model testing provides only predictions of resistance and some main performances without analyzing and evaluating for hull design, leading to planing hull may not achieve optimum resistance or desired performances, and the economic-techno efficiencies of the ships are greatly affected. So evaluating the design, which is essentially analyzing and correcting the hull form and hydrodynamic parameters, is very important to ensure that the planning hull can work properly. Our review of this problem has shown that most of the related works either research to establish empirical formulas/curves or use available empirical formulas and computation methods for prediction resistance or performances of the planing hulls. In general, studies related to the planning hull performances can be classified into experimental and theoretical studies. Experimental studies are usually performed based on testing a series of hull models in the towing tank to determine and analyze the resistance or performances of planning hulls [3]. The models which are used in the series test are developed by systematically modifying the main hull form parameters of the parent hulls while keeping the remaining ones unchanged, such as Series 62 (Hubble), SSPA series, NPL series, etc. [4]. The data obtained from such experimental studies are often used to establish empirical formulas or curves for predicting the resistance and some performances of the planing hulls. Due to the differences of hull model parents used for testing, there are many empirical formulas for predicting planing hull resistance with different accuracy and ranges of use, such as Kafali [5], Nordstrom [6], Groot D. [7], Almeter [8], etc. However, according to many researchers, among the existing formulas, the Savitsky method is the most efficient and is usually used to predict the resistance of the planing hulls [9]. This method was first published in 1964 by D.Savitsky [10] and continued to be refined by other researchers to apply in ship design such as Mercier et al. [11], Blound et al. [12], Brown et al. l [13], Abbas [14], Ghassemi et al. [15] and so on. One of the recent experimental studies was performed by Dong-Jin Kim et al. (2013), in which three planning hull models were designed, analyzed, and adjusted based on the results of model testing to improve their resistance and seakeeping [16]. Theoretical studies are often developed based on using numerical methods to predict characteristics parameters for hydrodynamic performances of planing hulls such as resistance, trim angle, running attitude, porpoising limit, etc. Previous studies usually use potential flow methods such as the Boundary Element Method (BEM) (Ermina 2015) [17], or the Panel method (Iskender et al. [18], Krishana [19]), etc., but due to these methods have low accuracy and are not applicable for the viscous flows, so in many recent studies, a modern numerical method, Computational Fluid Dynamics (CFD), has been used to predict planing hull performances, such as Daniele [20], Brizzolara et al. [21], Svahn [22], Iacono [23], Bakhtiari et al. [24], Yumin Su et al. [25], etc. Also, in our reviews, some comments can be drawn, such as (i) Most of the studies use the Savitsky empirical method and CFD analysis to predict the resistance of the planing hulls. However, they do not always give the expected accuracy, and (ii)There have not been any studies on the approach or solution to assist designers in analyzing and modifying existing hull design to improve resistance or performance of planing hulls.

In this paper, therefore, a new approach to analyze, evaluate, and modify existing hull planning design will be present to improve the vessel resistance and performance.

II. MATERIAL AND RESEARCH METHOD

The computational planing hull used in this study is a SESCO K88 passenger high-speed vessel which is designed by Southern Vietnam Engineering Shipbuilding Company and tested at the towing tank of National Taiwan Unversity in 2013, at three displacements (1) 170 tons, (2) 200 tons, and (3) 230 tons, and the shipping speed is from 10 kn to 30 knots [26]. Although it has been model tested in practice, this vessel has not run at full speed and is often jammed at high speed. Fig.1 shows and Table 1 show a body plan and hull form parameters of the computation planing hull.

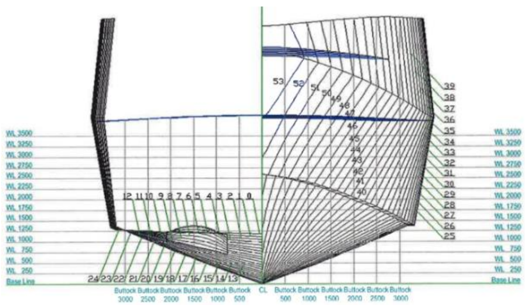

Fig. 1. The body plan of the computation planing hull

Table 1. The hull parameters of the computation vessel

Parameters	De-note	Values		
		1	2	3
Length overall, m	L_{OA}	42.20	42.20	42.20
Length between perpendiculars, m	L_{PP}	36.93	36.93	36.93
Length of the waterline, m	L	37.92	38.05	38.17
Breadth maximum, m	B_{max}	7.85	7.85	7.85
Breadth on the waterline, m	B	6.76	6.81	6.85
Draft, m	d	1.70	1.85	1.98
Displacement, tons	Δ	170	200	230
The longitudinal position of gravity center (from aft)	LCG	15.81		
The vertical position of gravity center (from the base line), m	VCG			
Block Coefficient	C_B	0.409		
Prismatic Coefficient	C_P	0.667		
Required Horse Power, HP	EHP	2525		
Desired angle, degree	β	22.39		
Thrust line inclination angle relative to keel line, degree	ε	3		
Distance between (T) and center gravity (measured normal to T), m	F	1.53		

Fig. 2 shows a photograph test of the computational vessel

Fig. 2. The photograph test of the computational vessel

Table 2 and Fig. 3 show resistance values and curves of computation vessels, which are converted from the model test results at three designed displacements (Δ).

