Size Optimization of Foil-shaped Center Bulb on Catamaran Hull Form to Reduce Resistance

Eko Sasmito Hadi, Muhammad Iqbal and Gana Pranamya
Department of Naval Architecture, Universitas Diponegoro, Semarang, Indonesia

Keywords: Catamaran, Foil-shaped Center Bulb, Resistance.

Abstract: The interference of resistance between the two catamaran hulls is a very popular topic to discuss. Errors in designing hull form and determining the distance between the hull will result in a large amount of interference that causes the resistance of the catamaran increased. Some researchers try to reduce the resistance of catamaran due to interference such as changing the shape of the demihull, giving a bulbous bow, and adding a center bulb. The idea to use center bulb on catamarans is still relatively new and still requires a lot of studies. Therefore, in this study the elliptical center bulb will be replaced with a foil-shaped center bulb. The purpose of this study was to obtain the optimal length ($X1$) and diameter ($X2$) foil-shaped centrebulb on the NPL hull catamaran scale model with Fr 0.7 using Response Surface Method (RSM). The optimal size of foil-shaped center bulb is determined by the size that the most makes of ship wave resistance (Rw) to a minimum. The results of the regression equation in Order 1 are $Rw = -0.168X1 + 0.378X2 + 14.862$ and the results of the regression equation in Order 2 are $Rw = -0.020239X1 + 0.061318X2 + 0.201557(X1)^2 + 0.261325(X2)^2 + 0.015(X1X2) + 13.34806$. Optimal center bulb size is obtained at a length of 103.78 mm and a diameter of 26.30 mm with a wave resistance value of 13.23 N. The center bulb size can reduce wave resistance by 11.74% from the initial center bulb model and reduce 4.72% compared to not using a center bulb.

1 INTRODUCTION

Catamarans are double hull ships, which have many advantages over single-hull boats with the same displacement. Among these advantages is the catamaran has a broad deck so that designers are more flexible in arranging the ship's accommodation space. Besides, catamarans have excellent ship stability so that catamarans are safer and more comfortable for passengers (Seif & Amini, 2004; Zouridakis, 2005).

Because catamarans have two hulls, interference between the two hulls is a prevalent topic to be discussed on catamarans. Errors in designing the hull shape and determining the distance between the hulls will result in the amount of interference of the ship's resistance, which makes the resistance of the catamaran ship to increase by almost four times even though the displacement has increased two times compared to each demihull. (Samuel, et al., 2015).

Some researchers researched to reduce the resistance of catamarans due to interference. Iqbal and Samuel have researched to reduce the resistance of catamaran fishing vessels by modifying the shape of the ship's demihull hull using the Luckenby method. The method changes the CSA form of the boat to create a new hull. This method succeeded in reducing the total resistance by 6.5% (Iqbal & Samuel, 2017). The method has been successfully used by Iqbal and Rindo to improve the quality of the seakeeping of catamarans (Iqbal & Rindo, 2015).

Samuel et al. have also used the bulbous bow on catamaran fishing vessels to reduce ship resistance. Ship resistance can either be reduced or increase depending on the type of bulbous bow used. In that case, the kind used to overcome resistance is the nabla type, where the resistance can reduce by 10% (Samuel, et al., 2018).

Other research conducted to reduce the resistance of catamaran vessels has been carried out using the concept of the center bulb, which is bulbous that is between the hulls of the catamaran (Saha, et al., 2005; Danisman, 2014). The center bulb is bulbous between the two hulls of the catamaran (in the middle). The purpose of this center bulb installation is to provide wave interference between two catamaran hulls. When the waves were interfered, it expects that the

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waves will break and reduce the wave resistance. In addition to reducing ship resistance, the utilization of center bulb can also improve the quality of seakeeping of catamaran vessels (Bruzzone, et al., 2008; Zotti, 2007; Aprjal, et al., 2018).

In Saha's research, the center bulb that used is large and placed in the front and rear positions, as in Figure 1. The results of the study provide recommendations that the wave resistance on the catamaran ship with the center bulb depends on size and position of center bulb against catamaran hulls and the interaction of the catamaran wave resistance (Saha, et al., 2005).

Zotti gives fins at center bulb to examine its effect on resistance and the motion of the ship (see Figure 2). The results of the study are center bulb with fin reducing ship resistance at Fr> 0.3 and increasing resistance at Fr <0.3. RAO curve peaks from heaving and pithing center bulb with fins are lower than catamarans without center bulb. This method indicates center bulb with fins has a positive impact on seakeeping ships (Zotti, 2007).

