Hull-form optimization of KSUEZMAX to enhance resistance performance

Jong-Heon Park¹, Jung-Eun Choi¹ and Ho-Hwan Chun²

¹Global Core Research Center for Ships and Offshore Plants, Pusan National University, Busan, Korea
²Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan, Korea

ABSTRACT: This paper deploys optimization techniques to obtain the optimum hull form of KSUEZMAX at the conditions of full-load draft and design speed. The processes have been carried out using a RaPID-HOP program. The bow and the stern hull-forms are optimized separately without altering neither, and the resulting versions of the two are then combined. Objective functions are the minimum values of wave-making and viscous pressure resistance coefficients for the bow and stern. Parametric modification functions for the bow hull-form variation are SAC shape, section shape (U-V type, DLWL type), bulb shape (bulb height and size); and those for the stern are SAC and section shape (U-V type, DLWL type). WAVIS version 1.3 code is used for the potential and the viscous-flow solver. Prior to the optimization, a parametric study has been conducted to observe the effects of design parameters on the objective functions. SQP has been applied for the optimization algorithm. The model tests have been conducted at a towing tank to evaluate the resistance performance of the optimized hull-form. It has been noted that the optimized hull-form brings 2.4% and 6.8% reduction in total and residual resistance coefficients compared to those of the original hull-form. The propulsive efficiency increases by 2.0% and the delivered power is reduced 3.7%, whereas the propeller rotating speed increases slightly by 0.41 rpm.

KEY WORDS: Bow and stern hull-form optimization; KSUEZMAX; RaPID-HOP; Parametric modification function; Computational fluid dynamics (CFD); Parametric study; Sequential quadratic programming (SQP); Model test.

INTRODUCTION

Hull-form designing in a ship yard is a continual process including the modifying of the hull form, performing calculations and analyzing computational results. This routine is mainly based on subjective judgment hinging on the keen insight and extensive experience of the designer. The speed performances of the initial and the final hull forms are compared with the model tests at the towing tank. Min et al. (2002) investigated the resistance and propulsion characteristics for three different aft-body hull forms of 309k VLCC, i.e., basic, extreme U- and extreme V-form.

It is necessary to apply optimization techniques coupled with hull-form variation and CFD as an objective and practical hull-form design tool. The hull-form optimization using a CFD is composed of three processes which are the variation of the initial hull-form, the performance prediction via a flow analysis of a varied hull-form, and the selection of the optimized hull-form. These three approaches have each developed to be applied in various ways. Various hull-form variation techniques have
been deployed - vertex control, modification function, and form-parameter variation. Vertex control involves expressing the initial hull-form as a curved surface such as a B-spline, and shifting the hull-form with the vertex as the design parameter (Kim and Chun, 2000; Choi et al., 2003; 2005). The upside to this technique is the flexibility of the hull-form variation, but poor fairness after the variation and the challenging control of the hull-form are the downsides. Modification function calculates the varied full-form by reflecting the variation amount that taps into the modification function of the initial hull-form (Suzuki et al., 2004; Tahara et al., 2004). Flexibility and fairness are the advantages, while it is not as easy to manipulate for the designer. The form-parameter variation defines the hull-form with a form parameter for surface modeling (Nowaki, 1993; Softley and Schiller, 2002; Harries et al., 2003; Lowe and Steel, 2003; Jacquin et al., 2004; Han et al., 2012). It boasts strong flexibility and fairness, and ease-of-use; but the initial hull-form is not readily conveyed with a form parameter. Recent research taps into parametric modification function which does not require the initial hull-form to be defined by a form parameter (Kim et al., 2007a; 2008). It shares the advantages of the modification function form-parameter variation, but the variation is restricted by the modification function. There are two ways to conduct flow analysis using CFD, potential and viscous analyses (Kim et al., 2011). Earlier hull-form optimization researches were about decreasing wave-making resistance using potential flow analysis which requires less time for interpretation (Kim and Chun, 2000; Ragab, 2001; Dejhalla et al., 2002; Choi et al., 2003; 2005; Saha et al., 2004; Suzuki et al., 2004; Chen et al., 2006; Choi et al., 2011). The use of viscous analysis has been growing as flow interpretation techniques and computing power develops (Duvigneau et al., 2003; Tahara et al., 2004; 2008; Peri and Campana, 2005; Kim et al., 2007b). One of the optimization techniques widely used in the hull-form optimization in a shipyard is the Sequential Quadratic Programming (SQP, Rao, 1999), which is the gradient-based technique that taps into the differential value of the objective function or the constraint’s design parameter (Kim and Chun, 2000; Choi et al., 2003; 2004; 2005; 2006). The advantages are rapid convergence and computational efficiency. However, this is a local optimizer which may prove challenging to employ in local minima and non-connected feasible regions. The SQP is suitable for a single objective optimization. An advanced Particle Swarm Optimization (PSO; Pinto et al., 2007) is recently used, which is derivative–free and suitable for a multi-objective optimization (Peri and Campana, 2005; Tahara et al., 2006; 2008; Kim et al., 2010).