Table 2. The resistance values (R) of computation vessel at three designed displacements (Δ)

No.	V (knots)	Δ_1 = 170 tons	Δ_2 = 200 tons	Δ_3 = 230 tons
		R_1 (kN)	R_2 (kN)	R_3 (kN)
1	10	15.53	20.93	24.55
2	12	30.56	34.56	38.98
3	14	46.38	57.83	67.68
4	16	65.14	78.84	95.38
5	18	75.80	98.43	120.94
6	20	96.75	116.67	145.67
7	22	109.07	130.97	162.43
8	24	118.74	142.44	173.76
9	26	128.14	150.93	185.35
10	28	136.69	158.38	194.20
11	30	146.67	169.55	203.42

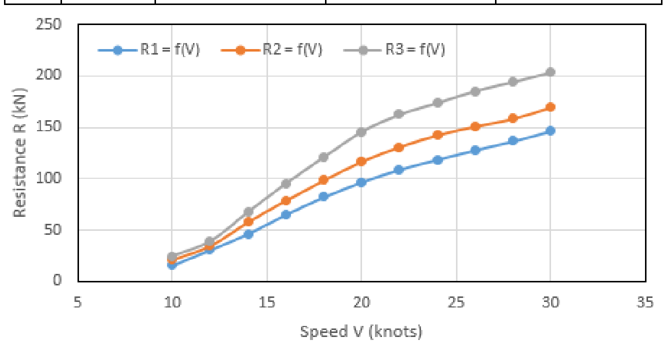

Fig. 3. Resistance curves R = f(V) of computation vessel

In our approach, planing hull designs will be analyzed and evaluated starting from a prediction of hull resistance by the Savitsky empirical method and CFD analysis as presented. The problem is how to ensure the accuracy of resistance prediction by these methods, as stated in comment (i) above. In one of our studies [27], solutions to improve the accuracy of hull planing resistance prediction have been analyzed and detailed, and therefore, here, it is only presented as a basis for solving the problem outlined in this paper.

A. For the Savitsky empirical method

Our study analyzed and pointed out the incompletion in the equilibrium condition of the Savitsky empirical method, and added an equilibrium equation to get a complete equilibrium, form a system of equilibrium equations for the planing hull, which includes Savitsky's longitudinal equilibrium equation (1), and vertical equilibrium equation (2) according to our proposal, specifically as follows:

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

$$\Delta.\cos\tau.LCG - N.C_p\lambda B - D_f.d = 0 \qquad (2)$$

The original symbols and meanings of the quantities included in the above equations can be found in reference [10] and are described in detail, as shown in Fig. 5.

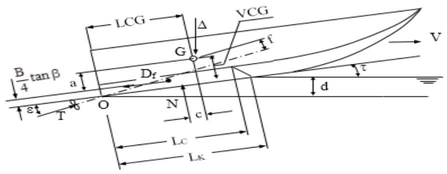

Fig.4. Diagram of forces acting on a non-stepped planing hull

For programming, the convergence conditions of the planning hull equilibrium equations are express as follows:

$$\Delta.\cos\tau.LCG - N.C_p\lambda B - D_f.d \le \xi_1 \qquad (3)$$

$$\Delta\left[\frac{1-\sin\tau.\sin(\tau+\varepsilon).c}{\cos\tau} - f\sin\tau\right] + D_f(a - f) \le \xi_2 \qquad (4)$$

Where ξ_1, ξ_2 are the given error constants used to solve the nonlinear equations by the numerical computation method, their minimum value is usually chosen to be 10e-2.

Fig.5 shows the algorithm flowchart of our new modified computation procedure according to the Savitsky method. Compared with the known original computation procedure of the Savitsky method, our new procedure is added two loops, where the first loop is to find the correct value of the mean wetted length to-beam rato (λ) from the condition satisfying equation (3) instead of using the Savitsky's approximation, and a second loop is to solve the nonlinear equation (4) to find the equilibrium trim angle (τ_e) of the planing hull by the numerical method instead of using linear interpolating which is very less accurate in this case.

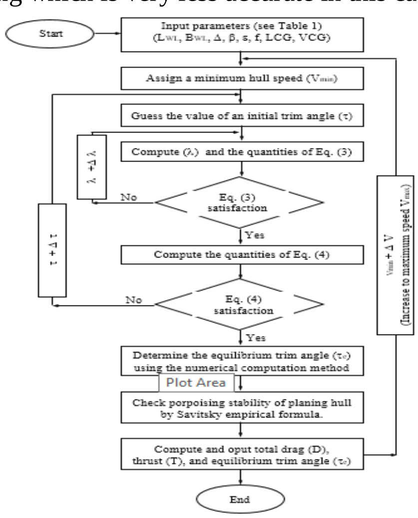

Fig. 5. Algorithm flowchart of our modified procedure

The computation results for the SESCO K88 vessel in Table 3 validated the accuracy of our modified procedure, with the deviations (δ) between the resistance values (R_{sm}) computed by our procedure and the model test data (R_t) at three test displacements and all speeds are in the range of ±5% (lower part of table 3), while the corresponding deviations (δ_m) for the resistance values (R_s) computed by the original computation procedure of Savitsky method are very large (upper part of table 3).

