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CFD Based Analysis of Resistance and Pitch Motion of Novel Flat Plate Panel Hull Vessel

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Abstract

This paper provides analysis regarding a phenomenal hull shape called the flat panel concept, the flat panel hull is an axe bow vessel at the front part and semi trimaran at the stern part. This concept is for small vessels such as fishing vessels, patrol vessels and prototypes have been built. Resistance and motion are an important part of a vessel design, this paper compares a flat plate vessel with 282.56 ton displacement with a conventional vessel with the same displacement and same speed. The resistance comparison was conducted using Computational Fluid Dynamics (CFD) on each ship with a speed range of 5-10 knots of operational speed. The resistance shows that the flat panel vessel generates higher resistance compared to the conventional vessel where the difference varies from 8.388% to 19.954% depending on the speed. It also found that the pitch motion (Ry) of the flat panel vessel is positive which indicates the bow draft is lower during the simulation in calm water. The highest value of pitch is 1.13 degrees measured at the amidships or zero point or -0.3 m at the bow. These two While the relative velocity or flow analysis indicates that the flow of the flat panel vessel has enormous turbulence flow around the stern hull and a smoother flow pattern at the bow, this may cause the increase of resistance and bow diving in calm water phenomena. However since the most accurate test is based on a model test in a hydrodynamic laboratory, it is recommended to conduct the comparison experiment in a hydrodynamic laboratory.

1. Introduction

The emergence of a new hull concept especially for small vessels provides a wider spectrum of ship design. One of the latest concepts is the flat plate panel hull concept where the prototype has been built. The flat panel hull concept is a ship which flat on all sides and has an axe bow hull with a semi-trimaran design [1,2]. There are several advantages offered by the designer of a flat panel hull, the first advantage is able to break the sea waves so that the ship is more stable and wave flow toward the propeller at the rear is expected to help increase the trust of the ship. The second advantage offered is lower resistance compared to the conventional vessel, the third advantage is lower production cost and a more simple process compared to the conventional vessel production process [2-4].

The design of the flat panel can be shown in Fig. 1. It can be seen that the flat panel vessel has a unique hull design, it has similarity to an axe bow at the front and the lines of the hull evolve into semi trimaran shape in the aft section [5,6]. The new hull shape is proposed to be built in 3500 units for fishing vessels by the Ministry of marine and fisheries [6].

There are several advantages of flat panel vessels, the first advantage is the simple production process, and the second advantage is lower resistance compared to conventional vessels [7]. An experiment and simulation have been conducted by a previous researcher in 2017, compares the resistance of flat panels and conventional vessels and found that the resistance of flat panels resistance is higher compared to the conventional vessel. The model used in the analysis is shown in Table 1.

It can be seen from Fig. 2 that the left hull is a flat panel vessel adopting a trimaran shape at the stern section and axe bow, while the second hull is a flat panel without a trimaran shape at the stern and no axe shape at the bow

Besides numerical analysis, the previous research also conducted an experiment to measure the resistance of both vessels where the setup can be shown in Fig. 3 the experiment is set in a towing pool and uses a voltage sensor to measure the resistance and converted to newton force (N).

The results of the simulation based on the numerical resistance prediction show that the flat panel vessel shows a higher resistance value compared to the conventional vessel even though not mentioned the method used in the simulation. Based on Fig. 4, it can be concluded that the flat panel resistance is higher compared to the conventional vessel. While the design of the vessel can be shown in Fig. 1 The previous research uses two 3D models as shown in Fig. 2, the numerical model was built based on Maxsurf software.

Table 1. Principal Dimension Comparison

	Flat Plate	Conven	Unit
Displ	4	4	kg
LWL	90	90	cm
B	22.5	22.5	cm
T	7.8	5.3	cm
Cp	0.597	0.788	
Cb	0.305	0.489	

Figure 1. Flat Panel Vessel Prototype

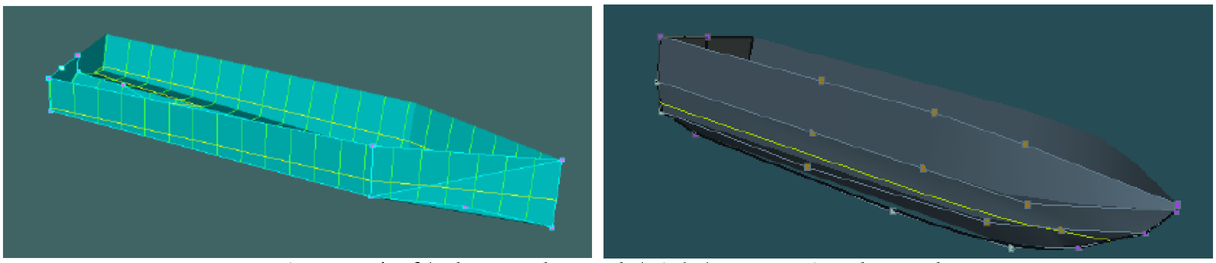
Figure 2. (Left) Flat Panel Vessel, (Right) Conventional Vessel

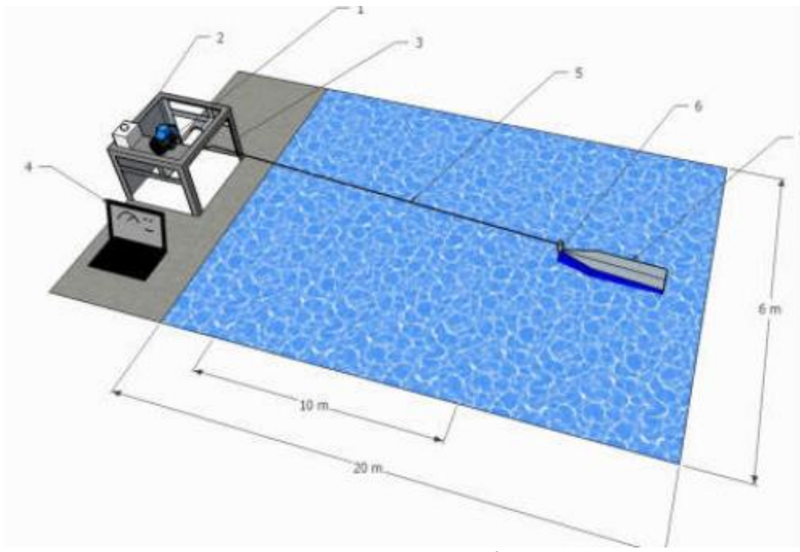

Figure 3. Experimental Setup

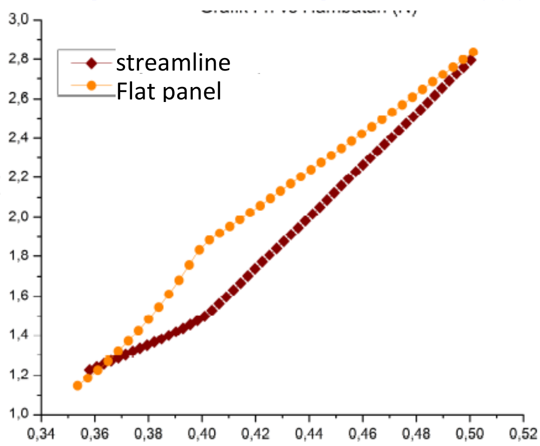

Figure 4. Resistance comparison based on simulation [7]

