CFD Analysis into the Drag Characteristics of Trimaran Vessel: Comparative Study between Standard NPL 4a and the use of Axe-Bow

Sutiyo, I Ketut Aria Pria Utama
Institut Teknologi Sepuluh Nopember, Surabaya, 60111
sutiyo.19041@mhs.its.ac.id

Abstract. Recently, there has been an increased demand for multihull vessels for military and commercial applications. This demand for multihull vessels is to balance speed with payload requirements. One such hull form is the trimaran. This research conducted a CFD analysis of resistance for trimaran hull forms as a parameter range of practical hull forms is established round bilge trimaran hull forms based on the NPL systematic series and Axe-Bow Modification at the main hull. The resistances of trimaran hull forms are, therefore, estimated by using ANSYS CFX, a commercial CFD software package. Trimaran model was analysed on variation of main hull and side independently, S/L = 0.3 and S/L=0.4 at Fr = 0.15, 0.2, 0.25, 0.3, 0.4 and 0.5. The results showed that the trimaran ship with the Axe-Bow modification showed better results when compared to the NPL Hull, with an average value of 26.6%. This shows a positive influence with the use of Axe-Bow on the modification of the NPL Hull in the trimaran ship configuration.

1. Introduction
There is an increased interest in trimaran vessels due to their advantages and applications [1]. Because of the stability gained from the side hulls, the trimaran can use slender hulls that reduce residuary resistance. Therefore, the trimaran reduces fuel consumption compared to an equivalent monohull. The trimaran’s three hulls have the flexibility to accommodate many propulsion plant arrangements. An important feature of the trimaran form is the additional upper deck and upper ship space that is created. For the same displacement or volume as a monohull, the trimaran form will generate a ship with a greater length and, in the useful central region, a greater upper deck beam that is extreme breadth between the two side hulls, giving the possibility for many potential uses.

Considering the advantages of the trimaran concept, a lot of research has been done during the last decades. When the literature on trimarans is examined in general, it can be seen that the most important parameter in resistance optimization is the configuration of the outriggers because of the flow interference effect between center-hull and outriggers [2]. Optimum placement of them will result in an interaction between the wave train produced by the center-hull and the wave trains produced by the outriggers that ideally counteract each other at the primary speed(s) of interest [3].

Preliminary researches on trimaran were carried out [4]. In this study, resistance characteristics of a trimaran hull form with different arrangements were investigated to verify the theoretical prediction by comparing towing test. CFD method was utilized by [5] to analyze the hydrodynamic performance of a trimaran hull form with small-sized outriggers to determine optimum outrigger positions for minimum
wave resistance performance. They also considered the wave interactions between the center-hull and outriggers to predict the total wave-making resistance.

Mahmood and De-bo [6] investigated the prediction of wave resistance on the trimaran hull forms using CFD software. Three different mesh sizes and two different turbulence models were used to investigate the effect of mesh structure and turbulence models on the prediction of the resistance. CFD analyses were realized corresponding to Froude Number ranges from 0.14 to 0.75 and the results were compared with the experimental data. Son [7] performed CFD computations of a systematic series of trimaran hull forms. The center-hull form of the trimaran was developed based on the NPL (National Physical Laboratory) systematic series of round bilge hulls and the side-hulls were created by scaling the center-hull to one-third size.

Further, the development for hull optimization was using Axe-Bow. It uses straight vertical sides to dampen waves from the bow, this can result in a smooth pitching motion. Basically, the Axe-bow in the extended section is an empty space. The study of Axe-bow shows an increase in efficiency and a reduction in pitch acceleration, because of which ships with Axe-bow have less resistance in conventional models and reduce fuel use [8].

The Axe-Bow developed by Damen Shipyard has better efficiency as well as better head sea performance with less slamming and higher speeds [9]. Damen Shipyard [10], made the delivery of the first ship, the Patrol Boat with axe-bow. The ship exhibits effective movement behavior and significantly lower drag while sailing. This provides a 20% reduction in fuel use and consequently lower emissions.

Romadhoni and Utama [11], conducted a study specifically discussing the use of Axe-bow using CFD. The results of the study based on numerical analysis (Maxsuft–Hullspeed) and CFD showed that at speeds of 17 knots to 25 knots the Axe-Bow hull form has a smaller resistance value than the planning hull chine (HPC) and rounded hull (RH) ship models. The results of numerical calculations and CFD have almost the same value for each variation of the model. The results of the comparison of the total resistance on the use of axe-bow and conventional bow models obtained a difference of 4-8%. In this study, the main objective is to analyze the resistance configuration on a trimaran resistance with Axe-Bow modification at the main hull by utilizing CFD method based on RANS (Reynolds- averaged Navier-Stokes). A brief introduction of the CFD solver is presented, followed by the description of the numerical setup consisting of mesh generation and boundary conditions. The interference effect is calculated to define the best configuration.