Table 3. Computation and comparision of resistance values of SESCO K88 planing hull in all tested cases

V(knot)	Δ_1=170 tons			Δ_2=200 tons			Δ_3=230 tons		
	R_{s1}(kN)	R_{t1}(kN)	δ_1(%)	R_{s2}(kN)	R_{t2}(kN)	δ_2(%)	R_{s3}(kN)	R_{t3}(kN)	δ_3(%)
Computing by Savitsky's original computation procedure									
10	28.97	15.53	46.45	37.39	20.93	44.02	46.97	24.55	47.73
12	55.18	30.56	44.03	61.97	34.56	44.23	68.56	38.98	43.05
14	87.73	46.38	46.82	104.58	57.83	44.71	123.20	67.68	45.07
16	109.73	65.14	40.42	132.78	78.84	40.62	158.78	95.38	39.93
18	124.88	75.80	39.19	151.67	98.43	35.10	182.08	120.94	33.58
20	135.69	96.75	28.67	164.70	116.67	29.16	197.64	145.67	26.30
22	143.91	109.07	24.26	174.18	130.97	24.81	208.53	162.43	22.11
24	150.69	118.74	21.34	181.68	142.44	21.60	216.76	173.76	19.84
26	156.83	128.14	18.51	188.24	150.93	19.82	223.70	185.35	17.15
28	162.84	136.69	16.34	194.53	158.38	18.58	230.20	194.20	15.64
30	169.01	146.67	13.56	200.94	169.55	15.62	236.76	203.42	14.08
Computing by our modified computation procedure									
V(knot)	R_{sm1}(kN)	R_{t1}(kN)	δ_1(%)	R_{sm2}(kN)	R_{t2}(kN)	δ_{m2}(%)	R_{sm3}(kN)	R_{t3}(kN)	δ_{m3}(%)
10	15.63	15.53	0.64	20.08	20.93	-4.23	25.15	24.55	2.39
12	30.19	30.56	-1.23	33.51	34.56	-3.13	37.63	38.98	-3.59
14	48.45	46.38	4.27	57.98	57.83	0.26	69.26	67.68	2.28
16	67.90	65.14	4.06	76.75	78.84	-2.72	97.72	95.38	2.39
18	79.15	75.80	4.23	95.80	98.43	-2.75	124.49	120.94	2.85
20	101.58	96.75	4.75	122.74	116.67	4.95	148.65	145.67	2.00
22	113.89	109.07	4.23	132.17	130.97	0.91	159.61	162.43	-1.77
24	117.28	118.74	-1.24	140.34	142.44	-1.50	168.80	173.76	-2.94
26	124.37	128.14	-3.03	147.98	150.93	-1.99	177.18	185.35	-4.61
28	132.75	136.69	-2.97	155.57	158.38	-1.81	185.39	194.20	-4.75
30	139.90	146.67	-4.84	163.43	169.55	-3.74	193.82	203.42	-4.95

Fig 6 shows the resistance curves plotted from the results in Table 3.

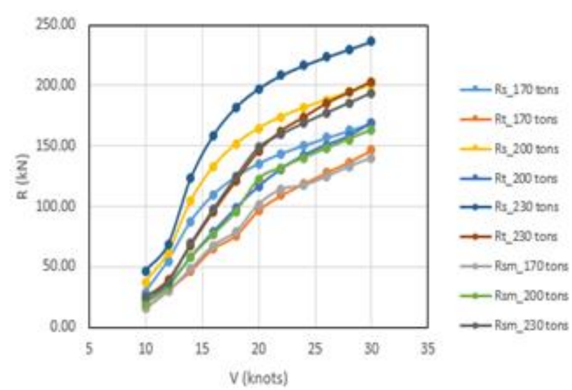

Fig. 6. The resistance curves of SESCO K88 planing hull

B. For the CFD analysis

In our study, the accuracy of the CFD-based resistance prediction is ensured based on determining the appropriate input parameters of the CFD solver for the planing hull, including the computational domain size used in numerical simulation, turbulence model, and running trim angle [27]. Also, in this study, the specific values of computational domain size and Smagorinsky constant C_s= 0.12 of turbulence model [28], which is built-in to Xflow [29], the common CFD software used in this study to predict planing hull resistance, is determined using the known trial and error method, and an equilibrium running trim angle $\tau_o = 2.5$ degrees is found by our modified computation procedure of Savitsky method. Based on this, the resistance values of the SESCO vessel at a displacement of 200 tons are predicted using Xflow CFD software at three cases (i) use the value C_s = 0.12 and τ_o = 0; (ii) use the default value C_s in Xflow and τ_o = 0; (iii) use the value C_s = 0.12 and τ_e = 2.5 degrees (see Table 4 and Fig. 7). These results showed that our proposed approach gave good results with deviations (δ) of CFD-based resistance values (R_{xa}) in case (iii) and model test data (R_t) are within ±3% at all computation speeds, while the corresponding deviations in case (i) (R_{xo}) and (ii) (R_{xm}) are large, especially in case (ii).

Table 4. Compute and compare the resistance results of the SESCO K88 planing hull in the computation cases

V (knots)	R_t (kN)	Case (i)		τ_e (degree)	Case (ii)		Case (iii)	
		R_{xo} (kN)	δ_i (%)		R_{xm} (kN)	δ_{ii} (%)	R_{xh} (kN)	δ_{iii} (%)
(1)	(2)	(3)	-27.1	(4)	(5)	(6)	(7)	(8)
10	20.98	26.66	7.9	1.86	30.52	45.5	20.55	-2.1
12	35.21	32.43	13.5	1.92	43.32	23.0	34.46	-2.2
14	55.86	48.34	-21.2	1.98	68.51	22.7	54.32	-2.8
16	77.14	93.53	-40.8	2.04	99.74	29.3	76.55	-0.8
18	98.99	139.41	-6.0	2.12	117.87	19.1	99.17	0.2
20	114.43	121.32	9.9	2.20	164.13	43.4	113.47	-0.9
22	130.54	117.68	-8.4	2.29	192.47	47.4	127.23	-2.6
24	142.94	154.95	1.5	2.39	209.74	46.7	142.09	-0.6
26	150.89	148.65	7.5	2.50	232.77	54.3	153.99	2.0
28	158.65	146.76	5.9	2.62	317.86	100.4	155.38	-2.1
30	168.99	159.01	-27.1	2.74	324.61	92.1	166.07	-1.8