The previous paper also mentioned that the resistance experiment shows that the flat panel resistance is higher compared to the conventional panel as shown in Fig. 5. On contrary in several media, it is mentioned that the flat panel vessel provides better maneuvering and is more fuel-efficient compared to conventional vessels [8,9].

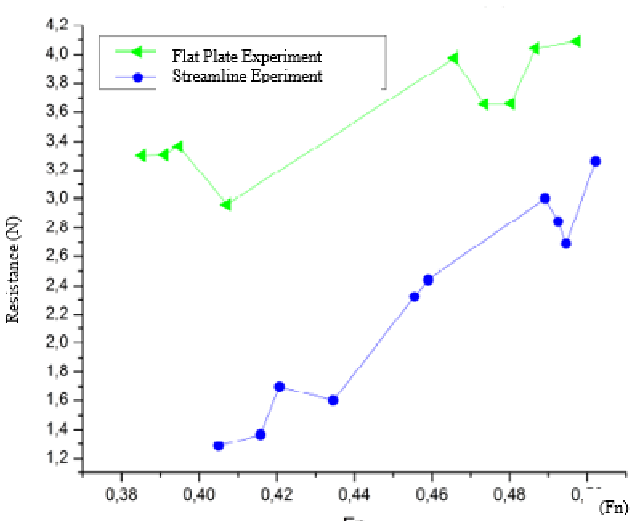

Figure 5. Previous Experimental Results

There is another concept of flat panel vessel, the concept is for passenger vessel servicing as a connector between islands in Indonesia with a size of 750DWT [10]. The paper analyses the resistance, stability, and motion of two variations of the flat panel compared to a conventional vessel hull. Fig. 6 shows the conventional hull shape.

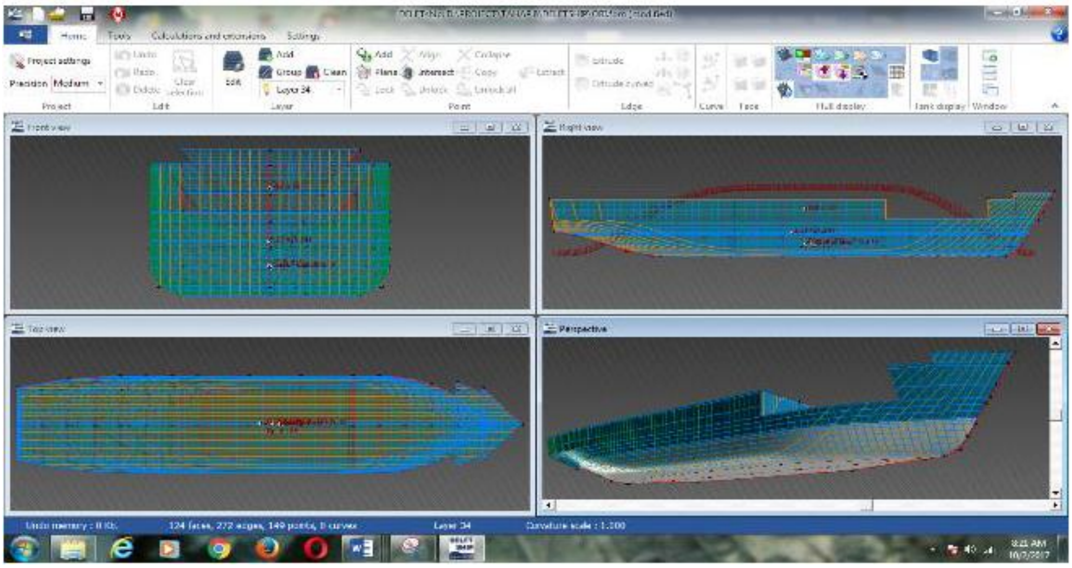

Figure 6. Conventional Vessel 750DWT

The principal dimension of the 750 DWT vessel is shown in Table 2, it is a twin-engine vessel designed to carry passenger and cargo at the front main deck where at least there are 5 units has been built.

Table 2 Principal Dimension Original 750 DWT

Length(LOA)	58.5	m
Breadth (B)	52.3	m
Height (H)	4.5	m
Draft (T)	2.9	m
Engine Power	2x829	HP
Endurance	3500	nm

While the first modification (ver. 1) can be shown in Fig. 7 where the bow is using an axe bow, and the second modification (ver.2) can be shown in Fig. 8. The modification is maintaining some parameters in order to be comparable to the original vessel, the draft is maintained at 2.9m, and the waterline length is maintained at around 54.4 m as shown in Table 3.

