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Optimization Modelling of a Catamaran Hull Form towards Reducing Ship's Total Resistance

Ahmad Fitriadhy[1,*], Nurul Shukna Rizat[1], Atiyah Raihanah Abd Razak[1], Sheikh Fakhruradzi Abdullah[1], Faisal Mahmuddin[2], Alamsyah Kurniawan[3]

[1] Programme of Naval Architecture, Faculty Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, Malaysia
[2] Department of Marine Engineering, Engineering Faculty, Hasanuddin University. Jalan Perintis Kemerdekaan km. 10, Tamalanrea, Makassar, Indonesia
[3] Ocean Engineering Program, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung. Jl. Ganesa No.10, Lb. Siliwangi, Bandung, Jawa Barat 40132, Indonesia

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ABSTRACT

Due to the increasing of fuel prices and volatile of environmental regulations, it is a challenge for Naval Architects to design a ship dealing with an optimum ship's total resistance. The conventional design of catamaran hull has not satisfied yet to reduce the ship's total resistance, RT. This paper presents a numerical investigation into gaining sufficient reduction of the ship's total resistance of catamaran through optimizing her hull form. To achieve this research objectives, a numerical optimization modelling coupled with a Computational Fluid Dynamics (CFD) approach has been successfully conducted. Several parameters such as length, beam and draft of catamaran hull have been taken into account towards reducing the ship's total resistance. Here, the simulation constraints are applied to obtain the optimum dimension, where the length, beam and draft of the catamaran hull were optimized within the range of 1.2 m to 1.5 m, 0.11 m to 0.14 m and 0.07 m to 0.08 m, respectively. In general, the optimization simulation revealed that the optimum dimension of the catamaran hull resulted in reduction of the total ship's resistance. The results showed that the optimum length, beam and draft of hull led to reduce RT by 21.08%, 16.95% and 17.91%, respectively. Merely, this numerical optimization simulation provides a useful way for reducing the total ship's resistance of the catamaran at the preliminary design stage.

1. Introduction

A catamaran ship is one of the multi-hull vessel types that geometrically consists of two demihulls. Multi-hull ships have been earned attention among the naval architecture because of their advantages such as the ability to provide lower draught, excellent seakeeping performance, better transverse stability and wider deck area Gunawan *et al.,* [1], Luhulima *et al.,* [2], Sun *et al.,* [3] and Setyawan *et al.,* [4]. Typically, catamaran ship has more advantages as compared to the monohull

* *Corresponding author.*
E-mail address: a.fitriadhy@umt.edu.my (Ahmad Fitriadhy)

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ship through offering larger dock area, comfortability and safety (Seif *et al*., [5]), (Zouridakis *et al.,* [6]). This inherent configuration deals with less resistance than a monohull ship at the same displacement. In presence of the hydrodynamic interaction between these two demihulls such as the pressure and viscous resistance components, which result in significant effect to the magnitude of her total resistance. Demand for optimizing the catamaran hull form towards reducing the total ship's resistance is then necessary.

Several researchers have investigated the catamaran's resistance using both of theoretical and experimental approaches. Doctors *et al*., [7] and Fitriadhy *et al.,* [8] predicted the total ship's resistance using the theoretical and Computational Fluid Dynamic (CFD) approaches, respectively, Everest *et al*., [9]; Oving *et al*., [10]; Pien *et al*., [11] conducted experimental model test. In addition to the CFD solution, the ship's resistance characteristics can be captured through explaining the fluid flow phenomenon and the interference resistance components around the catamaran hull of the ship. Meanwhile, this CFD offers reliability results, which are more practical as compared to the experimental model test (complex procedure, costly and time-consuming) reported by Vakilabadi *et al*., [12] , Yanuar *et al*., [13] , Abdul Ghani *et al*., [14] , and Zotti *et al.,* [15]. In other words, the CFD result has basically well-agreement as validated by the experimental data (Haase *et al*., [16]), (Iglesias *et al*., [17]), (Salas *et.al*., [18]) and (Swidan *et al.* [19]). Nowadays, the CFD's application has been extended and become the main tool to assist an optimisation modelling in obtaining optimum hull form towards reducing the ship's total resistance, in which this CFD approach is coupled with the numerical optimisation model; even, is also capable of simulating the flow field around the hull.

Improving the hydrodynamic performance through optimising the ship's hull has been investigated for the last decades towards reducing the total ship's resistance. Mahmuddin *et al*., [20], and Kashiwagi *et al*., [21] , conducted 2D and 3D shape optimisation modelling using genetic algorithm. It should be noted here that the effect of pressure, viscous and interferences waves around the ship's hull contributes to the characteristics of the total ship's resistance. Therefore, the optimisation by means of parameterising the demihull of the existing design plays an important role towards reducing the total ship's resistance of the catamaran.

In this present study, a numerical optimization modelling on the catamaran hull form has been conducted using Genetic Algorithm (GA) towards reducing the total ship's resistance. Here, the optimization's software called CAESES has been utilized to achieve the objective, whilst the results are then evaluated using the CFD approach to visualise the candidate of the optimal hull form that satisfies hydrodynamic performances. This investigation proposes to obtain the optimum hull form of the catamaran, where the ship's displacement is assumed to be constant. Several parameters such as variation of the lengths, beams and drafts have been accordingly taken into consideration in the simulation. In addition, the various geometric parametric constraints by structure or other operating constraints for instance her displacement and hull main dimensions are set up during optimisation modelling. The optimum candidate of the catamaran hull form was then selected with respect to her lowest total resistance value. Merely, this finding will be further assessed using the computational simulation as well-presented in Section of Results and Discussion.

2. Methodology

2.1 Methods and Materials

Computer simulations of physical processes are utilized in research, within the analysis and style of engineered systems in these few decades. CFD is an engineering tool which able to solve the basic non-linear equation to describes the fluid flow for predefined geometries and boundary conditions employing a numerical method. It is used by many industries in their development work to analyze, optimize, and verify the performance of designs before costly prototypes and physical tests (Wendt, J. F. *et al*., [22]). CFD also allows the visualization of complex patterns of fluid flow in an exceedingly physics-based model. Thus, CFD is more reliable and widely applied in various application, such as automobiles, aircraft design, weather science, civil engineering, oceanography, and so on, as result generated by the use of CFD is reliable and its numerical schemes and method are much more accurate in visualization when compared to analytical and experiment methods.