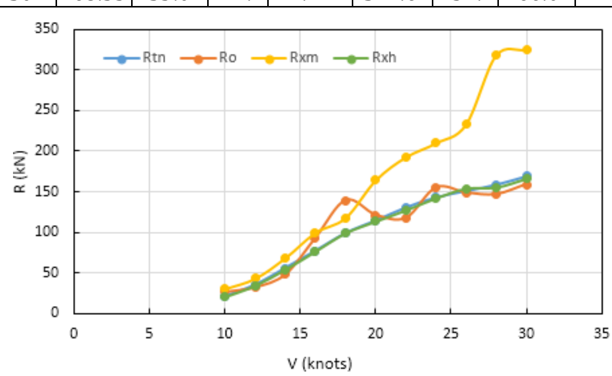

Fig. 7. The resistance curves in computation cases

III. RESEARCH RESULTS AND DISCUSSION

Based on the planning hull theory and our analysis, the hull parameters that greatly affect resistance and performance of planning hull are chosen and classified as follows:

(i) Hull form parameters as the non-dimensional coefficients, including the waterline length to breadth ratio (L/B), the longitudinal position of gravity center to waterline length ratio (LCG/L), the longitudinal position of gravity center to waterline breadth ratio (LCG/B).

(ii) Hydrodynamic parameters including static loading coefficient (C_T) and dynamic loading coefficient which are computed by the following formula:

$$C_T = \frac{\Delta}{\gamma B^3};\ C_D = \frac{\Delta}{0.5.\rho V^2 B^2} \qquad (5)$$

where Δ is displacement (tons); V is ship speed (knots); ρ, γ are density and specific density of water, respectively.

(iii) Construction parameters including the deadrise angle (β), which is defined as the angle between the bottom of the planing hull with the horizontal

By varying the above parameters as inputs in our modified computation procedure of the Savitsky method, the graphs which show the relationships between hull form parameters and hull resistance values will be determined (see Fig. 8). Then, a planning hull design can be analyzed and evaluated based on the results of comparing the hull parameters with their optimal values corresponding to minimum resistance.

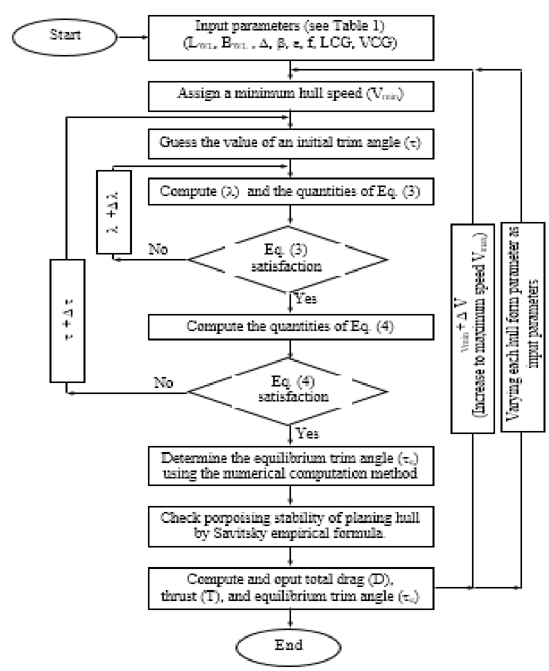

Fig. 8. Algorithm flowchart of the computation procedure to determine the effect of the hull parameter on the resistance

A. Study on the effects of changing hull form parameters on resistance and trim angle of planing hull

All computations below will be performed at displacement Δ = 200 tons and vessel speed V = 25 knots, corresponding to the operating design mode of the computation planing hull.

a) Effects of changing ratio (L/B)

In planning hull design, the length (L) is often determined based on the owner's requirements and general arrangement. So a change in the ratio (L/B) is only a change in breadth (B) which greatly affects ship performances, especially stability. Table 5 shows the values of resistance (R) and trim angle (τ) corresponding to the change of ratio (L/B) computed at some typical vessel speed values.

Table 5. Values of resistance and the trim angle corresponding to the change of the ratio (L/B)

V	L/B						
(knots)	4.00	4.40	4.80	5.20	5.60	6.00	6.40
24	134.89	135.15	136.23	138.02	140.45	143.37	146.72
25	145.33	144.58	144.63	145.39	146.76	148.64	150.94
28	157.98	156.29	155.40	155.20	155.60	156.52	157.88
30	169.18	166.71	164.98	163.91	163.42	163.46	163.94
	τ (degree)						
24	3.343	3.350	3.363	3.380	3.400	3.422	3.445
25	3.481	3.480	3.485	3.495	3.509	3.526	3.544
28	3.624	3.617	3.615	3.619	3.627	3.638	3.652
30	3.765	3.756	3.750	3.749	3.752	3.758	3.767

Fig. 9 shows the graphs of resistance (R) and trim angle (τ) with the change of ratio (L/B) at a speed of 25 knots.

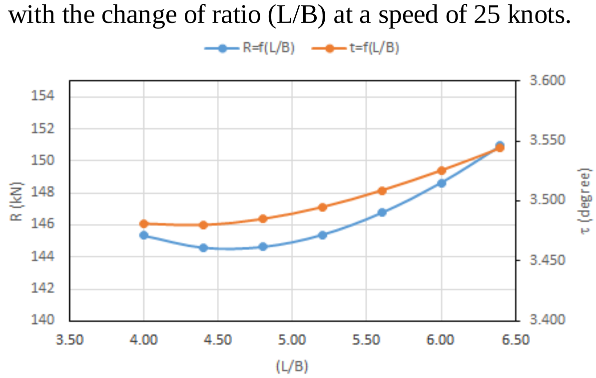

Fig. 9. Effects of changing ratio (L/B) on-resistance (R) and trim angle (τ) of the computation planing hull.