2. Method

2.1. Ship Model
As shown in Figures 1 and 2, the hull geometry of a trimaran with conventional NPL Hull dan Axe-Bow modification. The main hull provides most of the buoyancy during forwarding motion, while the demi-hull is designed to keep the directional stability. The main dimensions of the model are listed in Table 1.

| Parameter | Unit | Mainhull NPL | Mainhull Axe-Bow | Sidehull NPL |
|-----------|------|--------------|------------------|-------------|
| Lmodel    | m    | 1.252        | 1.252            | 1.058       |
| Lwl Model | m    | 1.218        | 1.252            | 0.990       |
| Bmodel    | m    | 0.168        | 0.168            | 0.096       |
| Tmodel    | m    | 0.067        | 0.096            | 0.058       |
| WSA       | m    | 0.17         | 0.19             | 0.114       |
| Displacement | kg  | 3.119        | 3.119            | 1.560       |
2.2. Numerical Simulation

During the simulation, the governing equation of incompressible viscous flow is described by the Reynold–Averaged Navier–Stokes Equations (RANSE) which is the most widely used method in engineering. The equation is described as following,

\[
\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial }{\partial x_j} \left( \bar{u}_i u_j \right) = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j}
\]

(1)

where \(\bar{u}_i, \bar{u}_j\) denote the time averaged velocity components, \(u'_i, u'_j\) are the fluctuations of the velocity components, \(\bar{p}\) is the time averaged pressure, \(\rho\) is dynamic viscosity coefficient, \(t\) is time, and \(x_i, x_j\) are unit vectors in directions of \(i\) and \(j\). To close this set of equations, the Shear Stress Transport (SST) turbulence model is used.

The transported variable of turbulent kinetic energy, \(k\), is defined as follows,

\[
\frac{\partial}{\partial t} \left( \rho k \right) + \frac{\partial}{\partial x_i} \left( \rho k u_i \right) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k
\]

(2)

The second transported variable \(\omega\) is defined as follows,

\[
\frac{\partial}{\partial t} \left( \rho \omega \right) + \frac{\partial}{\partial x_i} \left( \rho \omega u_i \right) = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega
\]

(3)
\( G_k \) and \( G_\omega \) represent the turbulent kinetic energies due to the average velocity gradient, \( Y_k \), \( Y_\omega \) are turbulent dissipation terms, \( \Gamma_k \) and \( \Gamma_\omega \) denote the effective diffusion terms, \( D_\omega \) is the orthogonal divergence term.

The volume of fluid (VOF) model is applied to track the location and evolution of the free surface [12]. The basic idea of the VOF is to define the marking function \( \alpha \) in the discrete domain and to determine the value of the volume function in one grid according to the volume of the fluid in it when the value of \( \alpha \) is 1 or 0, there is only one fluid in the grid. When the value of \( \alpha \) is between 0 and 1, it is occupied by two kinds of fluids, which means there is a free surface in the grid. \( \alpha \) satisfies the following transport equation,

\[
\frac{\partial \alpha}{\partial t} + u \frac{\partial \alpha}{\partial x} + v \frac{\partial \alpha}{\partial y} = 0
\]  

(4)

2.3. Domain and Boundary Conditions

The domain dimensions and boundary conditions are specified in Figure 3. Considering the symmetrical characteristic of the flow field, only half of the hull body is modeled. The boundary conditions are specified as follows: the hull body is a moving boundary and a no-slip condition is imposed on the hull surface; the free-slip condition is applied to the top, side, and bottom walls; symmetry condition is used for the hull center plane; the flow velocity at inlet is defined as the tested speed; at the outlet, the hydrostatic pressure defined as a function of water level height is applied; furthermore, the initial location of the free surface is determined by defining the volume fraction function of water and air at the inlet and outlet.