In NUMECA FINE^{TM}/Marine, the CFD flow solver is based on the incompressible unsteady RANSE, which means that finite volume is applied to the solver to build a spatial discretization of transport equation (Fitriadhy, *et al.,* [23] , Fitriadhy, *et al.,* [24]). Meanwhile, the momentum equation is used to derive the velocity field, while the mass conservation equation, otherwise continuity equation is transformed into pressure equation to extract the pressure field. The flow is assumed to be incompressible and isotropic Newtonian as it is a non-linear free surface flow between air and water.

2.2 Conservation Equations

Basically, the CFD solution approach has applied the Navier-Stokes equation, which inherently includes continuity and momentum equations as expressed in Eqs. (1)-(4) . The CFD flow solver on Flow3D is based on the incompressible unsteady RANSE in which the solver applies the volume of fluid (VOF) to solve a free surface model [25-27].

$$\frac{\partial(\mathrm{u})}{\partial \mathrm{x}}+\frac{\partial(\mathrm{v})}{\partial \mathrm{y}}+\frac{\partial(\mathrm{w})}{\partial \mathrm{z}}=0 \tag{1}$$

$$\frac{\partial}{\partial \mathrm{t}}(\rho \mathrm{u})+\frac{\partial}{\partial \mathrm{x}}(\rho \mathrm{uu})+\frac{\partial}{\partial \mathrm{y}}(\rho \mathrm{vu})+\frac{\partial}{\partial \mathrm{z}}(\rho \mathrm{wu})=-\frac{\partial \mathrm{P}}{\partial \mathrm{x}}+pgx+\mu\left(\frac{\partial^2 u}{\partial \mathrm{x}^2}+\frac{\partial^2 u}{\partial \mathrm{y}^2}+\frac{\partial^2 u}{\partial \mathrm{z}^2}\right) \tag{2}$$

$$\frac{\partial}{\partial \mathrm{t}}(\rho \mathrm{v})+\frac{\partial}{\partial \mathrm{x}}(\rho \mathrm{uv})+\frac{\partial}{\partial \mathrm{y}}(\rho \mathrm{vv})+\frac{\partial}{\partial \mathrm{z}}(\rho \mathrm{wv})=-\frac{\partial \mathrm{P}}{\partial \mathrm{y}}+pgy+\mu\left(\frac{\partial^2 w}{\partial \mathrm{x}^2}+\frac{\partial^2 w}{\partial \mathrm{y}^2}+\frac{\partial^2 w}{\partial \mathrm{z}^2}\right) \tag{3}$$

$$\frac{\partial}{\partial \mathrm{t}}(\rho \mathrm{w})+\frac{\partial}{\partial \mathrm{x}}(\rho \mathrm{uw})+\frac{\partial}{\partial \mathrm{y}}(\rho \mathrm{vw})+\frac{\partial}{\partial \mathrm{z}}(\rho \mathrm{ww})=-\frac{\partial \mathrm{P}}{\partial \mathrm{x}}+pgz+\mu\left(\frac{\partial^2 w}{\partial \mathrm{x}^2}+\frac{\partial^2 w}{\partial \mathrm{y}^2}+\frac{\partial^2 w}{\partial \mathrm{z}^2}\right) \tag{4}$$

where u, v, w, is the component of velocity in the x, y, z direction, respectively. ρ is the density, p and μ is the pressure and the viscosity, respectively.

2.3 Turbulence Model

We have applied RNG k-ε turbulence model in the current computational simulation. This turbulent model defined the region flows between open water and floating object that employed the double averaging strategy to the transport equations model. These turbulence models are simplified constitutive equations that predict the statistical evolution of turbulent flows [27].

3. Simulation Condition

Here, the computational fluid dynamic simulation has conducted to obtain the total resistance at various speeds. The results are remarked as the initial data for the optimisation modelling processes. Furthermore, the optimum hull form candidates are then evaluated using the CFD approach.

3.1 Principle Data of Catamaran

The geometrical model of the catamaran is clearly shown in Figure 1. Several data of the ship's particulars is completely presented in Table 1.

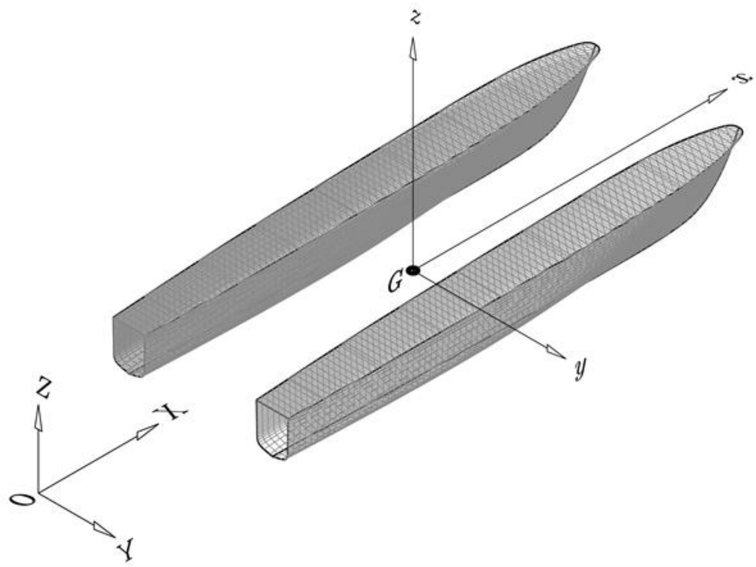


Fig. 1. The geometrical model of catamaran

Table 1
Principle of dimension

Description	Demi-hull	Catamaran
Length Overall, LOA (m)	1.433	1.433
Length Between Perpendicular, LBP (m)	1.372	1.372
Beam, B (m)	0.138	-
Draft, T (m)	0.078	0.078
Wetted Surface Area (m2)	0.2511	0.5022
Displacement, Δ (tonnes)	6.8184	13.6368

3.2 Geometrical Constraints

To achieve the objectives, the geometrical constraints have been set up with respect to the optimisation objectives including length, beam and draft of the catamaran hull. The detailed simulation conditions are presented in Table 2.