The breadth (B) is usually computed as a compromise based on satisfying many mutually contradictory conditions. For the planning hull, increasing ratio (L/B), i.e., decreasing (B), will decrease the hydrodynamic parameters (see formula 5), results in decrease resistance. However, a breadth that is too small will not ensure enough stability and lift for the planning. Therefore, resistance will increase again, as shown in Fig. 9. The computation planing hull with given length L = 38.05 m, from graphs in Fig. 9, it is possible to determine the optimal value of the ratio $(L/B)_{opt}$ is about 4.55, i.e., B_{opt} = 8.36 m, corresponding to minimum resistance value R_{min} = 141.3 kN, and trim angle τ = 3.48 degrees.

b) Effects of changing ratio (LCG/B)

Table 6 shows the resistance values corresponding to the change of the ratio (LCG/B) in the case of keeping B unchanged and in the case of keeping LCG unchanged.

Table 6. Resistance values corresponding to the change of ratio (LCG/B)

V	LCG/B (B is unchanged)						
(knots)	1.70	1.90	2.10	2.32	2.50	2.70	2.90
22	199.38	164.73	144.56	132.17	127.12	125.06	125.82
24	214.59	176.27	153.95	140.34	134.83	132.61	133.40
25	226.11	185.36	161.32	146.70	140.80	138.43	139.23
28	239.86	197.22	171.39	155.57	149.21	146.65	147.47
30	249.69	207.03	180.15	163.43	156.69	153.98	154.83
	τ (deg.)						
22	6.505	4.983	4.012	3.298	2.891	2.552	2.296
24	6.859	5.213	4.165	3.399	2.965	2.607	2.337
25	7.207	5.457	4.330	3.508	3.046	2.666	2.382
28	7.518	5.703	4.505	3.626	3.133	2.729	2.429
30	7.763	5.937	4.684	3.751	3.227	2.798	2.481
V	LCG/B (LCG is unchanged)						
(knots)	1.70	1.90	2.10	2.32	2.50	2.70	2.90
22	122.77	124.71	127.73	132.17	136.50	141.9	148.09
24	134.87	135.53	137.30	140.34	143.52	147.6	152.49
25	146.34	145.77	146.31	146.70	150.04	152.9	156.47
28	157.52	155.81	155.19	155.57	156.58	158.3	160.65
30	168.55	165.86	164.23	163.43	163.48	164.1	165.38
	τ (deg.)						
22	3.217	3.238	3.265	3.295	3.328	3.361	3.397
24	3.344	3.355	3.373	3.396	3.423	3.451	3.482
25	3.480	3.482	3.491	3.506	3.526	3.549	3.575
28	3.622	3.615	3.617	3.625	3.639	3.655	3.676
30	3.762	3.753	3.749	3.751	3.758	3.769	3.784

Fig.10 shows the graphs of the effect of changing ratio (LGG/B) on resistance and trim angle at a speed of 25 knots.

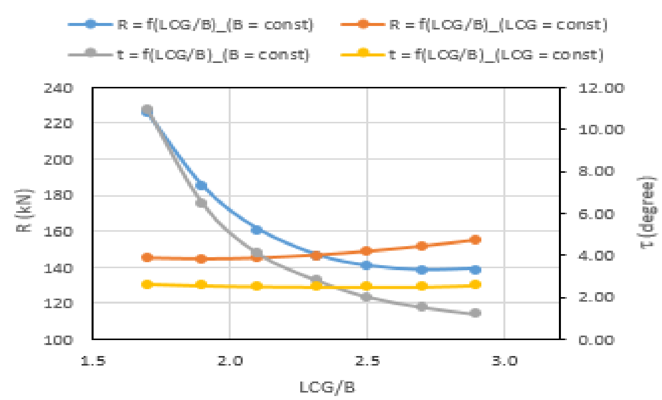

Fig. 10. Effects of changing ratio (LGG/B) on resistance and trim angle of the computation planing hull.

Some discussions can be drawn based on the results in Table 6 and the graphs in Fig.10 as follows:

- Change ratio (LCG/B) by changing LCG (B is unchanged)
  - When the planing hulls run at low and medium speeds, corresponding to the volume Froude number $Fn_\nabla \leq 2.5$, since residual resistance accounts for most of the total resistance, increasing the ratio (LCG/B) (B is unchanged) will shift the center of gravity towards the bow, so the total resistance will decrease due to trim angle is decreased. When the planing hulls run at high speeds, due to the predominant friction resistance, shifting the center of gravity towards the stern will reduce the wetted lengths, resulting in a decrease in the frictional resistance. Therefore, the total resistance will be decreased.
  - For the SESCO K88 planing hull design, the optimal value of the ratio $(LCG/B)_{opt}$ about 2.7, i.e., the optimal value $(LCG)_{opt}$ = 18.5 m corresponding to optimal resistance value R_{opt} = 140.0 kN, and trim angle τ = 2.67 degrees. This means that the computation planing hull can be redesign to achieve greater resistance and performance by shifting the center of gravity towards the bow about 3 m, but shifting too much will slightly increase the resistance.
- Change ratio (LCG/B) by changing B (LCG is unchanged)
  - Increase the ratio (LCG/B) will reduce the wetted length to waterline breadth ratio (λ), so the resistance decrease. For the SESCO K88 planing hull, the optimal value of the ratio $(LCB/B)_{opt}$ about 1.90, that is, the optimal breadth B_{opt} = 8.30 m corresponding to optimal resistance value R_{opt} =145.8 kN and running trim angle τ = 3.48 degrees. This proves that the SESCO K88 vessel can achieve better resistance if it is redesigned with a breadth of 8.30 m compared to the initial waterline breadth of 6.81 m. However, if increasing the waterline breadth beyond this value, from the formula (5), it can be seen that the value of the dynamic loading coefficient (C_D) decreases rapidly, resulting in a decrease in the longitudinal and directional stability and the planing hull can be skidded or leaped on the water. Therefore, the total resistance is increased again.
  - When increasing the ratio (LCG/B) (LCG is unchanged), the running trim angle (τ) will be decreased gradually. This will result in an increase in the wetted keel length and a decrease in the wetted chine length of the planing hulls, and a slight change in the immersion of the aft transom. The minimum values of the resistance in the two cases are close together.
  - The slope of the curve R = f (LCG/B) (B is unchanged) is much greater than the curve R = f (LCG/B) (LCG is unchanged), shows that adjustment the longitudinal position of gravity center (LCG) will improve resistance values much than with adjustment waterline breadth (B), although this should be considered early in the ship design because the adjustment (LCG) is less flexible and depends on the general arrangement design.

c) Effects of changing ratio (LCG/L)

Similar to the above case, the computation results of the effect of changing ratio (LGG/L) on resistance and trim angle of the computation planning hull are shown in Table 7.

Table 7. Effect of changing ratio (LGG/L) on resistance and trim angle of a computation planing hull

V	LCG/L						
(knots)	0.25	0.30	0.35	0.40	0.45	0.50	0.55
12	66.06	42.47	34.85	33.49	34.08	35.972	38.87
14	111.98	80.03	65.72	59.09	56.64	56.869	59.06
16	159.39	111.11	89.18	78.64	74.19	73.561	75.64
18	209.10	142.64	112.70	98.38	92.25	91.118	93.46
20	278.28	186.77	145.64	126.21	117.96	116.38	119.32
22	307.14	204.85	157.96	136.06	126.87	125.12	128.26
24	328.30	220.60	168.76	144.59	134.57	132.65	135.97
25	338.59	232.40	177.29	151.26	140.53	138.47	141.88
28	347.76	246.26	188.58	160.50	148.91	146.68	150.23
30	348.71	255.90	198.12	168.66	156.38	154.00	157.69
V	τ (degree)						
(knots)	0.25	0.30	0.35	0.40	0.45	0.50	0.55
12	7.974	5.291	3.915	3.106	2.589	2.237	1.989
14	8.470	5.509	4.031	3.175	2.634	2.268	2.012
16	9.056	5.762	4.163	3.253	2.684	2.302	2.036
18	9.723	6.053	4.313	3.340	2.739	2.339	2.063
20	10.429	6.381	4.482	3.436	2.799	2.379	2.091
22	11.096	6.739	4.669	3.544	2.865	2.423	2.121
24	11.625	7.111	4.874	3.661	2.938	2.471	2.154
25	11.942	7.470	5.093	3.789	3.017	2.522	2.190
28	12.030	7.784	5.317	3.927	3.102	2.578	2.228
30	11.923	8.023	5.537	4.071	3.194	2.637	2.268

Fig.11 shows graphs of the relationships between the change in the ratio (LGG/L) to resistance and trim angle (τ) of the computation planing hull at a design speed of 25 knots. The graphs above show that the law of these effects is also similar to the change of a quantity (LCG), with the optimal value of the ratio $(LCG/L)_{opt}$ = 0.49, i.e., LCG = 18.65 m, corresponding to the minimum resistance value R = 138.0 kN, trim angle τ = 3.00 degrees very close to the above cases.

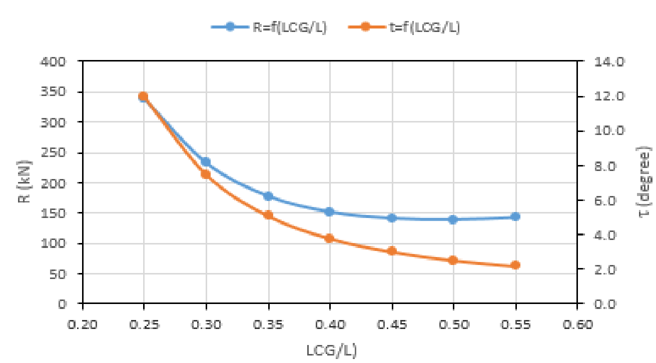

Fig. 11. Effects of changing ratio (LGG/L) on-resistance (R) and trim angle (τ) of the computation planing hull.