![Figure 3. Boundary Condition.](image)

2.4. Meshing and Grid Independence Study

The mesh generation in this study is accomplished using Design Modeler. The calculation domain is discretized using structured and unstructured meshes. Considering the complex geometrical characteristics of the hull, a mesh with triangular elements is generated on the hull surface and the boundary layer is refined with prism elements created by extending the surface mesh node. The region around the boat is filled with tetrahedral elements with inflation, while in the far-field, unstructured mesh with grid generation is generated for reducing the number of elements.
The mesh size plays an important role in the calculation procedure, a fine mesh can always bring credible results in ANSYS CFX but at the same time increases the computational cost and time consumption due to the large element number. Therefore, to determine the mesh size with acceptable numerical accuracy and element number, mesh convergence studies are carried out for the trimaran model of NPL hull with S/L=0.3 at a Froude number of 0.4. The grid independence study is shown in Figure 4.

| Total Element (x1000) | 192 | 398 | 823 | 1,583 | 2,876 |
|------------------------|-----|-----|-----|-------|-------|
| Resistance Total Coefficient (C_T) (x10^-3) | 13.365 | 9.6136 | 8.1033 | 7.2356 | 7.1153 |
| Different (%) | 28.07 | 15.71 | 10.71 | 1.66 |

Figure 4. Grid Independence Study.

3. Result and Discussion
The calculation of the trimaran vessel with axe-bow modification shows a smaller value than the trimaran NPL hull vessel, as shown in Figure 5 and Table 3. This is due to the modification of the axe-bow which can reduce wave generation around the ship. Modification of Axe-bow without hull interaction can reduce the drag of the trimaran NPL hull by an average of 3.71%.
Figure 5. Resistance Total Coefficient of Trimaran hull independently.

Figure 6. Resistance Total Coefficient of Trimaran hull with variation configuration.

Table 3. Total Resistance Coefficient ($C_T$).

| Fr | NPL Hull (x 10^{-3}) | Axe-Bow (x 10^{-3}) | difference (%) | NPL Hull (x 10^{-3}) | Axe-Bow (x 10^{-3}) | difference (%) | NPL Hull (x 10^{-3}) | Axe-Bow (x 10^{-3}) | difference (%) |
|----|----------------------|----------------------|----------------|----------------------|----------------------|----------------|----------------------|----------------------|----------------|
| 0.15 | 4.2636 | 4.0986 | 3.87 | 4.5653 | 4.4586 | 3.21 | 4.4187 | 4.3956 | 1.41 |
| 0.2 | 4.5563 | 4.3235 | 5.11 | 4.8860 | 4.5683 | 4.70 | 4.6563 | 4.4513 | 2.56 |
| 0.25 | 4.9321 | 4.8692 | 1.28 | 5.5998 | 4.9683 | 8.45 | 5.1268 | 4.9156 | 1.06 |
| 0.3 | 4.5365 | 4.3256 | 4.65 | 5.0657 | 4.7569 | 6.16 | 4.7536 | 4.6854 | 1.50 |
| 0.4 | 6.5981 | 6.2351 | 5.50 | 7.2356 | 6.8685 | 4.42 | 6.9156 | 6.5346 | 2.27 |
| 0.5 | 5.5265 | 5.4253 | 1.83 | 6.2353 | 5.8683 | 8.01 | 5.7356 | 5.6769 | 3.26 |
| **Average** | **3.71** | **5.83** | **5.31** | **Average** | **5.83** | **5.31** | **Average** | **5.83** | **5.31** |

The interaction effect between hulls in the transverse direction (S/L) greatly affects the total drag coefficient ($C_T$), both trimaran NPL hull and trimaran with Axe-Bow modification, where for hull S/L = 0.3 greater than S/L = 0.4, as shown in Figure 6. CFD results show that the smaller the distance between the catamaran hulls (S/L), the greater the resistance that occurs. This phenomenon arises because of the effect of viscous and wave interaction between the hulls [13].

Figure 7. Velocity Distribution of Trimaran with NPL Hull at Fn = 0.4
Figure 8. Velocity Distribution of Trimaran with Axe-Bow Modification NPL Hull at Fn=0.4;

The CFD calculation shows that the difference between trimaran NPL hull and Axe-Bow modification is 23.94% at S/L = 0.3 and 30.92% at S/L = 0.4 as shown in table 3. The trimaran hull resistance with the Axe-Bow modification has a lower total drag coefficient value than the trimaran NPL hull with an average difference of about 26.59% because in this condition it appears that the interaction between hull of NPL trimaran is higher than the trimaran Axe-bow, as shown in Figure 7 and 8. This shows that the separation distance between the hulls (S/L) is very crucial for the interaction of wave-making opposing each other from the front (bow) and propagating to the back (stern) of the ship.