Table 2
Geometrical constraints on computational simulation conditions

Condition	Original Value
Length: 1.3 m up to 1.5 m	1.433 m
Beam: 0.11 m up to 0.14 m	0.138 m
Draft: 0.07 m up to 0.8 m	0.078 m

3.3 Optimization Modelling Phase

Here, the most optimum hull form of a catamaran will be evaluated to get the best design based on a set of prioritized criteria or constraints. Optimization would be a costly process for a limited number of designs. The performance of the algorithm is dependent on the types of constraints, the number of objectives, the function of the problem to solve, the period needed for the procedure and the precision of the objectives. The main design method used for process optimization is the Tsearch tool. In this method, a MOGA is conducted on a response surface that is iteratively built-up. The best designs of each MOGA run get evaluated and are added to the response surface by using DAKOTA. For final step, choose the best design of optimum model to observe the total resistance and compared the result with the origin model in FINE^{TM} Marine 3.1-1.

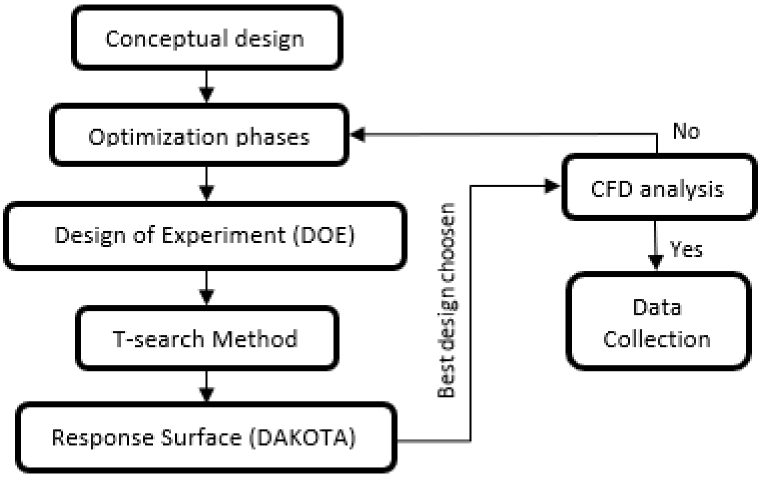


Fig. 2. Optimization process

3.4 Computational Domain and Boundary Conditions

In this phase, it mainly focuses on how to set the computational model associated with the unstructured hexahedral meshes as shown in Figure 3. In the mesh modelling, we employ the mesh generation setting, which is divided into five main steps namely initial mesh, adaption, snapping, optimization and viscous layer insertion. In addition, the local mesh refinement on the ship's hull form has been accordingly added in the current phase. An initial mesh is automatically proposed which corresponds to an isotropic subdivision of the computational domain bounding box. The authors have applied the symmetrical computational domain of the catamaran model to reduce the computational time.

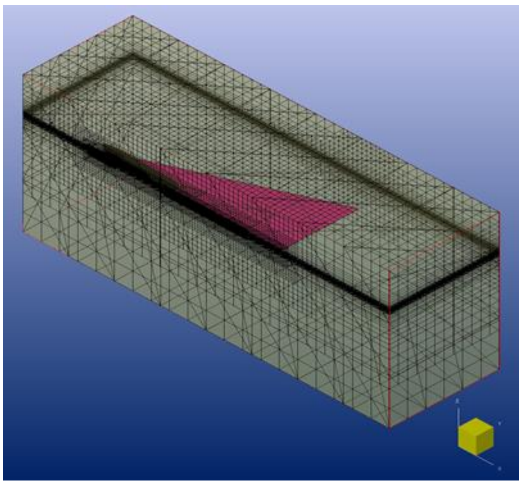


Fig. 3. Meshing setup

The initial domain was split up in many patches with the specific names and assigned in different boundary type condition. In initial mesh, only patch domain with SOL boundary type will apply in trimming action. Table 3 presents the specific names given to each patch and the boundary properties as well previously presented by Fitriadhy *et al.,* [23, 24]

Table 3
Boundary setting conditions

Condition	Description	Type	Setting	Distance of Boundary
Solid	Hull (H)	SOL	Wall-function	
	Deck (D)	SOL	Slip-wall	
	Transom (T)	SOL	Wall-function	
External	Xmin (Inlet)	EXT	Far field	1.0 L
	Xmax (Outlet)	MIR	Far field	3.0 L
	Zmin (Top)	EXT	Prescribed pressure	1.5 L
	Zmax (Bottom)	SOL	Prescribed pressure	0.5 L
	Ymin (Side)	SOL	Mirror	1.5 L
	Ymax (Side)	SOL	Far field	1.5 L

In general parameter, it was set up as steady and for body motion, a fixed, imposed, or solved body motion can be set up for each body and performed by the flow solver for two different parametric systems. The Imposed law of motion can be chosen independently for one or all degrees of freedom. In post-processing phase, compared and analysed between the original and optimum hull. If the total resistance of optimum hull was less than the original hull, visualization of wave elevation and total resistance was analysed.

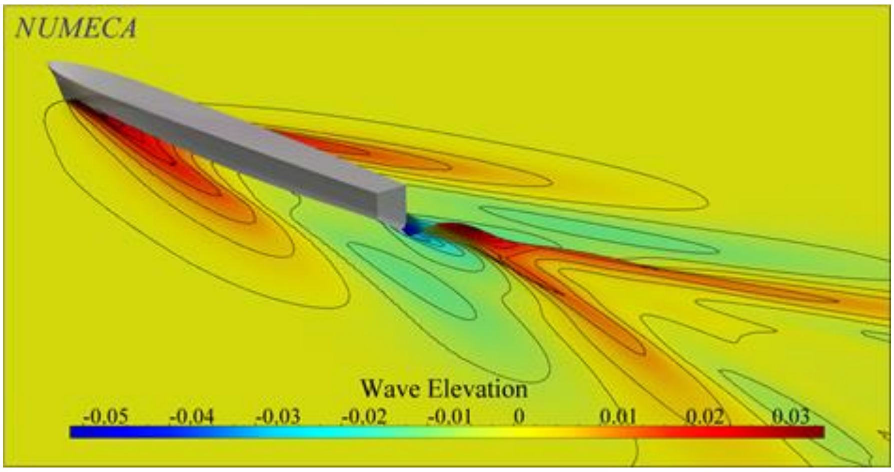


Fig. 4. CFD visualization on wave elevation around the existing (original) demihull

4. Results and Discussion

The purpose of this study was to analyse the pressure and viscous resistance characteristics of catamaran with respect to the different geometry of hull configurations (length and beam) and wave-making resistance using CFD software. In order to achieve the objectives, the pressure and viscous data analysis of catamaran with various hull design variables were carried out in CFD simulation. The results are divided into several aspects; effect of length of hull, and effect of beam of hull. The results data are displayed and discussed based on the graphs and tables.

