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Effect of Deadrise Angle on Wet Surface and Hydrodynamic Parameters of Planning Vessel by Experimental and Numerical Methods

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Abstract: Today, with the expansion of maritime trade and the need to use high speed in vessels, the analysis of this type of vessel is of particular importance. In this research, using numerical and Experimental methods, the effect of deadrise angle of vessel on hydrodynamic parameters is investigated. The experimental method has been used as an accurate and tested method for estimating hydrodynamic parameters. But in the case of planing vessels, determining the wet surface of the vessel is not easy. For this purpose, numerical method has been used to determine the wet surface of the planing vessel in this research. First, the experimental results of the current research are compared with the laboratory results of David Taylor, and then, the numerical results are validated with the experimental results. By validating the numerical and experimental results, the floating wet surface is calculated and finally the hydrodynamic dimensionless coefficients are calculated for each deadrise angle. Comparison of laboratory results of the present study with the laboratory results of David Taylor shows the recording of very good results in the laboratory. Also, the comparison of numerical and experimental results in this study, which is less than 10%, shows the high accuracy of numerical results. Finally, by comparing the percentage of wet surface increase in the two deadrise angles, it is concluded that at the speed of 5.71, there is a nearly 20% increase in the wet surface at the deadrise angle of 25 compared to the deadrise angle of 20°. Also, by comparing the coefficients of total resistance, at the speed of 5.71 m/s, the coefficient of total resistance of the boat with deadrise angle 20º, is %15 more than 25º.

Keywords: Dead rise angle, Model test, Planing model, CFD.

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1. Introduction

Humans have always been seeking for different ways to speed up their pace of lives. In the maritime industry, because of the high volume of sea transportation, increasing the speed of transportation has become significant issue. Ship owners can gain more by increasing their cargo speed and mobility. (The faster the cargo transportation, the richer the ship owners will become.)

But the speed growth can cause many problems such as increase in trim angle, resistance force, and the longitudinal and transverse instabilities. Therefore, designers should be able to design the most appropriate vessels by choosing (improving) the most effective design parameters.

In high-speed vessels, these parameters include Aspect Ratio, longitudinal center of gravity, deadrise angle, etc., each having their own effects. To this end, several methods have been used to investigate these parameters. One of these methods is model test in the towing tank that by generalizing the results to the main vessel, can observe the influence of important design parameters on the hydrodynamic behavior of the vessel. Also, the use of numerical methods such as computational fluid dynamics (CFD), which are widely used today, causes time and cost reduction in test process. There are some of the numerical and Experimental work done in the high-speed planing vessels below.

To determine the resistance of planing boats; different experimental, empirical (i.e., regression analysis), and numerical methods have been proposed. In this regard, Savitsky introduced a regressive method for establishing the resistance of a prismatic body [1]; which has remained as a simple, reliable, and popular solution to this date. Blunt and Fox [2], Savitsky and Brown [3], and Savitsky and Couble[4] correspondingly enhanced the given method. The original method used by Savitsky was based on regression analysis of a massive amount of empirical data. Therefore, a number of equations were proposed to calculate lift, resistance, center of pressure, trim, water contact, wet chine length, and keel which ultimately led to the body resistance. Besides, Savitsky modified his originally proposed method based on the drag caused by spray and aerodynamics, since the original method developed by Savitsky only consisted of resistance induced by viscosity and pressure [5].

Matcalf et al [6] and Coalishin and Matcalf [7] also published the results of a resistance test on a 47-foot model for the US Coast Guard. The series included the main model 5628 as an MLB body and two other models (5629 and 5630) with different length-width ratios along with another model (5631) with a different deadrise angle transom. The models had equal left-view chine lengths (LP) and centers of planing (AP). Resistance tests had been also conducted for a displacement weight between 298-680 Ibs and a longitudinal center of gravity at 38-42% of the lengths of both perpendicular lines and a transverse Froude number between 1 and 6.

As well, Tanton et al [8] tested four monohedral bodies with different length-width ratios and a constant deadrise angle of 22.5 degrees. The volumetric Froude number was 2.71-8.02 in all tests. They further obtained some data about sea-keeping performance abilities in rough water.