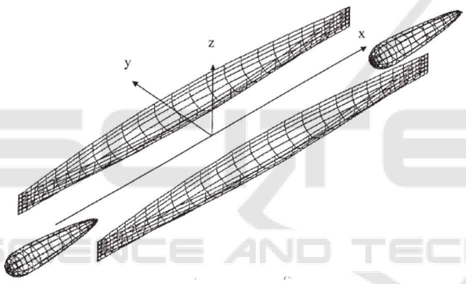


Figure 1: Concept of Center bulb on a catamaran (Saha, et al., 2005).

Danisman optimizes the position and geometry of the elliptical center bulb using Artificial Neural Networks (ANN). The research has succeeded in reducing wave resistance by 15% based on the results of numerical calculations and 13% based on the results of experimental tests in towing tanks (Danisman, 2014). The elliptical bulb center from Danisman has also been applied to catamaran fishing vessels by Samuel and can reduce resistance by 25.76% (Samuel, et al., 2018).

The idea to use center bulb on catamarans is still relatively new and still requires a lot of studies. Therefore, in this study, the elliptical center bulb form was replaced with a foil form. This form is expected to reduce ship resistance further because the tapered back shape of the foil will make the flow pattern streamlined and will not cause vortex shading or repetition as when flow passes through a circular or ellipsoid shape.

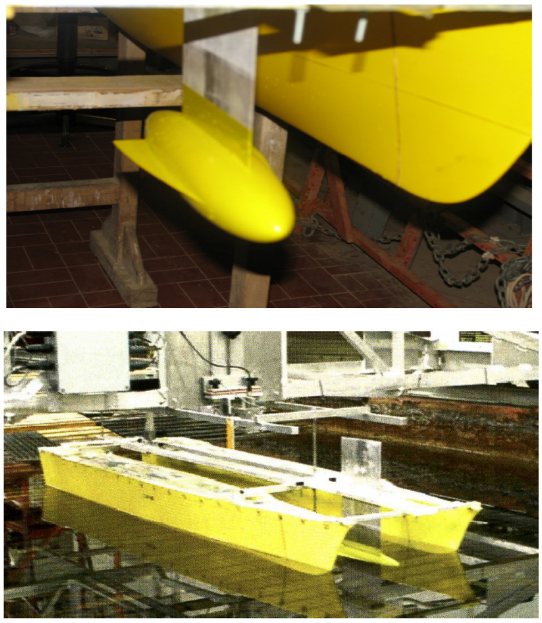


Figure 2: Concept of Center bulb on a catamaran (Zotti, 2007).

To producing maximum performance from the center bulb, the optimization method is used to get the optimal center bulb length and diameter. In this study, the optimization method used is Response Surface Methods (RSM). RSM is one of the most practical and economic optimization techniques that is widely used to evaluate variables from experiments that produce several responses (Bezerra, et al., 2008).

The advantage of this method is that Design of Experiments (DoE) based on RSM does not require a lot of trials/testing and does not require a lot of time compared to actual experimental studies (Ma, et al., 2015).

Some researchers have used this method to optimize several research variables. In the field of structure, Baroutaji optimizes the thickness, diameter, and width of the hollow cylindrical tube to produce the maximum capacity of Specific Energy-Absorbing (SEA) and minimize the Collapse Load (F) (Baroutaji, et al., 2015).

In the field of mechanical engineering, Awad et al., Used the RSM method to maximize brake power and thermal brake efficiency and minimize Brake Specific Fuel Consumption (BSFC) and emissions from NOx, HC, and CO by optimizing three variables, which are fuel, engine speed, and throttle valve (Awad, et al., 2017).

In the field of naval architecture, RSM is very rarely used. Therefore, the research tries to apply the method in the field of naval architecture to minimize the resistance of catamarans by optimizing variable length and diameter of the center bulb.

The purpose of this study was to obtain the optimal length ($X1$) and diameter ($X2$) foil-shaped centrebulb on the NPL hull catamaran scale model with Fr 0.7 using Response Surface Methods (RSM). The optimal size of foil-shaped center bulb is determined by the size that the most makes of ship wave resistance (Rw) to a minimum.