4.1 Effect Length of Demihull

Regardless of optimized length of demihull, the results showed the subsequent decrease compared to the original length demihull of catamaran as displayed in Figure 5. It was found that as the length of demihull increases, the total resistance, R_T decreases. As the optimized length of demihull increased up to 7.20% or 0.11m, the demihull of catamaran correspondingly experience decrement of R_T by 21.08% and decrement of C_T by 20.88%. This occurred mainly due to demihull becomes slimmer, which reduces the pressure resistance.

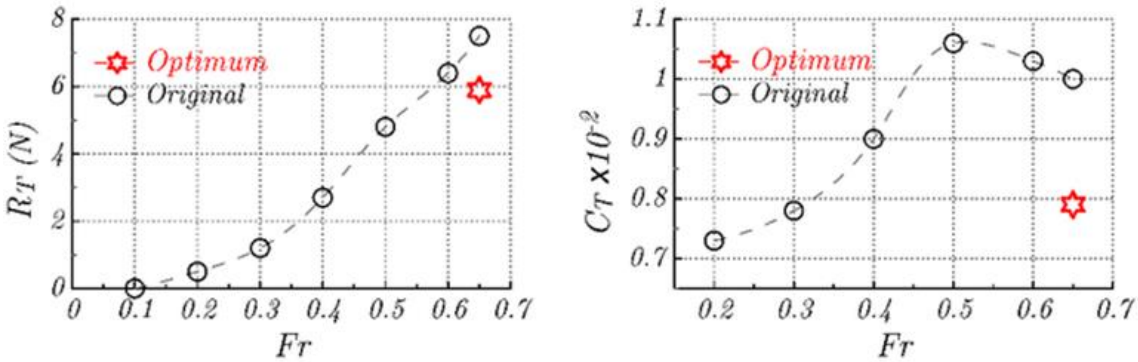


Fig. 5. Characteristics of ship's resistances between the original and optimum length of demihull

Table 4
Total resistance of original and optimized length of demi hull

Description	Fr	Length (m)	R_T (N)	C_T
Original Length	0.66	1.433	7.387	0.010040
Optimized length	0.66	1.544	5.838	0.007944

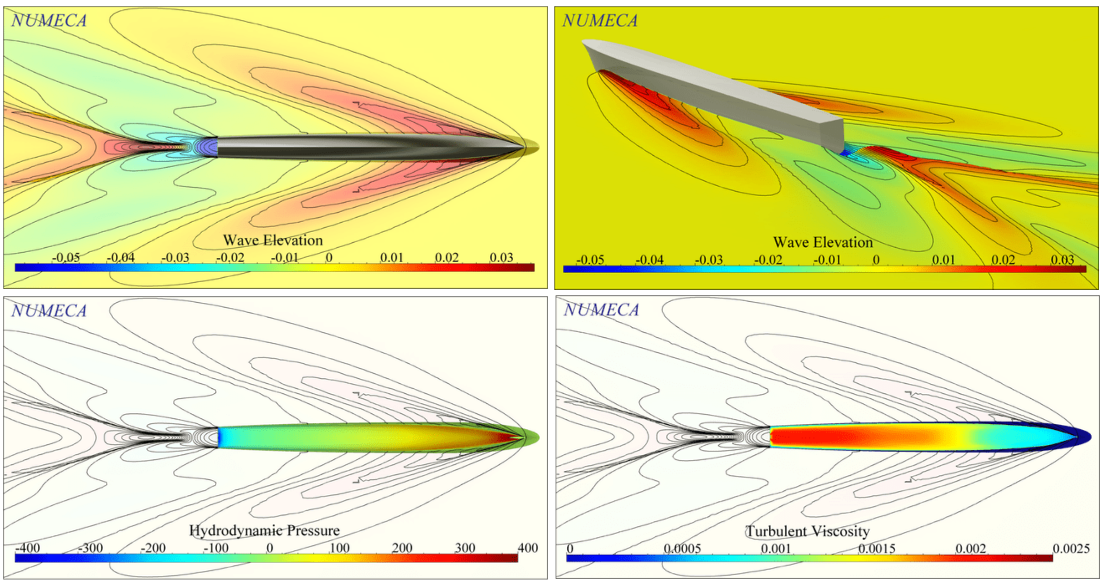


Fig. 6. The visualization of wave pattern and free surface for optimum length of demi hull

4.1.1 Effect length on symmetrical catamaran by lateral separation ratio (s/l)

The study shows a corresponding decrease, regardless of the lateral separation ratios relative to the original catamaran hull, as seen in Figure 7 of the graph. The increase in S/L ratios resulted in an almost insignificant effect on the total resistance coefficient (C_T). Referring Table 5 on S/L of 0.2, the catamaran correspondingly experience decrement of R_T by 13.27 % and decrement of C_T by 9.95 %. For S/L of 0.3, the catamaran correspondingly experience decrement of R_T by 9.57 % and decrement of C_T by 9.57 %. For S/L 0f 0.4, the catamaran correspondingly experience decrement of R_T by 9.61 % and decrement of C_T by 9.61 %. It can be concluded that the total resistance coefficient essentially depends upon the lateral separation ratio where increase in S/L ratio affects a proportionate decrease in the total resistance coefficient.