Table 3 Principal Dimension Comparison 750 DWT

	Ori	V-1	V-2	Unit
Displacement	1293	1233	1276	ton
Vol. displaced	1261.696	1203.213	1244.963	m3
Immersed depth	2.9	2.9	2.9	m
WL Length	54.492	54.393	54.419	m
Beam	12.198	11.708	11.721	m
Wetted Area	700.3	720.059	720.852	m2
Block coeff.	0.655	0.652	0.673	
Midship Coeff	0.951	0.867	0.915	
Trim (+ve by stern) m	0.048	0.034	0.037	m

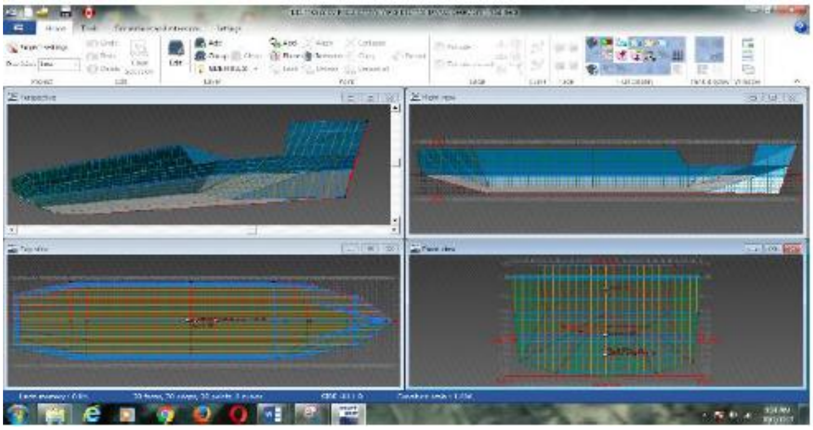

Figure 7. 1st modification concept of 750DWT (ver.1)

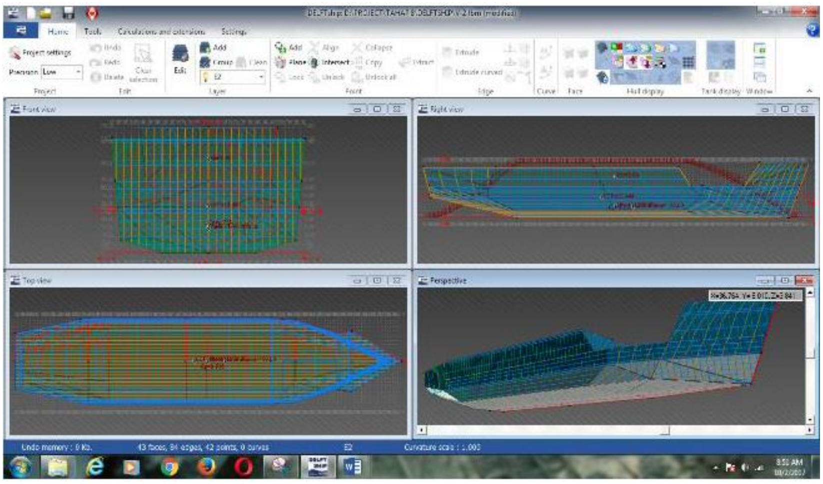

Figure 8. 2nd hull modification concept of 750DWT (ver.2)

In order to analyze all three vessels, a software is used where the software uses the Holtrop method to predict the resistance of the ship [11]. The Holtrop method is a resistance prediction based on a formula derived from statistical regression of the considerable resistance test data [12,13]. According to the formula, the total resistance of the ship is equal to the sum of frictional resistance considering the form factor of the hull ($R_{F(1+k)}$), appendage resistance (R_{APP}), wave resistance (R_W), the additional pressure resistance of bulbous bow near the water surface (RB), the additional pressure resistance of immersed transom stern (R_{TR}), and model-ship correlation resistance (R_A).

$$R_T = R_F(1+k) + R_{APP} + R_W + R_B + R_{TR} + R_A \quad (1)$$

The right-hand side of the equation has several components that can be explained as follows:
Frictional resistance (R_F)

$$R_F = \frac{1}{2}\rho C_F S_{BH} v^2 (N) \quad (2)$$

C_F is the frictional resistance coefficient based on ITTC 1957 [14], V is ship speed in m/s, S_{BH} is the wet surface area (m^2) and ρ is water density (ton/m^3)

$$C_F = \frac{0.075}{(Log_{10}Re - 2)^2} \quad (3)$$

Where Re is the Reynolds number

$$R_e = V.LWL/v \quad (4)$$

LWL is the length of the waterline, and v is kinematic viscosity, v= 1.13902×10^{-6} m^2/s for seawater (15°C), RV is the viscous resistance which can be described as 3D frictional resistance based on the form factor (1+k), The frictional resistance is 3-dimensionalized by the form factor ($1 + k_1$), which is expressed with the prismatic coefficient (CP), the prismatic coefficient based on the length at the waterline (LWL), and the length of the run (LR), as the following equation.

$$(1+k_1) = 0.93 + 0.487118.C_{14}\left(\frac{B}{LWL}\right)^{1.06806}.\left(\frac{T}{LWL}\right)^{0.46106}.\left(\frac{LWL}{LR}\right)^{0.121563}.\left(\frac{LWL^3}{\nabla}\right)^{0.36486}.(1-C_p)^{-0.6-247} \quad (5)$$

The complete resistance prediction method formula and procedure can be explored in [13,15].

The resistance analysis concluded that the original hull shape produces the lowest resistance compared to 1st or 2nd modification [10]. While the pitch motion analysis was conducted in three directions specifically 90° 135° and 180°, the analysis concluded that there is no significant difference between the three shapes of the hull as shown in Fig. 10 – 12 [10].