2 METHOD

In this study, the catamaran hull model used is the standard 4a hull model of NPL (Bailey, 1976). The principal dimension and experimental test results in towing tanks both as demihull and as catamarans are found in (Molland, et al., 2017). The shape of the body plan and 3D are shown in Figure 3. The principal dimension of the NPL ship model, when tested in towing tanks, are in Table 1. The results of the residual resistance in the experimental tests are shown in Table. 2.

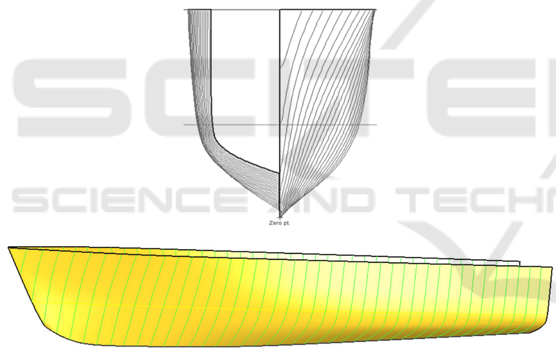


Figure 3. Body plan and 3D model of NPL hull.

Table 1: Principal Dimension of the NPL Hull Model.

Dimension	**Scale Model**
Lwl	1.60 m
B demihull	0.15 m
T	0.10 m
Cb	0.395
WSA	0.346 m^2
Displacement	0.0102 ton
S/L	0.3

Table 2: Residual Resistance of NPL Hull.

	Mode 4a residuary resistance ($C_T - C_{FITTC}$)				
Fr	Monohull	$S/L = 0.2$	$S/L = 0.3$	$S/L = 0.4$	$S/L = 0.5$
0.200	1.909	2.327	2.564	2.495	2.719
0.250	2.465	3.148	3.315	2.937	3.484
0.300	3.273	3.954	4.283	4.396	3.875
0.350	3.585	5.073	4.576	4.064	4.173
0.400	4.100	4.874	5.871	5.900	5.109
0.450	5.305	8.111	7.953	7.220	6.299
0.500	5.526	8.365	7.150	6.650	6.140
0.550	5.086	7.138	5.990	5.692	5.615
0.600	4.431	5.878	5.090	4.880	4.981
0.650	3.924	4.815	4.392	4.269	4.387
0.700	3.477	4.047	3.949	3.834	3.911
0.750	3.128	3.556	3.594	3.512	3.570
0.800	2.904	3.224	3.187	3.252	3.296
0.850	2.706	2.923	2.966	3.054	3.070
0.900	2.544	2.729	2.839	2.881	2.873
0.950	2.398	2.550	2.657	2.767	2.707
1.000	2.272	2.433	2.437	2.687	2.558

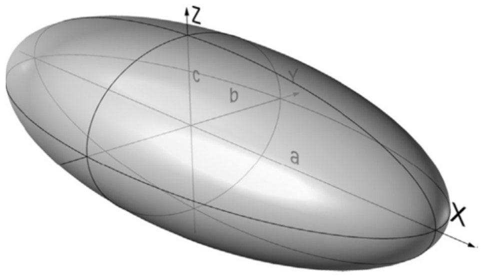
In this study, the optimal size of elliptical center bulb geometry in Danisman was adopted to determining the initial size of the center bulb by comparing its geometry to the ship's geometry (Danisman, 2014). Table 3 shows the principal dimensions of the Danisman ship model. The size and calculation of the center bulb dimensions are listed in Table 4. The comparison is used to determine the geometry of the center of the foil-shaped bulb as shown in Figure 4.

Table 3: Principal Dimension of Danisman's Catmaran (Danisman, 2014).

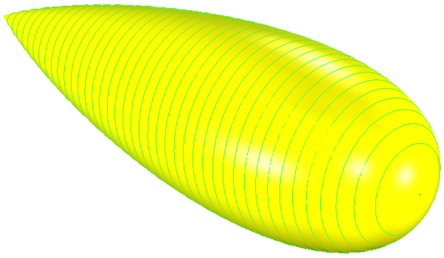
Lwl	2,525 m
B	0,26 m
T	0,14 m
Cb	0,41

Table 4: Comparison of Center bulb Dimension.

Elipsoidal Center bulb (Danisman, 2014)	Ratio	Foil-Shaped Center bulb
Length (a) = 0,141 m Width (b) = 0,062 m Height (c) = 0,034 m	0,141/2,525 = 0,0558 0,062/0,26 = 0,2384 0,034/0,14 = 0,2428	Length (a) = 0,089 m~ 0,090 m Width (b) = 0,037 m; Height (c) = 0,024 m Diameter (d) = (b+c)/2 = 0,0305 ~ 0,040 m



(a)



(b)

Figure 4: Elipsoidal Center bulb Geometry (Danisman, 2014) (a) Foil-Shaped Center bulb Geometry in this research (b).