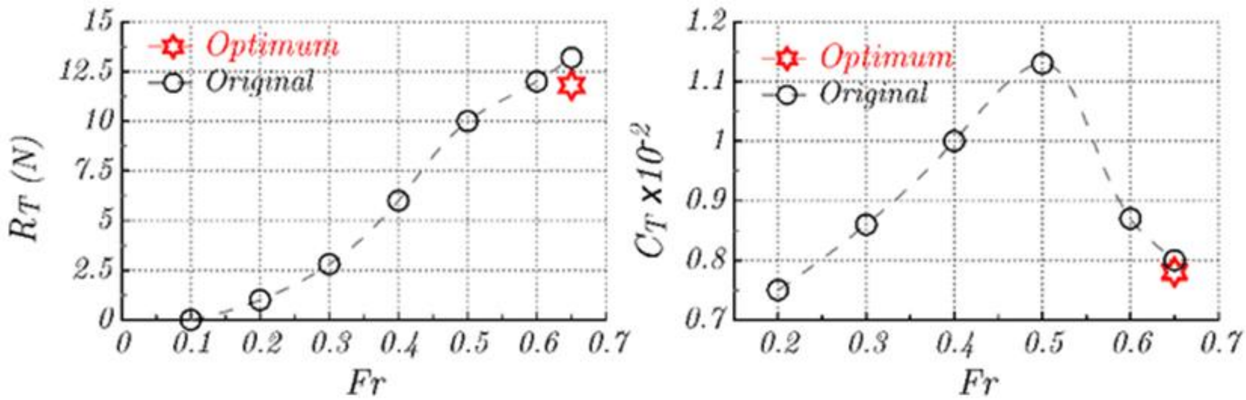


Fig. 7. Characteristics of ship's resistances between the original and optimum length of catamaran at S/L = 0.2

Table 5
Total resistance of original and optimized length of catamaran hull at various S/L ratios

S/L Ratio	Fr	Original R_T (N)	Optimum R_T (N)	Original C_T	Optimum C_T
0.2	0.66	13.210	11.458	0.00787	0.00779
0.3	0.66	12.228	11.058	0.00831	0.00752
0.4	0.66	12.214	11.039	0.00831	0.00751

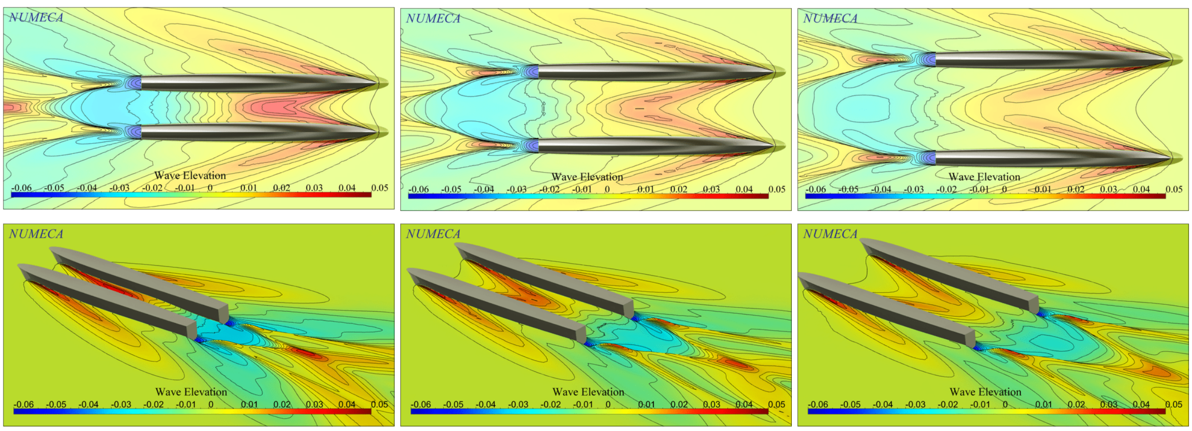
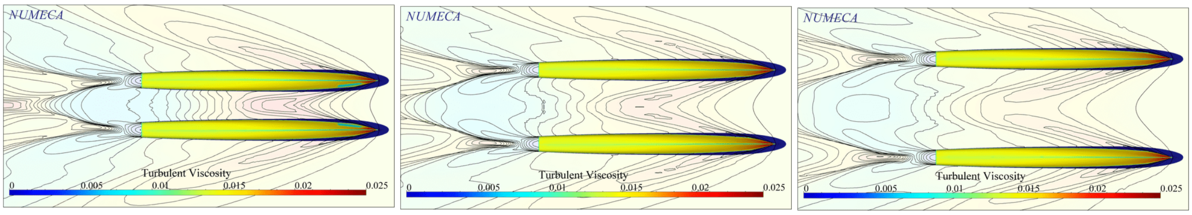
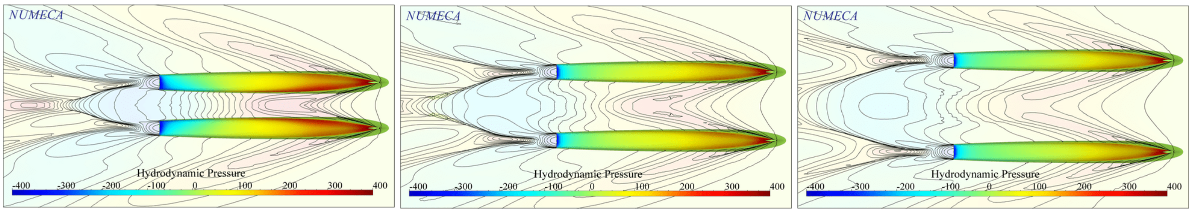


Fig. 8. Characteristics of wave pattern and free surface elevations on optimum length at S/L ratios



S/L 0.2 S/L 0.3 S/L 0.4

Fig. 9. Characteristics of turbulent viscosity on optimum length of catamaran at S/L ratios



S/L 0.2 S/L 0.3 S/L 0.4

Fig. 10. Characteristics of hydrodynamic pressure on optimum length at various S/L ratios

4.2 Effect Beam of Demihull

Figure 11 shows that the optimum with of the demihull results in the less total resistance. It should be noted here that the optimum beam of the demihulls has been trade-off with her draft values. This means that the beam of demihull increases, whilst the draft of the demihull decreases. The simulations revealed that the optimum total ship resistance has been obtained due to reduction of the beam of the demihull 0.1396 m, in which this directly leads to decrease the ship's total resistance by 16.95% as completely summarised in Table 6. The reason can be explained by the fact that the pressure and viscous resistances especially at the bow region has reduced indicated by the lighter red colour region relatively smaller (Figure 12) compared to the original beam of the demihull as seen in Figure 4 (darker red colour region).