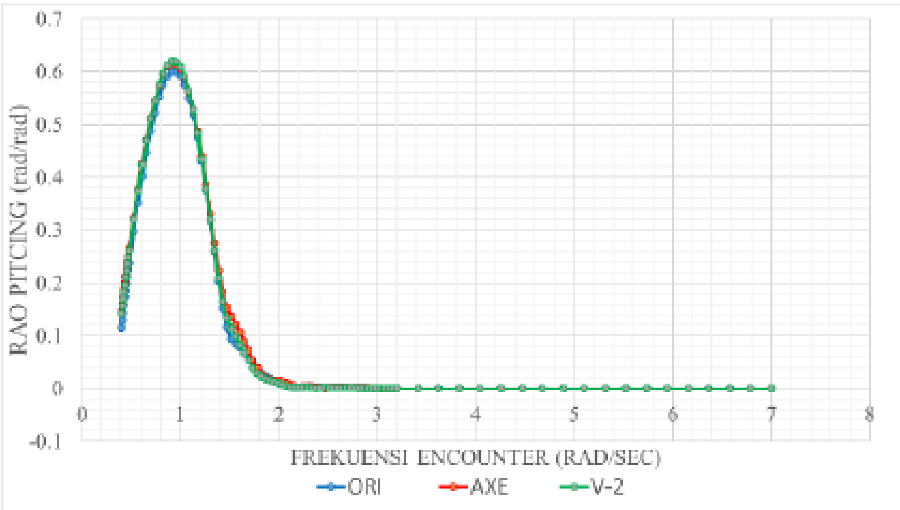

Figure 9. Comparison RAO of Pitching motion 90°

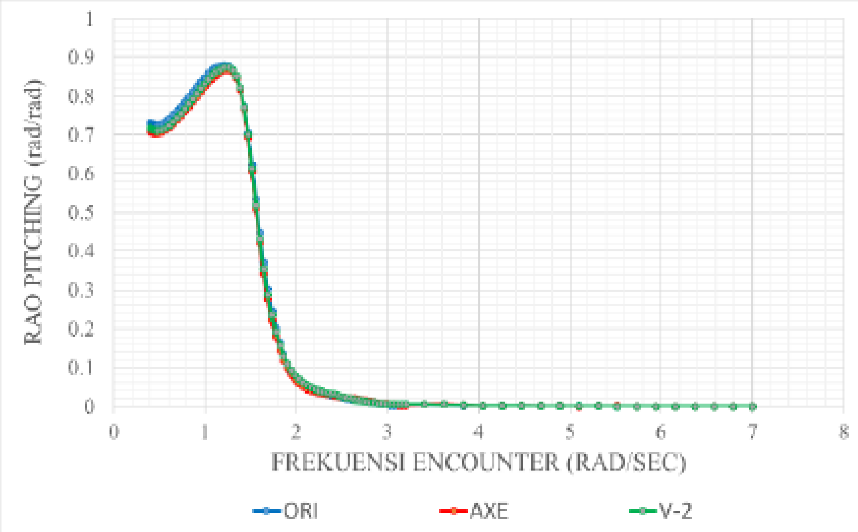

Figure 10. Comparison RAO of Pitching motion 135°

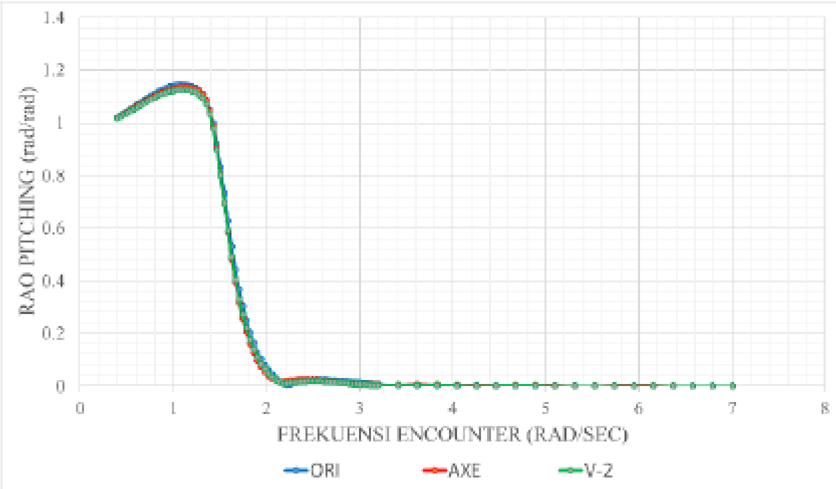

Figure 11. Comparison RAO of Pitching motion 180°

From several researches that have been published, it can be concluded that the resistance of flat panels is higher compared to conventional streamlined vessels. The first research is using an experiment that is not based on the standard towing tank ITTC as in a common hydrodynamic laboratory, and the method of simulation is not clearly mentioned. The second research is using the Holtrop-Mennen method to predict the resistance and uses Maxsurf software to predict the motion of the 750DWT vessel. Based on the previous research, there is still no publication found using CFD or standard towing tank ITTC for the prediction of resistance and motion. It is necessary to carry out a resistance and motion prediction using CFD as a comparison analysis regarding the flat panel vessel to confirm the previous findings.

This paper provides a comparison analysis of a flat panel vessel to the conventional vessel using the CFD method where the analysis includes resistance and pitch motion. This paper is comparing the resistance and motion of semi trimaran flat-panel vessels and conventional vessels with lengths around 30m using CFD which is a different vessel size from previous publications.

2. Methods

Computational Fluid Dynamic (CFD) has become a common method for resistance prediction method. The basic theoretical background of CFD begins with the potential flow. The steady potential flow assumption is made, and a velocity potential φ is introduced such that velocity $\varphi\nabla$=v. The fluid is assumed to be non-viscosity and incompressible. So that the continuity equation becomes $\nabla u = 0$, with u is velocity vector; and the vortices $\omega = \nabla$ u =0. For ship resistance, there is a function based on φ, so it can be written.

$$u = \nabla \phi \quad (6)$$

Where u is velocity vector, and ϕ is velocity potential function. The continuity equation can be rewritten using the Laplace equation [16]:

$$\nabla^2 \emptyset = 0 \quad (7)$$

$$\nabla^2(\frac{\partial \emptyset}{\partial t}+\frac{1}{2}\nabla\emptyset.\nabla\emptyset+\frac{p}{\rho}+gz)=0 \quad (8)$$

Where p is the pressure in the fluid, ρ is the fluid density, and g is the acceleration due to gravity. These governing equations are simply Laplace's equation and a form of Bernoulli's equation, respectively. After spatial integration and a simple redefinition of the potential for the elimination of any arbitrary integration terms the equation can be rewritten.

$$\frac{\partial \emptyset}{\partial t}+\frac{1}{2}\nabla\emptyset.\nabla\emptyset+\frac{p-p_a}{\rho}+gz=0 \quad (9)$$

The potential function can be solved by using a known boundary condition. Once □ is determined, the pressure p in the flow can also be found by solving the Bernoulli equation [17]

$$\frac{1}{2}\rho|\nabla\emptyset|^2+p=\text{Const} \quad (10)$$

2.1. Panel Method Ship Resistance Prediction

In case of ship resistance, the surface of the ship will be divided into small n panels and the total resistance will be obtained by integrating all the individual panels. The velocity potential is solved and also the flow field u is solved by the relationship

$$u=\frac{\partial \emptyset}{\partial n} \quad (11)$$

The total resistance for each panel is summarised from friction resistance (Rv)and wave resistance (Rw). The assumption developed for the calculation are non-viscosity and irrational fluid, the wave breaking resistance is neglected [18].