The position of Center bulb is at 0.5 Lwl and 0.5 T. Ship resistance is simulated at Fr 0.7 (2.77 m/s). Catamarans that use the center bulb at Fr 0.7 have lower resistance than that do not use the center bulb (Danisman, 2014) and (Samuel, et al., 2018).

Ship resistance calculation uses CFD Software called Tdyn. This software can be downloaded and used free of charge but with a limited amount of meshing. To getting the full version, the password was required. It can be downloaded by registering first. The password is valid for a month since registration. Like other CFD software, the Tdyn analysis process is carried out in 3 stages: pre-processor, solver, and post-processor.

Before simulating ship resistance in CFD, the design of the experiment is determined by using the Central Composite Design (CCD). The first stage is Order I by making the minimum and maximum limits of length ($X1$) and diameter ($X2$) center bulb variations. Furthermore, the design of the second phase of the experiment is Steepest Descent. This stage is to find the minimum response value based on the coefficients $X1$ and $X2$ of the linear equation generated from Order I.

Next, the results of $X1$ and $X2$ from Steepest Descent become the initial model in Order II. Like Phase I, the minimum and maximum limits of variation in length ($X1$) and diameter ($X2$) of the center bulb of Steepest Descent are determined again for later to be tested in CFD simulation.

3 RESULTS AND DISCUSSION

3.1 CFD Validation

The validation step is conducted to ensure that the results of the CFD calculation have a small difference to the experimental results. Validated results of the CFD setup, such as mesh sizing (as shown in Table 5), number of steps, initial steps, and time increment, are used to the condition of CFD simulation for other models. These variables affect simulation results.

Table 5: Mesh Sizing.

Ship Surface	0.005
Free surface	0.05
Other Surface	0.1
Max Element	0.5
Transitional	0.5

Mesh size was obtained from several experiments with consideration of the 3 Dimension shape of the ship. The next stage is determining the CFD set up like number of steps, time increments, and initial steps. The final results are presented in Table 6 with the total resistance results, RT of 19.11 N consisting of wave resistance, RW of 13,855 N and viscous resistance, RV of 6.0564 N.

Table 6: Tdyn Setup.

Fr	0.7
No. Of Steps	900
Time Increment	0.08
Initial Steps	81
V (m/s)	2.77
RT (CFD)	19.11 N
RT (Molland)	18.89 N
Error	0.12 %

3.2 Response Surface Methods

3.2.1 Order 1

There are various Designs of Experiment (DoE) (Bezerra, et al., 2008). In this study, the DoE is used using the Center of Composite Design (CCD) with two factors/variables. The regression equation that produced in Order 1 is linear. The variables used are length of center bulb, L (X1) and diameter of center bulb, D (X2). The difference given is ± 5%. The CFD simulation conditions in Table 6 are used for the calculation of wave resistance (RW) following the DoE contained in Table 7.

Table 7: Design of Experiment based on Central Composite Design and The Results of Wave Resistance, RW.

Model	Code		Parameter		Rw (N)
	X1	X2	L (mm)	D (mm)	
1	0	0	90	40	14.99
2	-1	-1	85.5	38	14.529
3	-1	1	85.5	42	15.466
4	1	-1	94.5	38	14.375
5	1	1	94.5	42	14.95

Through the regression method, a linear equation (found in Equation 1) is obtained from the experiments conducted in Table 7. This equation has the value R^2 = 0.908977, where the value can be considered valid enough to be used.

$$Rw = -0.168X1 + 0.378X2 + 14.862 \quad (1)$$

3.2.2 Steepest Descent

This process is carried out to determine the turning point of the tendency of wave resistance (Rw), which continues to fall and no longer matches the results of Equation 1. Based on the coefficients of each variable in the First Order model, the addition (Δ) of each coefficient for doing steepest descent was calculated by using the coefficient X1 as the basis as shown in Equations 2 and 3. Furthermore, the steepest descent process is shown in Table 8 and Figure 5.

$$\Delta X1 = \frac{-0.168}{-0.168} = 1 \quad (2)$$

$$\Delta X2 = \frac{0.378}{-0.168} = -2.26 \quad (3)$$

Table 8: Steepest Descent.