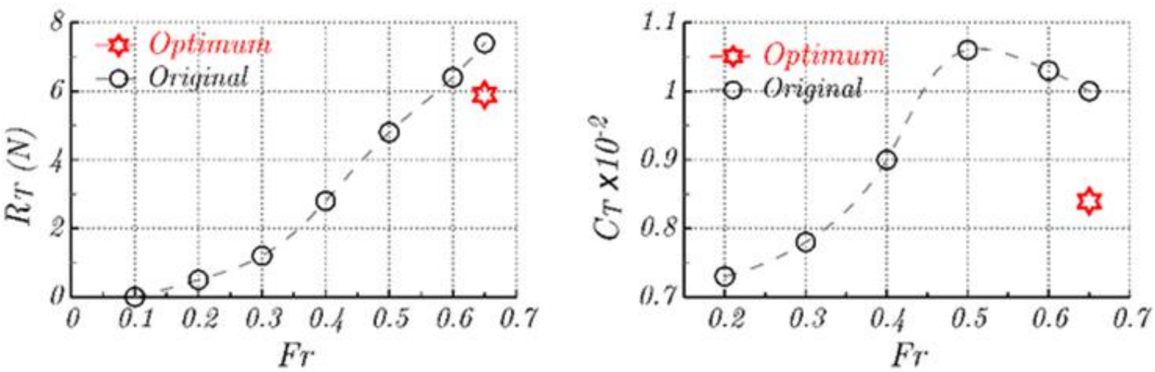


Fig. 11. Characteristics of ship's resistances between the original and optimum beam of demi hull

Table 6
Total resistance of original and optimized beam of demihull

Description	Fr	Beam (m)	R_T (N)	C_T
Original beam	0.66	0.123	7.397	0.01004
Optimized beam	0.66	0.139	6.144	0.00836

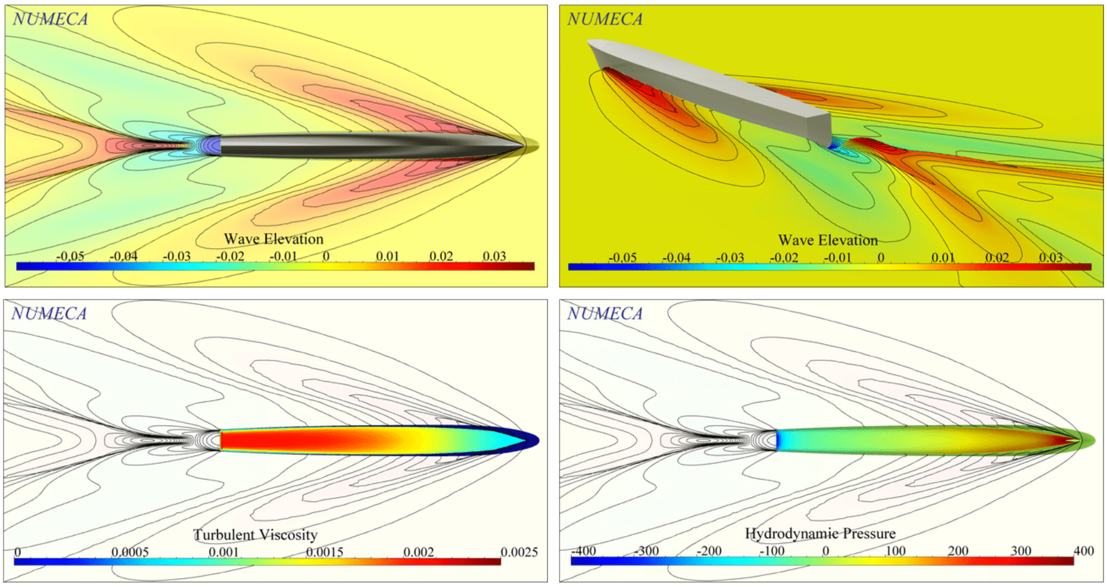


Fig. 12. The visualization of wave pattern and free surface for optimum beam of demi hull

4.2.1 Effect beam on symmetrical catamaran by lateral separation ratio (s/l)

The optimum beam leads to reduce the total catamaran resistance as compared to the original beam as displayed in Figure 13. Referring to Table 7 with S/L of 0.2, the total resistance of the catamaran decreases by 2.49%, while C_T by 11.35%. Regardless of the lateral separation ratios, the effect of S/L ratios resulted in having almost negligible effect on the coefficient of total resistance, C_T. The reason can be explained by the fact that the values of R_T and C_T of the catamaran with S/L = 0.3 and S/L =0.4 reduce by 0.07% and 0.07%, respectively and 0.58% and 0.10%, respectively. It is merely noted resistance coefficient depends on the lateral separation ratio, where an increase influences a proportionate decrease in the total resistance.