The hull is considered a surface with constant speed in calm water. The equation can be expressed $\Delta\emptyset = 0$ in a domain of fluid D, so the Laplace equation can be written as follows.

$$\left[\frac{\partial \emptyset}{\partial n}\right]_c=[\vec{V_0}\,\vec{n}]_c \quad (12)$$

Where the ship hull is assumed slip condition (C),

$$\frac{\partial \eta}{\partial t}+\vec{v}.\overrightarrow{\text{grad}\eta}=\frac{\partial \emptyset}{\partial z}|z_{=n} \quad (13)$$

The kinematic boundary at the surface is:

$$\eta=-\frac{1}{g}\left[\frac{\vec{v}^2}{2}+\frac{\partial \emptyset}{\partial t}\right]_{z=n} \quad (14)$$

The dynamic boundary at the surface is φ →0 at radiation conditions. The complete equation and derivation can be found in [17,18].

2.2. Principal Dimension and Design

In order to provide an equal comparison of both vessels, the displacement, Draft, Block coefficient (Cb), and breadth (B) of both vessel is equal as shown in Table 4.

Table 4. Principal Dimension Comparison

	Flat Plate	Conven	Unit
Displ	289.5	289.6	ton
LWL	31	33.25	m
B	7.9	7.82	m
T	3	3	m
Cp	0.705	0.663	
Cb	0.384	0.388	

The 3D design of the hull is generated in a computer model and incorporated into a Numeca CFD software where the design can be shown in Fig. 13.

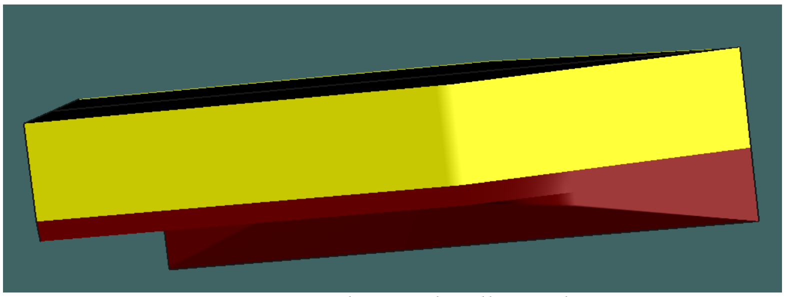

Figure 12. Flat Panel Hull Vessel

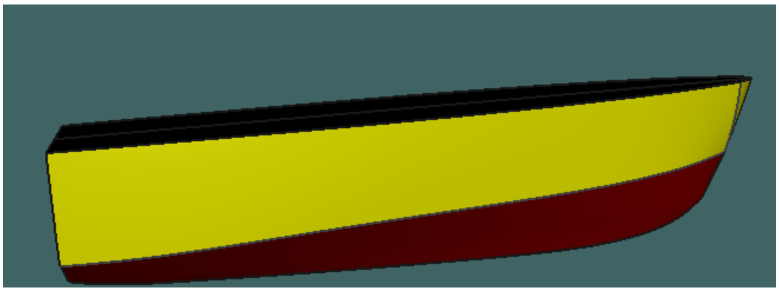

Figure 13. Conventional Hull Vessel

2.3. Resistance Prediction

The resistance prediction was measured using CFD where both are using the same speed variation ranging from 5 knots to 10 knots. The domain setup in CFD is based on the ITTC recommendation [19] and Krisso container ship (KCS) CFD setup which has been verified by experiment [20]. The domain setup of this paper is shown in Table V while the 3D domain setup is shown in Table 5.

Table 5. Domain Setup

Upstream to the Hull	2Lpp
Downstream to the hull	5Lpp
Tank wall to the midsection	3Lpp
The height of the top surface from the waterline	0.4Lpp

Meshing is a discretization of the body surface into small quadrilaterals that led to the designation of panel methods [21]. Each element in CFD must satisfy some parameters. The parameters are negative cell, concave and twisted cell. In a single cell as part of a complex system, mapping between the physical coordinate (x – y) and the natural coordinate (ξ – η) for heavily volumetrically distorted elements leads to a mapping of an area outside of the physical elements into an interior area in the natural coordinates as shown in Fig. 15 Fluid is volumetric, volumetric element distortion occurred in concave element. For concave elements, there are areas outside the elements which will be transformed into a coordinate system, this concave element volume integration will result in a negative value [22].

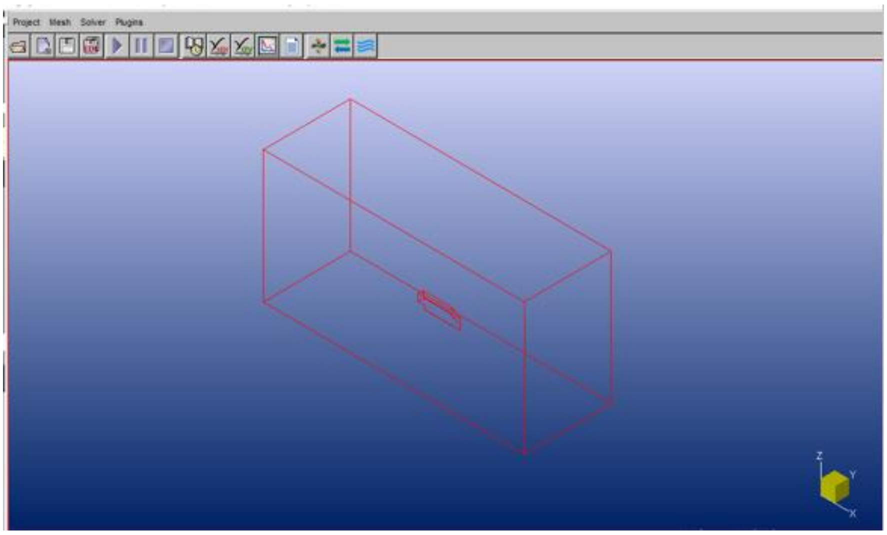

Figure 14 . Domain setup

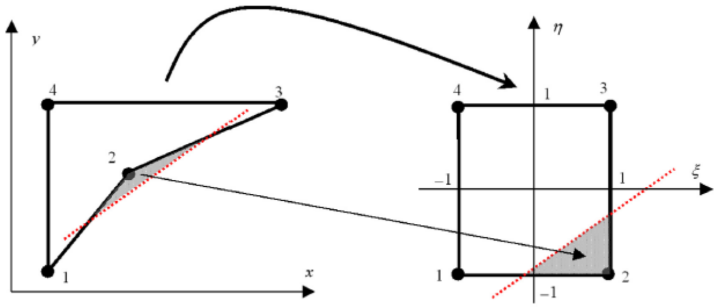

Figure 15. Cell Mapping

For both models of the conventional and flat panel after several times of meshing iterations and refinements, the meshing quality has satisfied the zero concave, negative cell, and twisted cells as shown in Table 6 While the number of cells and vertices can be shown in Table 7.