Step	Code		Parameter		Rw - CFD (N)
	X1	X2	L (mm)	D (mm)	
1 (Mod.1)	0	0	90	40	14.99
2 (Mod.6)	1.00	-2.26	94.50	35.49	14.19
3 (Mod.7)	2.00	-4.51	99.00	30.97	13.56
4 (Mod.8)	3.00	-6.77	103.50	26.46	13.35
5 (Mod.9)	4.00	-9.03	108.00	21.95	13.44

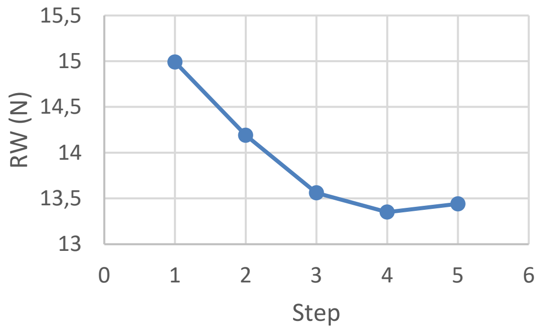


Figure 5: Steepest Descent.

Based on Figure 5, the lowest point is found in Step 4 or in Model 8. The wave resistance then increases in Model 9 so that the variables in Model 8 are used as the central point for experiments in Order 2.

3.2.3 Order 2

Experimental design in Order 2 produces non-linear equations for quadratic functions. For this reason, the number of experiments in DoE was added as in Table 9. The central points (X1 = 0 and X2 = 0) used were Model 8. The code used for the Second Order was set again as shown in Table 9. With reference to Table 9, DoE for Order 2 is shown in Table 10.

Table 9: Code for Orde 2.

	-1	0	1
*X*1, Length (mm)	98.33	103.50	108.68
*X*1, Diameter (mm)	26.46	26.46	27.78

Table 10: Design of Experiment in Order 2 and Wave Resistance, Rw.

Mod	X1	X2	$X1^2$	$X2^2$	X1*X2	Rw (N)
8	0	0	0	0	0	13.35
10	-1	-1	1	1	1	13.92
11	-1	1	1	1	-1	13.95
12	1	-1	1	1	-1	13.55
13	1	1	1	1	1	13.64
14	-1.414	0	1.9994	0	0	13.62
15	1.414	0	1.9994	0	0	13.98
16	0	-1.414	0	1.9994	0	13.79
17	0	1.414	0	1.9994	0	14.05

The regression equation from the experiments conducted in Table 10 is found in Equation 4. The equation has the value $R^2 = 0.540206$. The 3D Surface of Eq. 4 is shown in Figure 6.

$$Rw = -0.020239X1 + 0.061318X2 + 0.201557(X1)^2 + 0.261325(X2)^2 + 0.015(X1X2) + 13.34806 \tag{4}$$

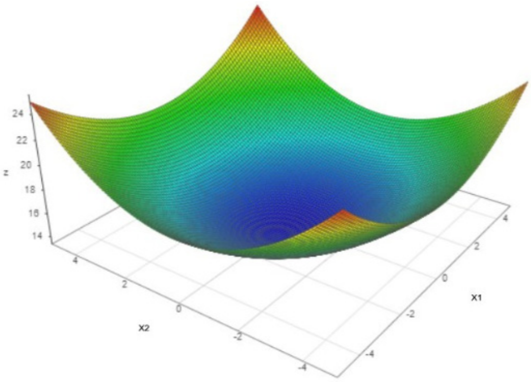


Figure 6: 3D Surface of Second Order Equation for wave resistance, RW.

3.2.4 Optimum Point

To find the minimum value of the Order 2 regression equation (Equation 4), then the first derivative of the equation must have a zero value according to Equations 5 and 6.

$$\frac{dRW}{dX1} = 0 \tag{5}$$

$$\frac{dRW}{dX2} = 0 \tag{6}$$

According to Equations 5 and 6, the optimum point is located at X1 = 0.0546 and X2 = -0.1189 are obtained. Based on the codification in Table 9, the optimum length and diameter are shown in Table 11. The center bulb length, which was 90 mm increased by 15.31% to 103.78 mm. While the center bulb diameter, which was 40 mm reduced by 34.25% to 26.30 mm. Visualization of the comparison of initial center bulb size with optimum center bulb size is shown in Figure 7.