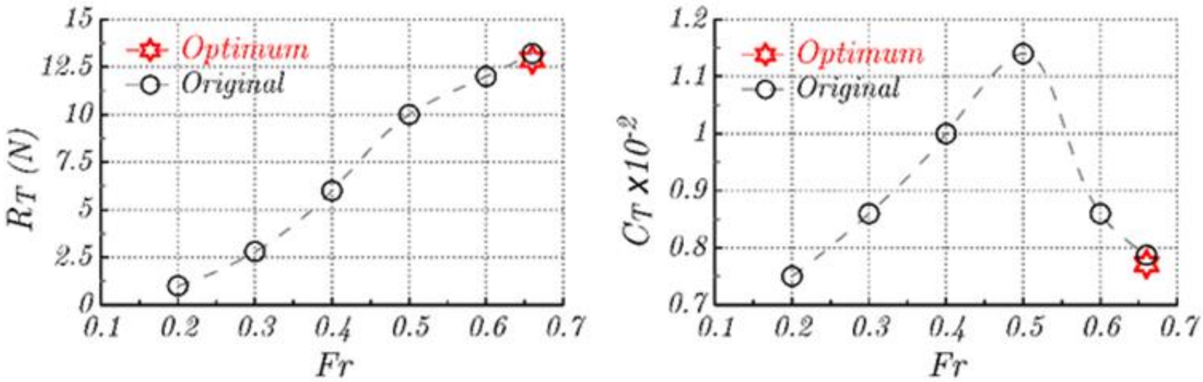
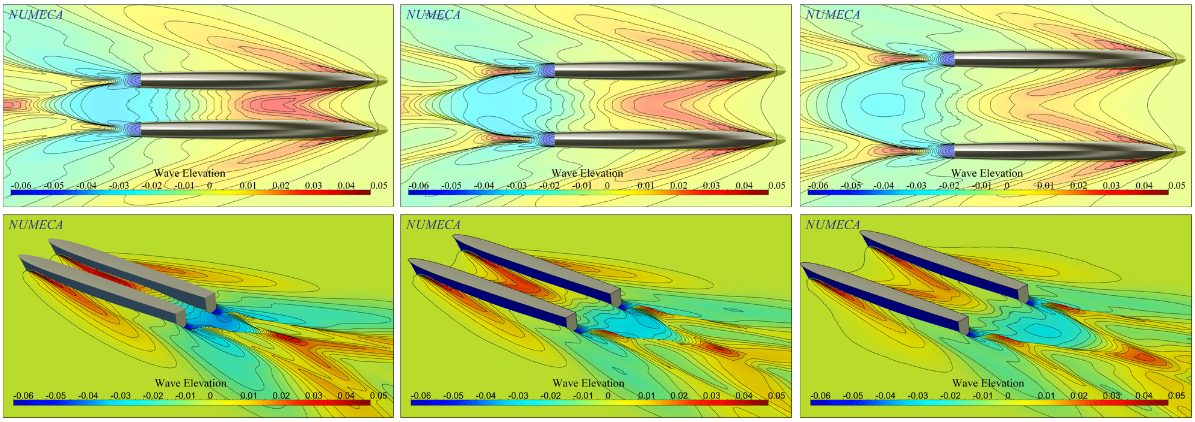
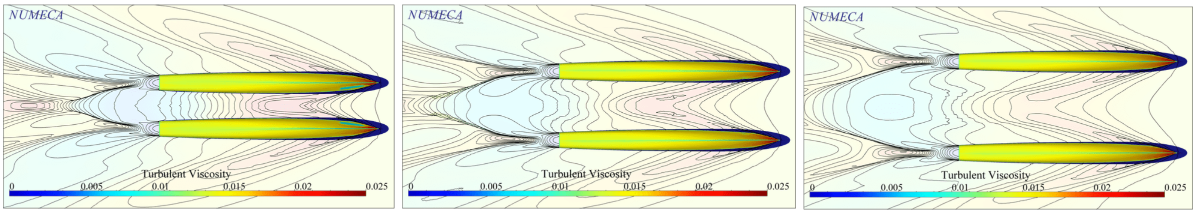


Fig. 13. Characteristics of ship's resistances between the original and optimum of beam at S/L = 0.2



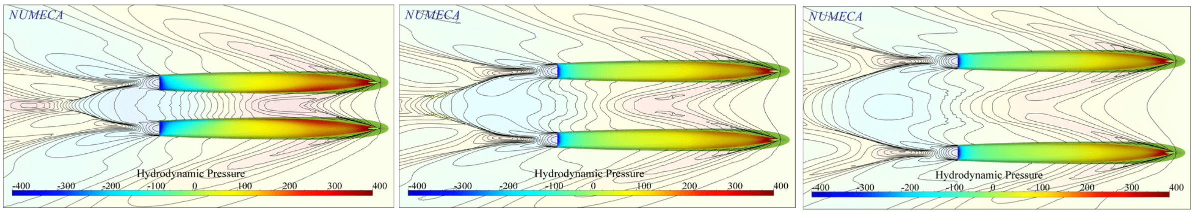
S/L 0.2 S/L 0.3 S/L 0.4

Fig. 14. Characteristics of free surface elevations on optimum beam at various S/L ratios



S/L 0.2 S/L 0.3 S/L 0.4

Fig. 15. Characteristics of turbulent viscosity on optimum beam of catamaran at various S/L ratios



S/L 0.2 S/L 0.3 S/L 0.4

Fig. 16. Characteristics of hydrodynamic pressure on optimum beam at various S/L ratios

Table 7
Total resistance of original and optimized beam of catamaran hull at various S/L ratios

S/L Ratio	Fr	Original R_T (N)	Optimum R_T (N)	Original C_T	Optimum C_T
0.2	0.66	13.2103	12.8806	0.00787	0.007712
0.3	0.66	12.2281	12.2196	0.008197	0.007314
0.4	0.66	12.2140	12.1433	0.008116	0.007262

5. Conclusions

The numerical optimization modelling incorporated with CFD simulation on predicting the optimum total resistance, R_T of catamaran hull has been successfully conducted. Several parameters of the catamaran dimension such as length and beam have been taken into account. Several results are drawn bellows:

i. Optimum length of demihull, the total resistance and coefficient of total resistance was decreased to 5.8378N and 0.007844. It reduced the total resistance and total resistance coefficient up to 21%.

ii. Optimum length for S/L 0.4 results into reduction of the total resistance and coefficient of total resistance reduces up to 10%.
iii. In addition to the optimum beam of demihull, her total resistance and coefficient of total resistance decreases by 16.95%.
iv. Optimum beam for S/L 0.4 results into decreasing of the total resistance and coefficient of total resistance up to 0.58%.