B. Study on the effects of changing the hydrodynamic parameters on hull planing resistance

Table 8 shows resistance values when changing the static loading coefficient (C_T) and dynamic loading coefficient (C_D)

Table 8. Values of resistance and the trim angle corresponding to the change of the hydrodynamic parameters

V	Static loading coefficient (C_T)					
(knots)	0.20	0.30	0.40	0.50	0.60	0.70
22	122.28	123.85	126.23	128.89	131.65	134.49
24	135.05	135.14	136.37	138.06	139.97	142.03
25	147.18	145.84	145.94	146.68	147.75	149.05
28	158.94	156.31	155.35	155.20	155.48	156.06
30	170.45	166.73	164.85	163.90	163.47	163.39
	τ (degree)					
22	3.210	3.230	3.252	3.274	3.294	3.314
24	3.343	3.350	3.364	3.380	3.396	3.412
25	3.484	3.480	3.486	3.495	3.506	3.518
28	3.628	3.617	3.615	3.619	3.625	3.633
30	3.769	3.756	3.750	3.749	3.751	3.755
V	Dynamic loading coefficient (C_D)					
(knots)	0.02	0.03	0.04	0.05	0.06	0.07
22	122.28	123.85	126.23	128.89	131.65	134.49
24	135.05	135.14	136.37	138.06	139.97	142.03
25	147.18	145.84	145.94	146.68	147.75	149.05
28	158.94	156.31	155.35	155.20	155.48	156.06
30	170.45	166.73	164.85	163.90	163.47	163.39
	τ (degree)					
22	3.206	3.233	3.270	3.309	3.348	3.385
24	3.343	3.352	3.377	3.408	3.440	3.472
25	3.488	3.481	3.494	3.515	3.540	3.566
28	3.635	3.616	3.618	3.631	3.648	3.669
30	3.774	3.755	3.749	3.754	3.764	3.779

Fig. 12 shows the graphs of the relationship between the resistance with the static and dynamic loading coefficients at the design displacement of 200 (tons) and speed of 25 knots.

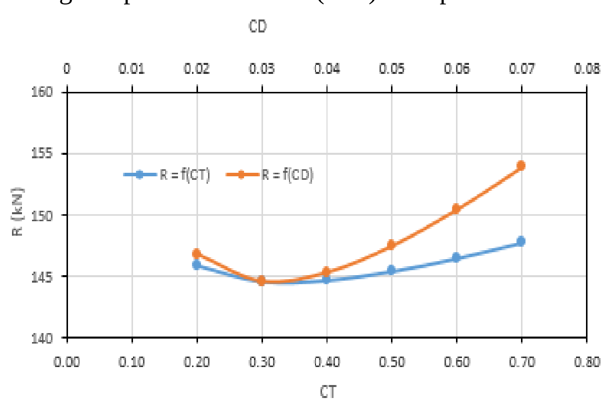

Fig. 12. Graphs of relationships between the hydrodynamic parameters with resistance and trim angle

Graph of relationship C_T = f (R) in Figure 12 shows that the optimal value of static loading coefficient $(C_T)_{opt}$ = 0.35, corresponding to B = 8.23 m, R = 145.7 kN, τ = 3.48 degrees. Similarly, the optimal value of dynamic loading coefficient $(C_D)_{opt}$ = 0.032 corresponding to B = 8.26 m, R = 145.5 kN, and τ = 3.49 degrees are very close to the above case.

C. Study on the effects of changing deadrise angle on the resistance and trim angle

The deadrise angle has complex effects on hydrodynamic performances in general and the resistance in particular [1]. Since it is also one of the inputs of the Savitsky method, so its effects are determined similarity to the above parameters. Fig. 13 shows the graphs of the relationships between resistance and trim angle with a deadrise of the computation planing hull, which are determined using the Savitsky method.

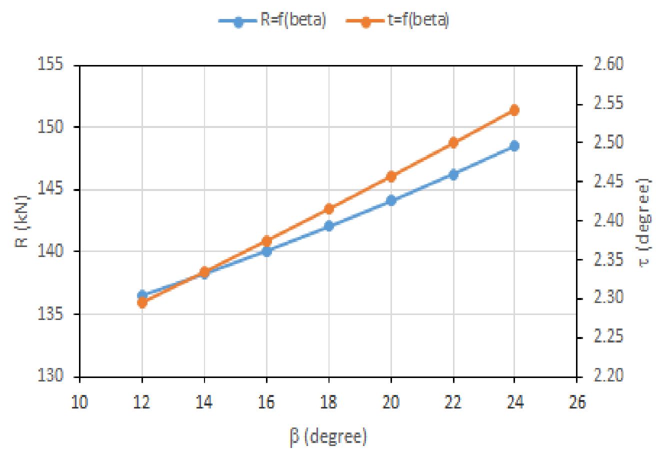

Fig. 13. Graphs of the relationships between resistance (R) and trim angle (τ) with deadrise angle (β)

In theory and practice, the planing hulls with a low deadrise move smoothly in the calm water but are easy to impact with opposite waves when moving in rough water (slamming). So decreasing the deadrise angle will reduce the resistance rapidly at first, but to a certain value, the resistance will increase again due to the slamming phenomenon, as stated. Thus, the obtained results in Fig. 13 are completely incorrect. The reason is that a change in the deadrise angle will cause a large change in the hull lines, so the effects of this change on the hull hydrodynamic performances are much more complex and different than when it is only an independent parameter in the known computation procedure of the Savitsky method. This problem can be solved by the CFD method, which is often used to predict ship performances based on the 3D hull model. Similar to solving a conventional CFD problem, in our study, the effect of changing deadrise on planing hull resistance is determined according to the following steps:

- Use Rhino, a popular modeling software, to generate a 3D model of the computation planing hull, as shown in Fig.14.

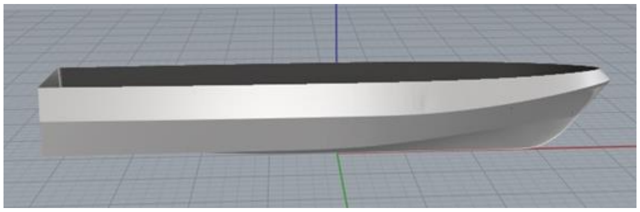

Fig.14. 3D hull model of computation planing hull in Rhino software

- Use the tools of Rhino software to generate a 3D model of the computation planing hull at different deadrise angles, as shown in Fig.15. This step was detailed in our study [29].