Table 6. Meshing Cell Quality Check

Parameter	Flat Plate	Conven
Concave	0	0
Negative Cell	0	0
Twisted	0	0

Table 7. Number of cells and vertices

	Flat Plate	Conven
Total cells	4,194,160	4,453,538
Total Vertices	4,425,448	4,690,360

To create equal resistance comparison for both vessels, the CFD test is conducted using the same speed variation which started from 5 to 10 knots.

3. Results And Discussion

There are three results of the simulation discussed in this paper, the first result is resistance and the other one is the pitch motion also the wave elevation generated by the hull. The results are still based on CFD and to capture the real value and motion of the vessel requires a model test in Hydrodynamic Laboratory based on ITTC Standard model testing.

3.1. Resistance Results

The first result of the simulation is resistance, The Table 8 shows that the flat panel generates higher resistance for the same speed. Fig 16 confirms the difference between the flat panel and conventional vessel.

Table 8. CFD Resistance Comparison

Speed	Resist (kN)		Difference	
knot	Convent	Flat Panel	(kN)	(%)
5	9.299	11.617	2.318	19.954
6	13.835	16.822	2.987	17.757
7	19.761	23.227	3.466	14.922
8	28.022	31.389	3.367	10.727
9	38.703	40.616	1.913	4.71
10	49.955	54.529	4.574	8.388

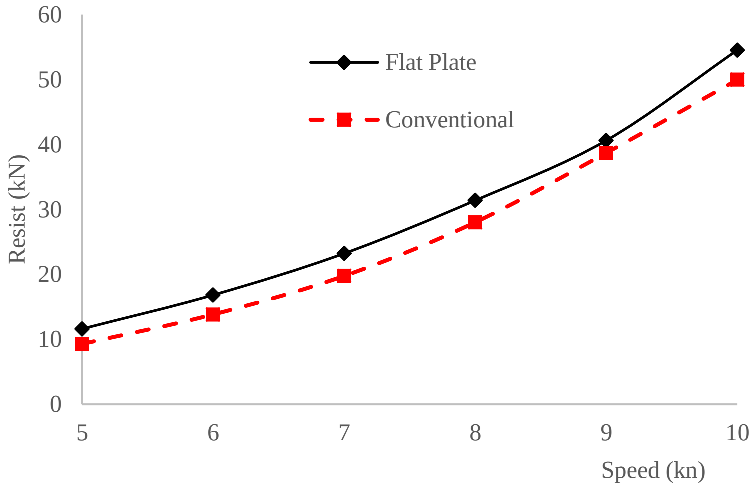

Figure 16. CFD Resistance Comparison Flat Plate vs Conventional

3.2. Pitch Motion

The motion direction convention used in the simulation is based on Fig. 17, where Pitch rotation is on the *Y*-axis (*Ry*), and when the rotation direction is counterclockwise, the value is negative and positive for the opposite direction. In other interpretation, when the value is negative (-) the ship is experiencing trim by stern due to the hull-fluid interaction.

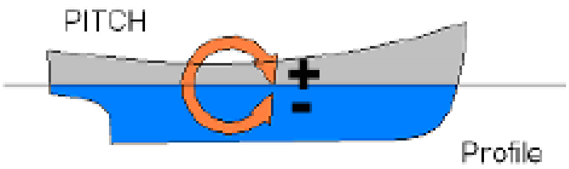

Figure 17. Pitch Motion Sign Convention

The results of the simulation show that all the Pitch (Ry) values for a flat panel are positive, it can be concluded that the flat panel vessel is experiencing trim by bow. The maximum pitch is 1.13 degrees or the bow draft decreases 0.3m compared to the original draft. The contrary condition occurred in the conventional vessel; all the value of Ry is negative or trim by the stern. The phenomena of the flat panel vessel are unique since the common condition of a vessel during its sailing is experiencing negative Ry or the bow is raised. A phenomenon where the draft of the bow is higher during sailing can be called bow diving in calm water.

Table 9: Motion Ry1 Comparison (pitch)

Speed (kn)	Motion Ry (pitch)	
	Flat Plate	Conven
5	0.23	-0.08
6	0.34	-0.12
7	0.47	-0.17
8	0.63	-0.23
9	0.83	-0.31
10	1.13	-0.41

3.3. Wave Elevation

The other result generated during simulation is wave elevation. This paper presents the comparison of the wave elevation produced from 7 to 10 knots. The results of the wave elevation can be analyzed in Fig. 18 -24.

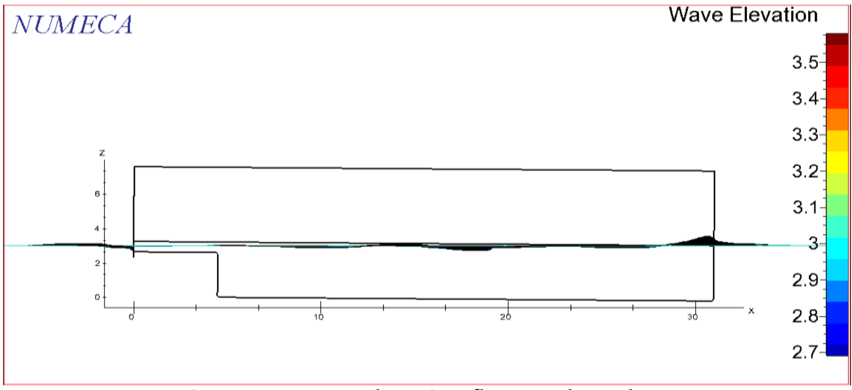

Figure 18. Wave elevation flat panel at 7 knot

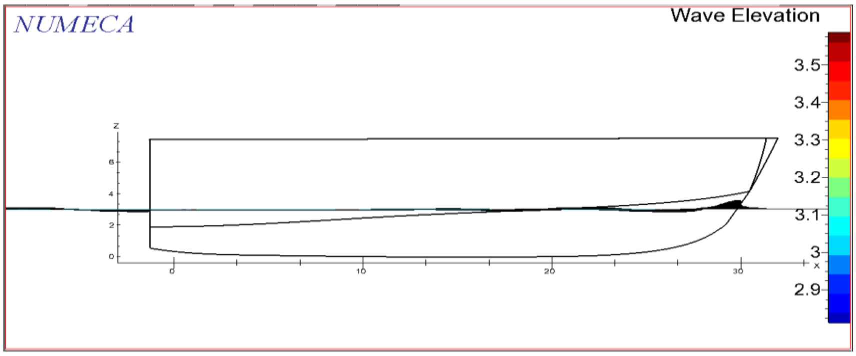

Figure 19. Wave elevation conventional at 7 knot.