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References

[1] Gunawan, Kurniawan T., and A. Jamaluddin. "Experimental study resistances of asymmetrical pentamaran model with separation and staggered hull variation of inner side-hulls." *International Journal of Fluid Mechanics Research* 42, no. 1 (2015). http://dx.doi.org/10.1615/InterJFluidMechRes. v42.i1.60.
[2] Luhulima, Richard B., D. Setyawan, and I. K. A. P. Utama. "Selecting monohull, catamaran and trimaran as suitable passenger vessels based on stability and seakeeping criteria." In *The 14th International Ship Stability Workshop (ISSW)*, vol. 29, pp. 262-266. (2014).
[3] Sun, Hanbing, Fengmei Jing, Yi Jiang, Jin Zou, Jiayuan Zhuang, and Weijia Ma. "Motion prediction of catamaran with a semisubmersible bow in wave". *Polish Maritime Research* 23, no. 1 (89) (2016): 37-44. http://dx.doi.org/10.1515/pomr-2016-0006
[4] Setyawan, D., I. KAP Utama, Murdijanto Murdijanto, A. Sugiarso, and A. Jamaluddin. "Development of catamaran fishing vessel." *IPTEK the journal for technology and science* 21, no. 4 (2010).
[5] Seif, Mohammad Saeed, and E. Amini. "Performance comparision between planing monohull and catamaran at high froude numbers." (2004): 435-441.
[6] Zouridakis, Fragiskos. "A preliminary design tool for resistance and powering prediction of catamaran vessels." PhD diss., Massachusetts Institute of Technology, 2005.
[7] Doctors, L. J. "Some hydrodynamic aspects of catamarans." *Transactions of the Institution of Engineers, Australia. Mechanical engineering* 16, no. 4 (1991): 295-302.
[8] Fitriadhy, A., S. A. Azmi, N. Aqilah Mansor, and N. Adlina Aldin. "Computational fluid dynamics investigation on total resistance coefficient of a high-speed" deep-V" catamaran in shallow water." *International Journal of Automotive & Mechanical Engineering* 14, no. 2 (2017). https://doi.org/10.15282/ijame.14.2.2017.18.0347
[9] Everest, J. T. "Some research on the hydrodynamics of catamarans and multi-hulled vessels in calm water." *National Physical Laboratory, NPL, Ship Division, Ship Report 128* (1968).
[10] Oving, A. J. "Resistance prediction method for semi-planning catamarans with symmetrical demi-hulls." *TUDelft, Faculty of Marine Technology, Ship Hydromechanics Laboratory Report 700-S-1, Student Thesis, Confidential* (1986).
[11] Pien, P. C. "Catamaran hull-form design". In: International Seminar on Wave Resistance, Society of Naval Architects of Japan (SNAJ) (1976).
[12] Vakilabadi, Karim Akbari, Mohammad Reza Khedmati, and Mohammad Saeed Seif. "Experimental study on heave and pitch motion characteristics of a wave-piercing trimaran." *Transactions of FAMENA* 38, no. 3 (2014): 13-26.
[13] Yanuar, Ibadurrahman, S. Karim, and M. Ichsan. "Experimental study of the interference resistance of pentamaran asymmetric side-hull configurations." In *AIP Conference Proceedings*, vol. 1826, no. 1, p. 020025. AIP Publishing LLC, 2017. https://doi.org/10.1063/1.4979241
[14] Abdul Ghani, Pauzi, and Philip Wilson. "Experimental analysis of the seakeeping performance of catamaran forms with bulbous bows." *International Shipbuilding Progress* 65, no. 1 (2018): 1-28. http://dx.doi.org/10.3233/ISP-170140.
[15] Zotti, Igor. "Medium speed catamaran with large central bulbs: experimental investigation on resistance and vertical motions." In *Proc. of International Conference on Marine Research and Transportation*, pp. 167-174. 2007.
[16] Haase, Max, Konrad Zurcher, Gary Davidson, Jonathan R. Binns, Giles Thomas, and Neil Bose. "Novel CFD-based full-scale resistance prediction for large medium-speed catamarans." *Ocean Engineering* 111 (2016): 198-208. http://dx.doi.org/10.1016/j.oceaneng.2015.10. 018
[17] Iglesias, A. Souto, R. Zamora, D. Fernández, and C. López Pavón. "Catamaran wave resistance and central wave cuts for CFD validation." In *Maritime Transportation and Exploitation of Ocean and Coastal Resources: Proceedings of*

the 11th International Congress of the International Maritime Association of the Mediterranean, Lisbon, Portugal. http://dx. doi. org/10.1201/9781439833728. ch1, vol. 8. 2006. http://dx.doi.org/10.1201/9781439833728.ch1 8

[18] Salas, M., R. Luco, P. K. Sahoo, N. Browne, and M. Lopez. "Experimental and CFD resistance calculation of a small fast catamaran." *Proceeding of International Cnference on High-Performance Vehicles* (2004).

[19] Swidan, Ahmed Abdelwahab Wahby. "Catamaran wetdeck slamming: a numerical and experimental investigation." PhD diss., University of Tasmania, 2016.

[20] Mahmuddin, Faisal, and Masashi Kashiwagi. "Design optimization of a 2D asymmetric floating breakwater by genetic algorithm." In *The Twenty-second International Offshore and Polar Engineering Conference*. OnePetro, 2012.

[21] Kashiwagi, Masashi, and Faisal Mahmuddin. "Numerical analysis of a 3D floating breakwater performance." In *The Twenty-second International Offshore and Polar Engineering Conference*. One Petro, 2012.

[22] Wendt, John F., ed. *Computational fluid dynamics: an introduction*. Springer Science & Business Media, 2008.

[23] Fitriadhy, A., Razali, N and Mansor, N. A. "Seakeeping performance of a rounded hull catamaran in waves using CFD approach." *Journal of Mechanical Engineering and Sciences, vol.* 11, no. 2 (2017): 2601-2614. http://dx.doi.org/10.15282/jmes.11.2.2017.4.0 238

[24] Fitriadhy, A., and N. Amira Adam. "Heave and pitch motions performance of a monotricat ship in head-seas." *International Journal of Automotive and Mechanical Engineering*, vol. 14 (2017): 4243-4258. https://doi.org/10.15282/ijame.14.2.2017.10.0339

[25] Fitriadhy, A., Syarifuddin, D., Mansor, N. A., Adam, N. A., Ng, C. Y and Kang, H. S. CFD investigation into ieakeeping performance of a training ship. *CFD Letters*, vol. 13, no. 1 (2021): 19-32. https://doi.org/10.37934/cfdl.13.1.1932

[26] Fitriadhy, A., Aldin, N. A and Mansor, N. A. "CFD analysis on course stability of a towed ship incorporated with symmetrical bridle towline." *CFD Letters*, vol. 11, no. 12 (2019): 88-98.

[27] Fitriadhy, A., Mansor, N. A., Aldin, N. A and Maimun, A. "CFD analysis on course stability of an asymmetrical bridle towline model of a towed ship." *CFD Letters*, vol. 11, no. 12 (2019): 43-52.