Begovich et al [9] similarly tested a body with a longitudinally-constant deadrise angles in addition to three other bodies with longitudinally-variable ones. Accordingly, they examined the effect of longitudinally-variable deadrise angles on resistance and sea-keeping performance of a planing boat.

One of the best methods for hydrodynamic assessment of planing hulls is CFD. Nowadays, the commercial CFD software can produce acceptable and well-converged results to analyze naval ships and high-speed planing boats.

In this regard, Masumi and Nikseresht [10] simulated two-dimensional (2D) motions of high-speed planing boats in waves.

Dustdar and Kazemi [11] also used CFD method to investigate hydrodynamic assessment parameters for high-speed planing hulls. To this end, they utilized dynamic mesh method in commercial Star-CCM+ software.

Najafi et al. [12] also shed light on stepped planing hull and calculated trim, rise up, resistance, and wetted surface. They correspondingly assessed the effect of number and position of these steps on hydrodynamics of stepped planing hull.

As well; Najafi and Nowruzi [13] calculated trim, sinkage resistance, and wetted surface using CFD method and compared the data with experimental results, which were well-converged and acceptable.

As noted, nowadays, with the increasing speed of maritime transportation and facing the need of increase in speed of vessels, designers have decided to design vessels with new body shapes. In designing high-speed vessels, many parameters such as longitudinal center of gravity, deadrise angle, mass inertia moment, mass, initial trim angle, and so on are among the effective parameters in designing rigid vessels.

As mentioned, the deadrise angle is one of the most important parameters of a high-speed planing vessel's design. For this purpose, in this research, two Fridsma vessels with angles of 20 and 25 degrees will be tested. Other design parameters including length, width, center of gravity, longitudinal center of gravity and moment of inertia of the pitch motion are considered. The results of the 20 deadrise angle test were compared and validated with Davidson's laboratory results. Hydrodynamic parameters including Rise up, Trim and Resistance have been calculated by model testing in the Persian Gulf National Laboratory towing tank (NIMALA). Due to the cost of model construction and laboratory testing, the numerical method has been used along with the model test method to calculate the hydrodynamic parameters and the wetted surface of the vessels. Comparison of the numerical and laboratory results indicates that the numerical results are acceptable. Numerical modeling has been used with the StarCM software [14].

2. Specifications of NIMALA towing tank

All of the tests of two Fridsma model with deadrise angles of 20 and 25 have run in NIMALA towing tank that specification of the NIMALA towing tank have shown in Table 1.

Table 1 specification of NIMALA towing tank

Parameter	Unit	Value
Length	[m]	402
Breadth	[m]	6
Depth	[m]	4
Maximum velocity of tow	$[{}^{m}/_{s}]$	19

3. The Model description

As mentioned, the model used in this paper is a (Fridsma 1969) prismatic model whose body shape is designed based on the equation shown in Fig. 1. Main parameter of 2 models (20^{o} and 25^{o} deadrise angles) have shown in Table 2.

Table 2 Main parameter of model

Parameter	unit	value
Overall length	m	1.5
Breadth	m	0.3
L/B	-	5
Draft at Aft	m	0.0942
Displacement	N	161.374
Displacement coefficient	-	0.608
Longitudinal center of gravity	m	0.974
Vertical center of gravity	m	0.0882
Trim	deg	2.2
breadth Froude number	-	0.664-3.992
Volumetric Froude number	-	0.722 – 4.338
Dead rise angle	deg	20,25

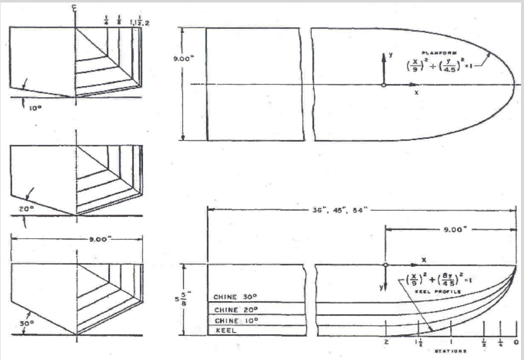


Fig. 1 Fridsma body line equation [15]

Fig. 2 Fridsma (a) 20 and (b) 25 deg model at 4.56 m/s

4. Resistance Equations

The wetted surface of the body of the planing boat could be divided into two parts: the first part (pressure surface) was bounded to wet chine length, wet keel length, and stagnation line. The hydrodynamic equations for lift, resistance, and pressure center were also defined for this surface. The second part was the spray surface, located in front of the stagnation line (Figure 3).