Table 11: Optimum Size of Foil-Shaped Center bulb.

Model	Code		Parameter	
	X1	X2	L (mm)	D (mm)
18 (Optimum)	0.0546	-0.1189	103.78	26.30

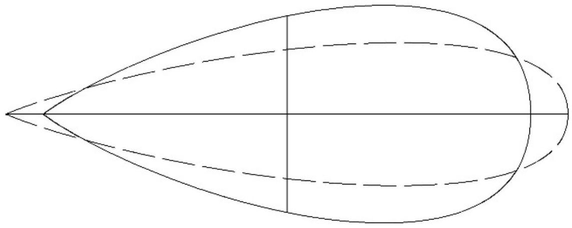


Figure 7: Model 1 (initial model) with solid lines and Model 18 (optimal model) with dashed lines.

3.3 Hydrodynamic Comparisons

The value of the wave resistance, RW from the optimum parameter based on CFD is 13.23 N, while based on Equation 4 is 13.34 N. The difference between the two is quite small at -0.83%.

The comparison of wave resistance between the optimum model (Model 18) and the initial model (Model 1) has been carried out. The optimum model reduces the wave resistance by 11.74% from 14.99 N to 13.23 N compared to the initial model, as presented in Figure 8. This optimization method successfully minimizes the wave resistance from initial center bulb models.

The next discussion is about the comparison of wave resistance using center bulb (initial and optimal models) to models that do not use center bulb. The value of wave resistance that does not use center bulb as stated in the validation section is 13.855 N.

As can be seen in Figure 8, the use of the initial center bulb model adds a wave resistance of 8.19%. This reason is that model has not been optimized. Center bulb configuration is also based only on center bulb geometry, not varying the position of center bulb placement. Besides, the determination of the

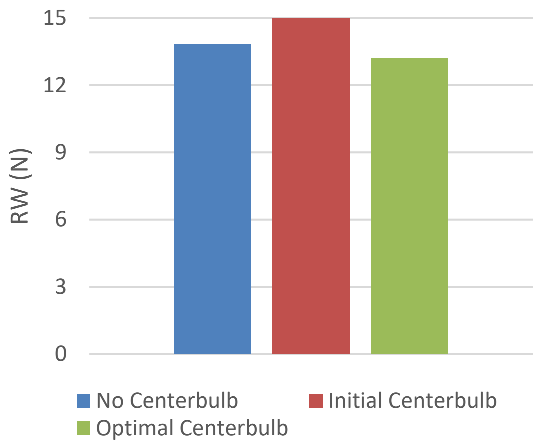
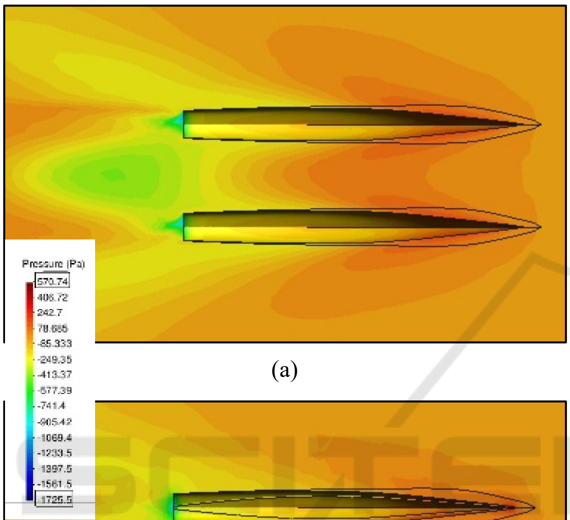


Figure 8: Comparison of Catamaran Without, Initial and Optimum Center bulb.

geometry of the initial model is obtained only by the ratio. So for the initial center bulb model, it is still far from the expectation to reduce wave resistance.

After the foil-shaped center bulb is optimized, the wave resistance decreases by 4.72%. When compared with the results of Danisman's research, this value is not significant enough. The reason is due to the optimization parameters still using two variables, namely length and diameter, whereas in Danisman's used 3 variables, namely height and width length of center bulb. Besides, the configuration of center bulb position was taken into account to produce a significant reduction in wave resistance.