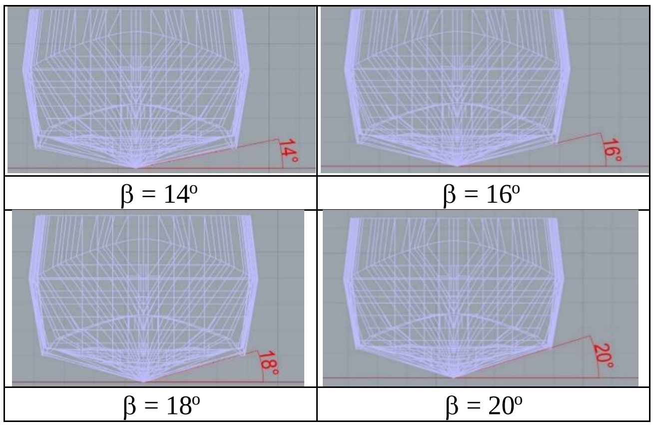

Fig. 15. The body plan of computation planing hull in some deadrise angle cases

- Use the XFlow CFD software with the appropriate input parameters, which are determined according to our method to predict the resistance of the computation planing hull.

Table 9 shows the resistance values (R) corresponds to the change of the deadrise angle (β).

Table 9. Resistance values change with the deadrise angle

β (degree)	12	14	16	18	20	22	24	26
R (kN)	148.92	146.78	142.54	142.07	144.29	146.63	149.12	151.75

Fig.16 shows a graph of the relationship between deadrise angle and resistance of the computation planing hull at a speed of 25 knots.

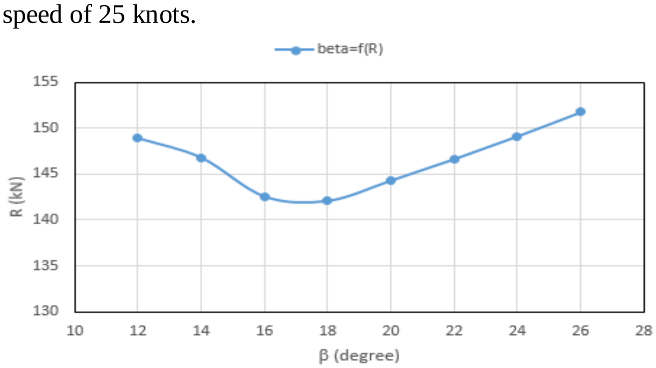

Fig. 16. Graph of the relationships between resistance (R) and deadrise angle (τ)

The good agreement of this result with theory and practice proves the correctness and reliability of our proposed method. In addition, it also shows that the optimal value of the deadrise angle of the computation planing hull is about 17 degrees, corresponding to the minimum resistance value R_{min}= 141 kN. It also should be noted that the change of deadrise angle will have a great effect on the change in the equilibrium trim angle. This is very important to avoid the porpoising phenomenon.

IV. CONCLUSIONS

Our study in this paper has provided an approach, which is based on our research results of accurate resistance prediction by Savitsky method and CFD tools, to analyze and evaluate a design for improving the performances of the planing hulls. This will assist the designer in reviewing and adjust the design before building for achieving the desired hull performances. The study has also been applied to the SESCO K88 vessel. Comparing with the initial hull parameters B = 6.81 m, LCG = 15.81 m, and model testing data R = 150 kN, τ = 2.5 degrees, the corresponding results are obtained as shown in Table 10.

Table 10. Options of changing hull parameters of planning hull design

No.	Parameter		Proposed values				
			B (m)	LCG (m)	β (deg.)	τ (deg.)	R (kN)
1	L/B		8.37	15.81	22.39	3.48	144.3
2	LCG/B	B = const	6.81	18.50	22.39	2.67	140.0
3		LCG = const	8.30	15.81	22.39	3.48	145.8
4	L/LCG		6.81	18.65	22.39	3.00	138.0
5	C_T		8.23	15.81	22.39	3.48	145.8
6	C_D		8.26	15.81	22.39	3.48	145.5
7	β		6.81	15.81	17.00	2.50	141.0

Depending on the case, the initial planning hull design can be improved by shifting the center of gravity toward the bow, increasing the waterline breadth, or decreasing the deadrise. In all cases, the resistance of the planing hull is reduced, with the maximum is about 9% and the minimum is about 3%. Importantly, however, increasing the breadth or decreasing the deadrise angle reduced the trim angle to within (3 ÷ 4) degrees compared to the deadrise 2.5 degrees of the initial hull planing. This has a good effect on the porpoising stability and ability to run on waves of planing hull, and trim angle of (3÷4) degrees is also the best value as recommended by the Savitsky method. In addition, some conclusions can be drawn as follows:

- The method can be applied to general cases because all hull parameters affecting planing hull resistance are selected in the form of non-dimensional coefficients.
- The analysis of the effect of only the change of each parameter on the resistance can be incomplete because there is always a mutual relationship between the parameters. However, it can be found that all computation cases converge to an optimal hull resistance value of

approximately 140 kN. This has demonstrated the well-suited suitability of our proposed modified Savitsky method in particular and the approach for evaluating the planning hull design in general.

- The good agreement between the achieved research results with the practice and theory of planning hull has validated the accuracy and reliability of our proposed method in general and the modified procedure of the Savitsky method in particular. This research can be applied in practice production to verify the planning hull design before construction to avoid similar problems occurring with the computation planing hull.

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