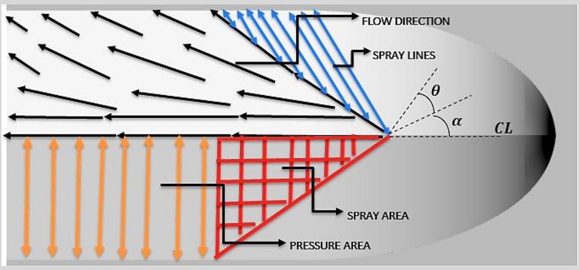


Fig. 3 Wetted surface zone [15]

The total resistance of the planing boat is given by the following equation [1]:

$$R_T = R_P + R_F + R_{Spray} \tag{1}$$

Where R_T is total resistance, R_P is pressure resistance, R_F is frictional resistance, R_{Spray} is spray resistance [1].

$$R_P = \Delta tan\tau \tag{2}$$

Where Δ is boat weight, τ is boat trim angle in degrees.

$$R_F = \rho C_F B^2 V^2 \lambda \,/ 2\, cos\tau \; cos\beta \tag{3}$$

Where ρ is water density, C_F is frictional resistance coefficient, B is boat width (beam), V is average water speed at the boat bottom, λ is mean wet length-width ratio and β is dead rise angle and τ is boat trim angle in degrees.

$$F_{Br} = \frac{VB}{\vartheta} \tag{4}$$

Where V is boat Speed, B is boat width and υ is kinematic viscosity.

5. Validation of Experimental results with Davidson Laboratory

In order to validate the experimental results of the present study and to ensure accurate recording of the results, the results of the Friedsma body strength test with a deadrise angle of 20º in were compared with the experimental results of David Taylor. The results of this comparison and the percentage of computational error are presented in Table 3.

Table 3 Comparison results of NIMALA with Davidson towing tank and Difference between them

NIMALA resistance(kgf)	Davidson resistance(kgf)	Difference (%)
0.115	0.11	4.54
0.129	0.13	0.8
0.152	0.15	1.33
0.172	0.17	1.17

As shown in Table 3, the experimental resistance test results of the present study are in agreement with the Fridsma experimental results for the Fridsma prismatic floating-point model with a 20-degree angle, with high accuracy.

6 Experimental Results of 20 and 25 deadrise angle Fridsma models

Both models developed based on Fridsma's work; with a length of 1.5 meters and deadrise angles of 20 and 25 degrees were tested in terms of resistance, trim, and rise up at different speeds (Tables ۴ and 5). Frb means breadth Froude number.

Table 4 Test results of 20º dead rise angle model

V (m/s)	F_{rB}	Trim (deg)	rise up (mm)	R (kgf)
0	0	2.20	0	0
1.14	0.66	2.40	-2.51	0.473
2.28	1.33	4.88	-6.24	1.885
3.42	1.99	5.37	6.89	2.118
4.56	2.66	6.09	24.31	2.491
5.71	3.33	5.43	36.03	2.819

Table 5 Test Results of 25º dead rise angle model

V (m/s)	F_{rB}	Trim (deg)	rise up (mm)	R (kgf)
0	0	2.28	0	0
1.14	0.66	2.52	-2.69	0.492
2.28	1.33	4.90	-3.20	1.920
3.42	1.99	5.17	9.87	2.125
4.56	2.66	5.83	24.64	2.540
5.71	3.33	5.28	35.38	2.840

According to Tables 4 and 5, which represent the trim angle, Rise up and the resistance of the two Fridsma models with deadrise angles of 20 and 25, increasing the deadrise angle decreases the trim angle. This is also due to the fact that with the change of the deadrise angle, the angle of impact of the flow and the hydrodynamic force on the float floor were changed and consequently the angle of float trim (no "is changed" needed).