From Fig. 18 and 19 it can be seen that the wave elevation for flat panel and conventional vessel at 7 knot still has no difference, and the vessel draft line still looks normal.

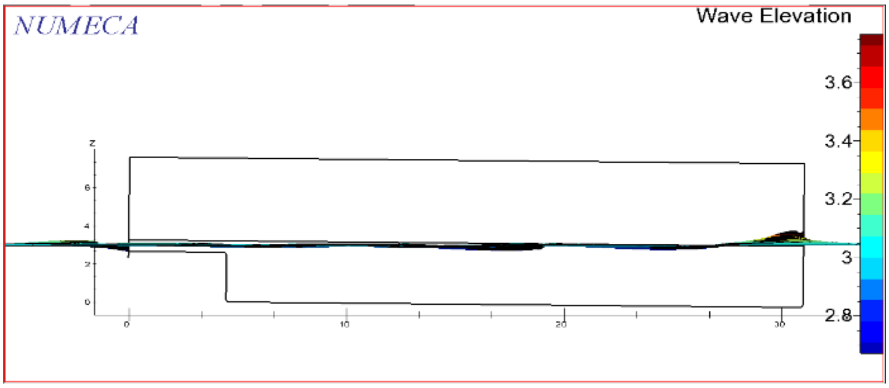

Figure 20. Wave elevation Flat Panel at 8 knot.

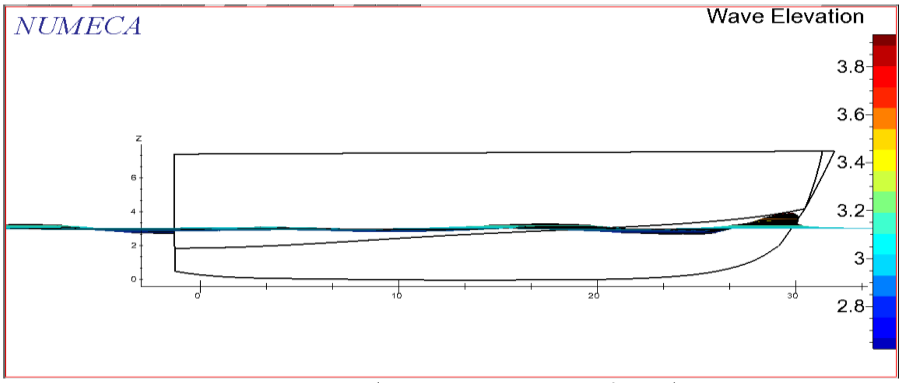

Figure 21. Wave elevation Conventional at 8 knot.

The wave elevation for flat panel and conventional vessel at 8 knot still has no difference, and the vessel draft line is still look normal, but there is a slight increase of wave elevation in both of the vessel.

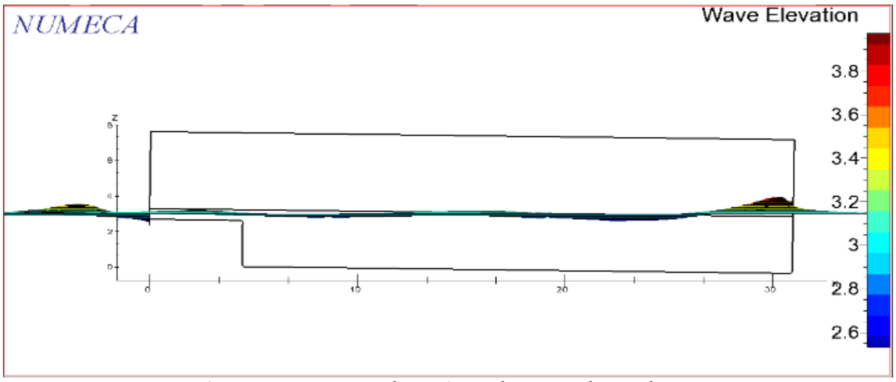

Figure 22. Wave Elevation Flat Panel at 9 knot.

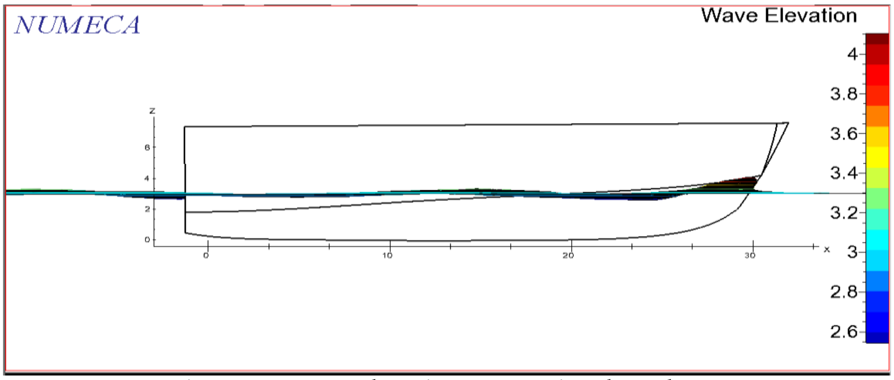

Figure 23. Wave Elevation Conventional at 9 knot.

Based on Fig. 22, it can be seen that the flat panel draft line is begin to shift below the water surface, while in Fig. 23 the conventional vessel is still above the water surface.