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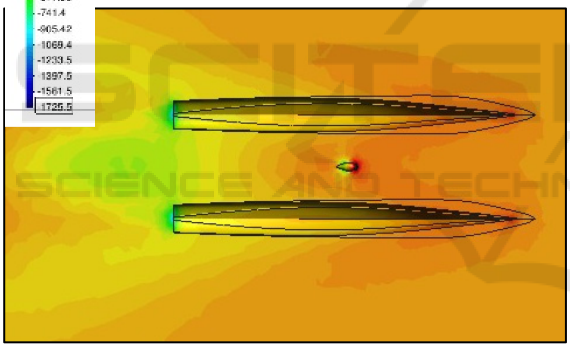

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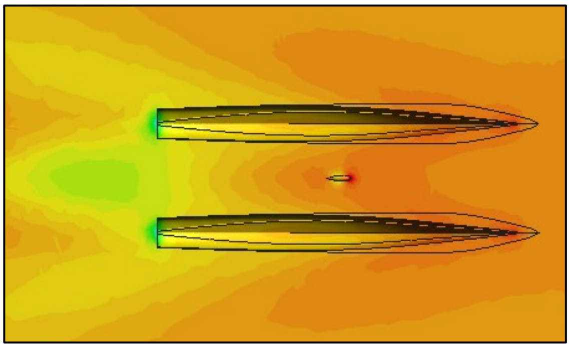


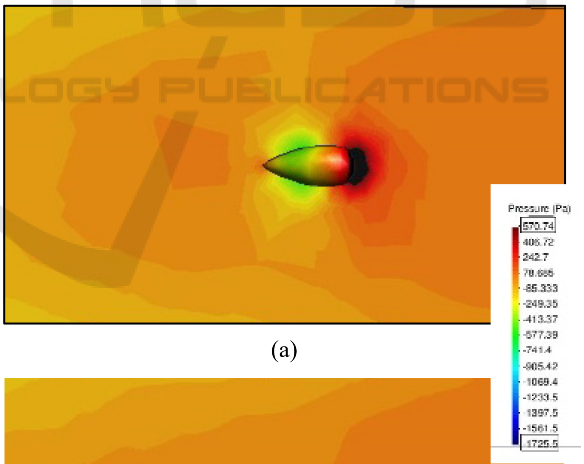
(c)

Figure 9: Comparison of Catamaran Pressure Contours that do not use Center bulb (a), Initial Center bulb (b) and Optimal Center bulb (c).

Figure 9 is an illustration of the pressure contour between the two catamaran hulls seen based on the intersection of the z-axis in the center of the center bulb. It can be seen in Figure 9.a that overall, the pressure between the two hull has a higher pressure than that using center bulb (b and c). This phenomenon indicates that center bulb reduces pressure between the hull.

However, in Figure 9.b the pressure contour increases significantly only in front of the center bulb. The initial center bulb has wide shape making the water flow hit the center bulb. The flow speed will stop for a moment causing the pressure increases. In Figure 9.c. the optimal center bulb shape is slender than the initial model. When the flow hit the center bulb, the pressure did not increase significantly. For more details, see Figure 10.

The results of this study prove that the Response Surface Method (RSM) can be used in field Naval Architecture and successfully implemented as an optimization tool to find the lowest wave resistance based on the size of the center bulb. Overall, the Response Surface Method (RSM) makes it easy to find the optimal value of the shape size of the center bulb.



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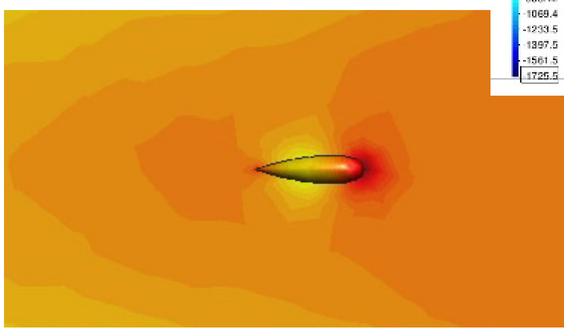

(b)

Figure 10: Comparison of Catamaran Pressure Contours Around Foil-Shaped Center bulb. (a) Initial model (b) Optimum model.

4 CONCLUSIONS

The optimal center bulb length is 103.78 mm or has 15.31% increase from the initial length of 90 mm. The optimal diameter size is obtained at 26.30 mm or reduced by 34.25% from the initial diameter of 40 mm. The optimal model reduces the wave resistance by 11.74% from the initial center bulb model and reduces by 4.72% compared to not using a center bulb. Overall, the Response Surface Method is another approach to determine the optimal size of foil-shaped center bulb in order to reduce wave resistance.

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