Also, according to Tables 4 and 5, increasing deadrise angle in some cases decreases the Rise up and, in some cases, increases it. This is due to the changes in buoyancy force and hydrodynamic forces with the deadrise angle changing and its wet surface area.

Based on the results of Tables 4 and 5, it can be concluded that increasing the deadrise angle increases the resistance. The reason is also clear, because by increasing deadrise angle, the wet surface of the vessel increased by draft immersion development. Mostly, by changing the angle of the attack plate to the water flow, the vector along resistance will become more.

7. CFD Results

Calculating wetted surfaces in experimental methods is very difficult. So, one of the best methods is to use CFD. For this purpose; firstly, CFD results need to be validated with experimental ones. Then, the results of wetted surface should be introduced. In this study, Reynolds-averaged Navier-Stokes (RANS) equations were utilized to simulate the fluid current. The volume of fluid (VOF) method was also employed for simulating free surface. Moreover, degree fluid body interaction (DFBI) equations were further used to solve rise up and pitch motions. In this simulation, overset technique was utilized to make the simulated motions better. Figure 4 shows domain region, overset region, and boundary conditions.

Also Figure 5 shows mesh grid on free surface and side view.

The number of mesh grids is 3200000 and the time step to solve the problems is 0.01 s.

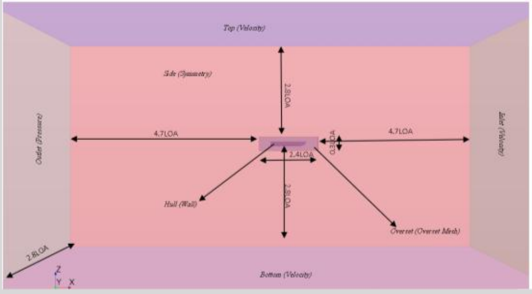


Fig. 4 Domain and Overset region and boundary conditions

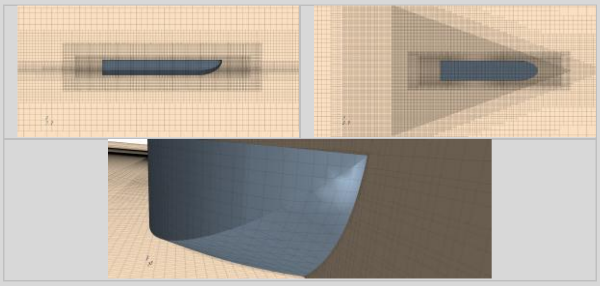


Fig. 5 Grid mesh in different view

The first results of deadrise angle of 20-degree model are presented in Figure 6.

a

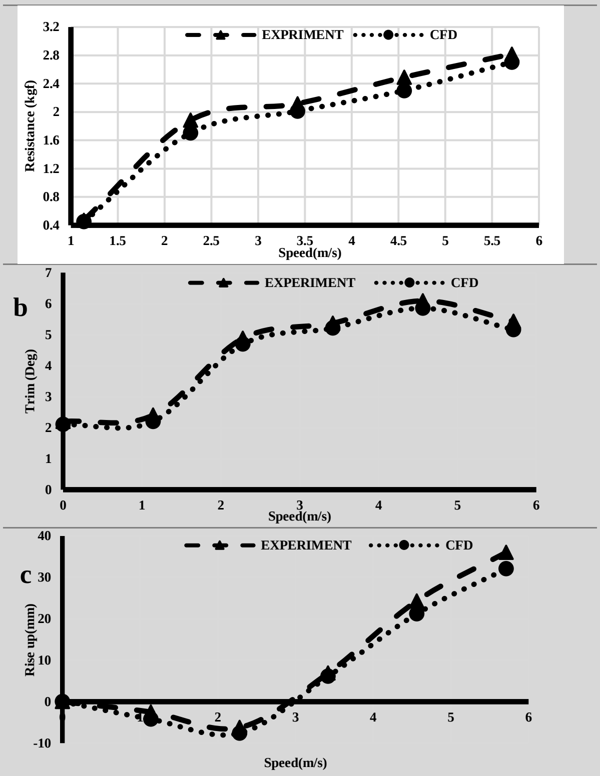
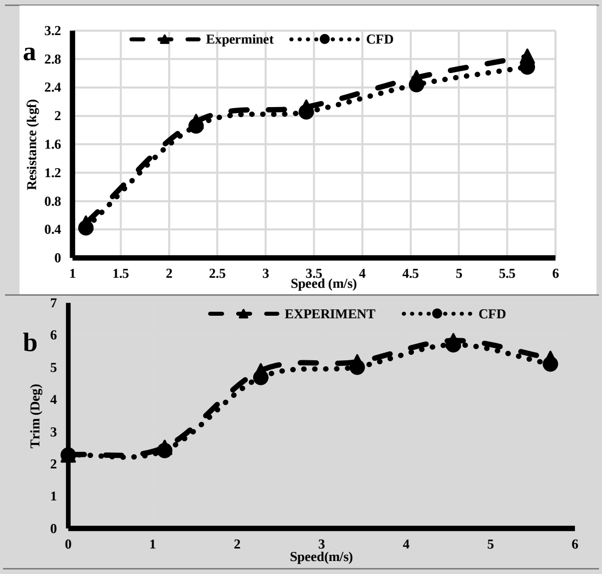