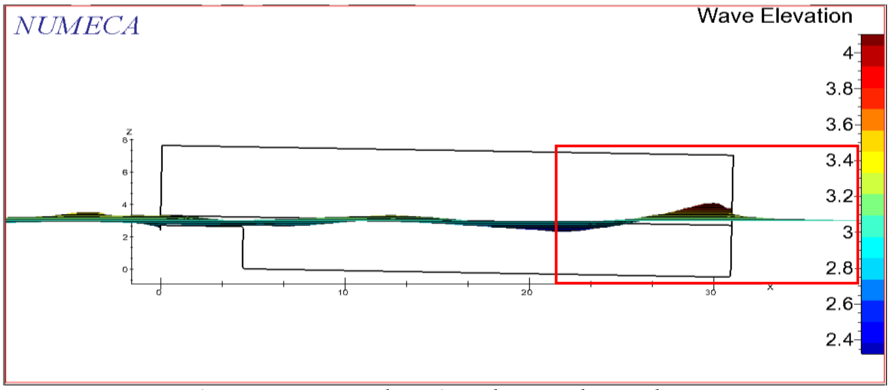

Figure 24. Wave Elevation Flat Panel at 10 knot

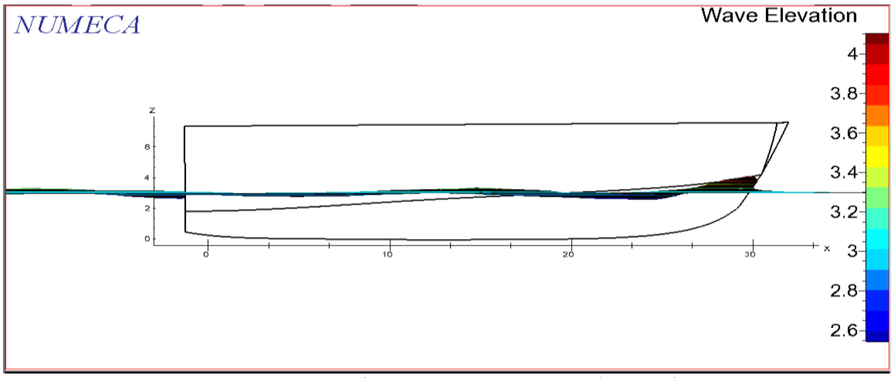

Figure 25. Wave Elevation Conventional at 10 knots

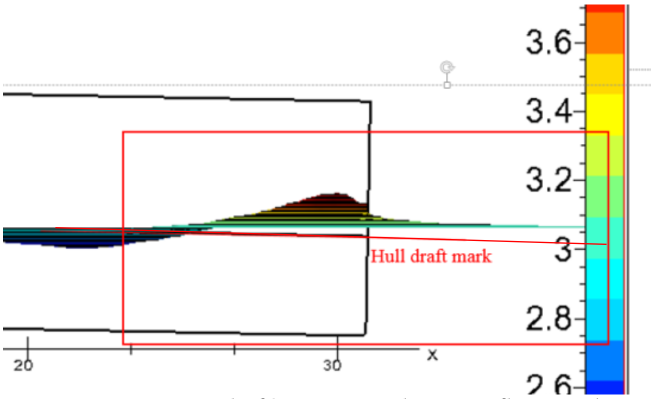

Figure 26. Detail of bow wave elevation flat panel

Based on Fig. 26, it can be seen that the bow draft mark is located underwater which indicates that the bow is experiencing diving.

3.4. Flow Around The Hull

From the perspective of resistance, the flat panel concept generated higher resistance compared to conventional vessels based on analytical Holtrop resistance or numerical CFD prediction. The flat panel hull is derived from the Axe bow which is commonly used for high-speed vessels and provides lower resistance compared to the conventional hull concept [23] [24], but the case of this paper shows the contrary results. The stern part of the hull form that was inspired by semi Trimaran might contribute to the additional resistance due to turbulence of fluid flow as shown by the relative velocity flow analysis in Fig. 27.

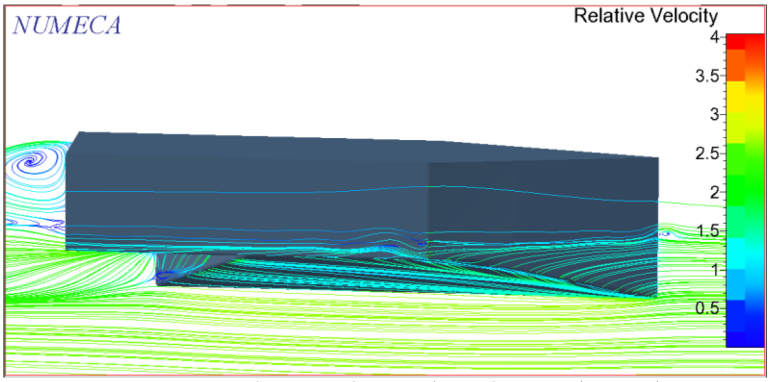

Figure 27. Relative Velocity Flow Flat Panel Vessel

While the relative velocity flow of conventional vessels has a different pattern, the flow is smoother compared to flat panel vessels as shown in Fig. 28 .

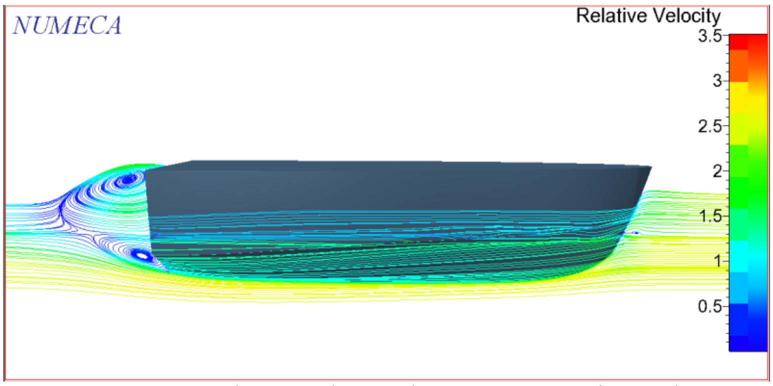

Figure 28. Relative Velocity Flow Conventional Vessel.

The flow of a flat panel vessel shows that their turbulence occurred at the stern part which creates high pressure. While at the front or bow section due to Xbow configuration, the flow is less turbulence that might generate low pressure. This condition may cause the bow is experienced a lower draft compared to the aft draft.

4. Conclusion

Based on the results and discussions regarding the resistance, it can be concluded that:

1) The flat panel generates higher resistance compared to the conventional vessel as shown by CFD or empirical analysis.

2) Besides the resistance, the pitch motion analysis shows that the flat panel hull experiences a lower bow draft compared to the conventional vessel. Both resistance and bow diving phenomena might cause by the flow of the flat panel vessel. The flow comparison and wave elevation strengthen the analysis of resistance and pitch motion.
3) All the comparison studies are based on CFD or analytical prediction, it is recommended to conduct the experiment based on ITTC standard in Hydrodynamic Laboratory to confirm the phenomena.

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