Figure 9. Water Volume Fraction NPL Trimaran Hull at Fn=0.4; a. S/L=0.3; b. S/L=0.4

Figure 10. Water Volume Fraction Trimaran with Axe-Bow Modification of NPL Hull at Fn=0.4; a. S/L=0.3; b. S/L=0.4

The CFD simulation shows that the speed distribution between the NPL trimaran hull is more rapid than that of a trimaran ship with Axe-Bow modification as shown in Figure 7 and 8 this causes the
resistance of conventional trimaran NPL hull to become bigger than trimaran with Axe-Bow modification. The bow shape of a trimaran with Axe-bow modification can reduce wave-making than trimaran vessels with conventional NPL hull, as shown in Figure 9 and 10. This is also reinforced by research conducted by Damen Shipyard [14] which states that the Axe-Bow modification can significantly lower resistance through the water.

4. Conclusion
This study explains that CFD provides a very good contribution related to the calculation of resistance on trimaran ships, both conventional NPL and with Axe-bow modification. Ships with Axe-Bow modifications have a positive effect on trimaran resistance at S/L = 0.3 and S/L = 0.4 with an average drag reduction of 26.6%. This can occur because the Axe-bow modification can reduce wave generation to reduce the interaction between the hulls. The positive value of Axe-bow modification can be inputted and considered for the initial design of the ship.

References
[1] Z. Elcin, “WAVE MAKING RESISTANCE CHARACTERISTICS OF TRIMARAN HULLS,” Naval Postgraduate School, Canada, 2003.
[2] B. Yildiz, B. Sener, S. Duman, and R. Datla, “A numerical and experimental study on the outrigger positioning of a trimaran hull in terms of resistance,” Ocean Eng., 2020, doi: 10.1016/j.oceaneng.2020.106938.
[3] Y. Chen, L. Yang, Y. Xie, and S. Yu, “The Research on Characteristic Parameters and Resistance Chart of Operation and Maintenance Trimaran in the Sea,” Polish Marit. Res., 2016, doi: 10.1515/pomr-2016-0041.
[4] Alexander W. Gray, “A Preliminary Study of Trimarans,” West Virginia Univ., 2003.
[5] M. Javanmardi, E. Jahanbakhsh, M. Seif, and H. Sayyaadi, “Hydrodynamic Analysis of Trimaran Vessels,” Polish Marit. Res., vol. 15, no. 1, pp. 11–18, Jan. 2008, doi: 10.2478/v10012-007-0046-5.
[6] S. Mahmood and H. De-Bo, “Resistance calculations of trimaran hull form using computational fluid dynamics,” in Proceedings - 4th International Joint Conference on Computational Sciences and Optimization, CSO 2011, 2011, doi: 10.1109/CSO.2011.225.
[7] C. H. Son, “CFD Investigation of Resistance of High-Speed Trimaran Hull Forms,” Florida Institute of Technology Melbourne, Florida, 2015.
[8] J. L. Gelling, “the Axe Bow: the shape of Ships to Come,” in International HISWA Symposium on Yacht Design and Yacht Construction, 19th. Amsterdam, NL, 13-14 November 2006, 2006.
[9] T. Buckley, “The Axe Factor : Damen dan Amels Take a Bow,” The Yacht Report, no. 111, 2010.
[10] Damen Shipyard, “P511-Guardián: Damen Shipyard’s first full axe-bow patrol vessel delivered to Cape Verdean coast guard,” Marit. by Holl., 2012.
[11] Romadhoni and I.K.A.P. Utama, “Analisa Pengaruh Bentuk Lambung Axe Bow Pada Kapal High Speed Craft Terhadap Hambatan Total,” Kapal, vol. 12, no. 2, pp. 78–87, 2015, doi: 10.12777/kpl.12.2.78-87.
[12] A. Caboussat, “Numerical simulation of two-phase free surface flows,” Arch. Comput. Methods Eng., 2005, doi: 10.1007/BF03044518.
[13] R. B. Luhulima, Sutiyo, and I. Utama, “An Investigation into The Correlation Between Resistance and Seakeeping Characteristics of Trimaran at Various Configuration and with Particular Case in Connection with Energy Efficiency,” Proc. Int. Symp. Mar. Eng. Oct. 15-19, 2017, Tokyo, Japan, 2017.
[14] Damen Shipyard, “DAMEN TAKES A BOW,” 2020. [Online]. Available: https://www.damen.com/en/innovation/some-key-projects/sea-axe-design.
Acknowledgment
The authors would like to thank the Directorate of Research and Community Services (DRPM) ITS for supporting the research financially under a scheme called "Postgraduate Research Grant (Hibah Penelitian Pascasarjana)" with the contract number: 920/PKS/ITS/2020.