Fig. 6 comparison of experiment a) Resistance b) Trim c) Rise-up result by CFD results for dead rise 25° model

In Figure 6, horizontal axis shows forward speed of the planing boat and vertical axis represents resistance. As observed, resistance results of CFD are well-converged compared with experimental data. Difference between CFD and experimental results in the best and the worst cases is 5% and 9.5%; respectively the results of CFD test of the 25-degree deadrise angle of the model are introduced as follows.



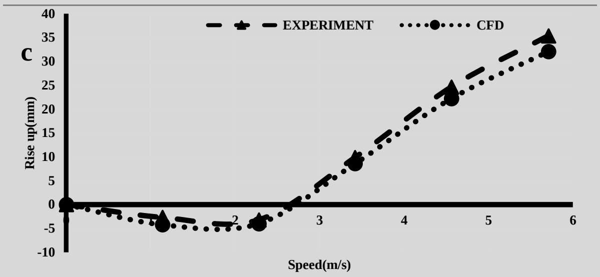


Fig. 7 comparison of experiment a) Resistance b) Trim c) Rise-up result by CFD results for dead rise 25° model

As observed in Figure 7, the CFD results of the 25-degree deadrise angle of the model are acceptable and well-converged compared with experimental data;

At the end, the most important CFD results are illustrated in Figures 6 and 7. The hull results of the wetted surface for deadrise of 20 and 25 are presented in Table 6.

Table 6 comparison wetted surface for 20 and 25 deadrise angle models

Speed ($^{m}/_{s}$)	Wetted surface for deadrise20(m^2)	Wetted surface for deadrise25(m^2)
1.41	0.41	0.4248
2.28	0.33	0.3445
3.42	0.1557	0.1661
4.56	0.08629	0.09634
5.71	0.06741	0.08039

As presented in Table 5, the wetted surface for higher deadrise angle is always more than that of lower one.

Figure 8 compares the percentage increase of wet surface area at different speeds between two deadrise angles of 20° and 25°.

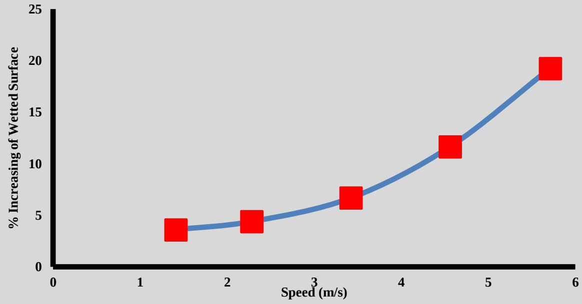


Fig. 8 Percent of Increasing Wetted surface vs Speed for 25° in comparing 20° deadrise angle.

As explained in Figure 3 about the different components of the resistance force, in the figure8 the distribution of the water flow on the body can be well observed, showing well the various areas that generate resistance.

Speed	20°	25°

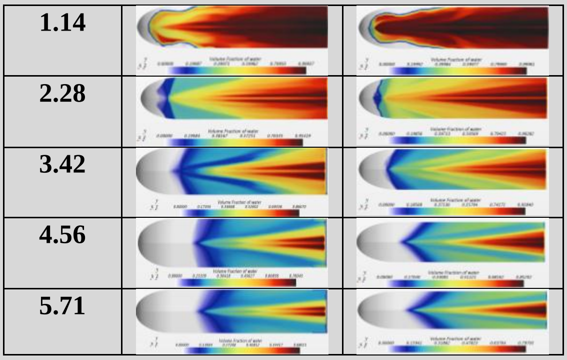


Fig. 9 Contour of volume fraction of water in 1.14m/s, 2.28 m/s, 3.42 m/s 4.56 m/s 5.71 m/s Speeds for dead rise 20, 25 models

As shown in the figure9 this theory that increasing the deadrise angle increases the wetted surface area and thereby increases the resistance force is well established. Because increase in deadrise angle can cause more pressure resistance. Because the bottom area is floating more in water flow. Figure 8 Shows the pressure dynamic of 20° and 25° deadrise angle models.

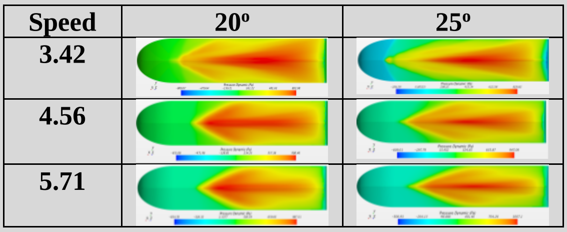


Fig. 10 Pressure Dynamic in, 3.42 m/s 4.56 m/s 5.71 m/s Speeds for dead rise 20, 25 models

Figure10 which shows the dynamic pressure distribution of the bottom of the two vessels, indicates that increasing the deadrise angle decreases the trim angle. As by increasing deadrise angle, the center of hydrodynamic forces occurs in an area closer to the center of gravity, so the trim angle of the vessel decreases. By comparing the maximum hydrodynamic pressure on the body, it is also proven that by increasing deadrise angle, the dynamic pressure increases and thus the resistance force increases.

In order for the results to be generalizable to the real boat, it is necessary to calculate the total resistance coefficient, which is calculated in the Table ۷ these coefficients.

Table 7 Total Resistance Coefficients in Different speed for deadrise angle 20° and 25°

Speed (m/s)	C_T for deadrise 20°	C_T for deadrise 25°
1.41	0.011407948	0.011452778
2.28	0.02160211	0.021077096
3.42	0.022864073	0.021503322
4.56	0.027293048	0.024926761
5.71	0.025215466	0.021301616

As can be seen in Table ۷, the total resistance coefficient of a vessel with a deadrise angle of 20 ° is higher than a vessel with a deadrise angle of 25 ° in all speed except 1.41. At the speed of 2.28 m/s, %2.43, at 3.42 m/s %5.95, at 4.56 m/s %8.67, and at 5.71 m/s %15.52, the total resistance coefficient has increased.

8. Conclusion

The effect of dead rise angle on some hydrodynamic parameters is as follows, these results can be used by designers in high speed and stable planing boat designing procedure:

- Calculating the wetted surface of the hull through CFD simulation clear that the wetted surface had increased as the dead rise angle had been enlarged.
- Increasing deadrise angle increases resistance and rise up, especially after reaching the planing regime. The main reason for the increase in resistance force is due to the increase in static and dynamic wetted surface of the body with increasing angle at the same weight.
- Increasing deadrise angle decreases dynamic trim angle that is the basis for long-term instability (porpoising).
- , the total resistance coefficient of a vessel with a deadrise angle of 20 ° is higher than a vessel with a deadrise angle of 25 ° in all speed except 1.41. At the speed of 2.28 m/s, %2.43, at 3.42 m/s %5.95, at 4.56 m/s %8.67, and at 5.71 m/s %15.52, the total resistance coefficient has increased.
- The ratio of the vessel wetted surface with the deadrise angle of 25° is higher compared to 20° at similar speeds. This increase reaches about 20% at a speed of 5.71.

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