This research has been optimized by changing the design parameters impacting performance through simulating the manual work of the past. The hull form was altered by adding the variation calculated with a parametric modification function to the initial hull-form. The work was conducted with the bow and stern separated, since the flow around the bow is more non-viscous while the flow around the stern is dominantly viscous. The objective functions for the optimization are the minimum wave-making resistance coefficient ($C_W$) for the bow, and the minimum viscous pressure resistance coefficient ($C_{VPM}$) for the stern.

<table>
<thead>
<tr>
<th>Objective Ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>The objective ship is a wide-breadth slow-speed KSUEZMAX tanker, and the principal dimensions of the full-load draft are the following.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1 Principal dimensions at full-load draft of KSUEZMAX.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length between perpendicular LPP</td>
</tr>
<tr>
<td>Length on waterline LWL</td>
</tr>
<tr>
<td>Breadth B</td>
</tr>
<tr>
<td>Draft T</td>
</tr>
<tr>
<td>Wetted surface S</td>
</tr>
<tr>
<td>Displacement $\nabla$</td>
</tr>
<tr>
<td>Block coefficient $C_B$</td>
</tr>
</tbody>
</table>
The parallel middle part is between St. 8 and St. 15 (33% of LPP). The development of the hull-form was undertaken at a model-ship scale ratio ($\lambda$) of 33.094, and the design speed ($V_S$) of the full-load draft was 16.0 knots, $F_{NM}=0.162$, $R_{NM}=9.86\times 10^6$. The subscript M and S each refer to the model and the ship scales.

**PROBLEM DEFINITION**

The ship sails at constant speed ($V_S$) on calm water. Such condition is assumed to be the same as uniform flow moving downstream at the condition of a fixed ship. The coordinate applied has the flow direction as the axis $x$ (+) and the starboard as the axis $y$ (+), and the opposite direction of the gravitation as the axis $z$ (+). The origin of the coordinate is located where the center plane, midship, and the undisturbed free surface meet. A local coordinate $(X, Y, Z)$ with an origin where the AP, hull bottom, and midship meets was used to effectively undertake hull-form optimization. In the local coordinate, the $X$ direction (+) goes from the AP to the FP, and the $Z$ direction (+) is vertical from the hull bottom.

The optimization was conducted with the bow and stern separated. The flow around the bow is more non-viscous flow, while the flow around the stern is dominantly viscous. The stern hull-form was fixed for the optimization of the bow in which the non-viscous flow is effective, and the bow was fixed for the stern where the flow is mostly viscous. The bow and stern hull-forms obtained through these processes were combined to figure the optimal hull form.

The objective function of bow hull-form optimization is a minimum $C_W$, which may be calculated as Eq. (1) from the potential flow interpretation.

$$C_W = \frac{1}{S} \int c_p \cdot n_x \cdot dS$$

(1)

where $c_p$ is the pressure coefficient non-dimensionalized by $\rho$ (fluid density) and $V_S$, $n_x$ is x-component of normal vector on the hull surface.

The objective function of stern hull-form optimization is minimum value of viscous pressure resistance coefficient ($C_{VPM}$). It has been assumed that the viscous resistance coefficient ($C_{VM}$) is the same as the resistance coefficient of the double-body model (Choi et al., 2010). Viscous resistance coefficient in model scale ($C_{VM}$) is divided into two parts; $C_{VFM}$ (frictional resistance coefficient in model scale) and $C_{VPM}$. $C_{VM}$ and $C_{VPM}$ are the resistance coefficients due to the tangential and the normal shear stresses on the hull surface, respectively.

$C_W$ and $C_{VPM}$ are obtained using the potential- and viscous-flow analysis code of WAVIS version 1.3 (Kim and Van, 2000; Kim et al., 2002). At each stage of the optimization, identical principal particulars of LPP, B, T are the constraints. The displacement is an inequality constraint, which is at least greater than that of the initial hull.

**HULL-FORM OPTIMIZATION**

Optimization was run on the RaPID-HOP code (Kim, 2008). The RaPID-HOP is an automatic optimization program for the hull-form design, which consists of three modules of automatic hull-form variations, numerical prediction of ship performance and optimization. This code is suitable for the hull-form optimization based on the local variations. The optimization based on the global variations of principal dimensions is not taken into consideration.

SQP is applied for the optimization algorithm. SQP is an efficient, gradient-based, local optimization algorithm. This method is to find the gradient ($d_i$) at the design variable ($x_i$) in which the objective function $f(x_i)$ decreases. Then the current design variable is moved along the direction of $d_i$. Two steps are mainly used in the iterative process. The opposite gradient of an objective function $f(x_i)$ is defined as expressed in Eq. (2).

$$d_i = -\frac{\partial f}{\partial x_i} \quad i = 1,2,\cdots,N$$

(2)
where $N$ is the number of design variables. Note that the gradient at a design variable $x_i$ indicates the direction of maximum decrease in the objective function. The current design variable is changed in the domain as expressed in Eq. (3).

$$x_i^{k+1} = x_i^k + \alpha_i^k \cdot d_i^k$$  (3)

where $k$ means $k$-th iteration and $\alpha_i$ represents step size.

Prior to undertaking the optimization utilizing parametric modification functions, a parametric study of the original hull-form was conducted. By studying the impact of the design parameter on the objective function in this study, information on the reference value and variation amount of the design parameter required in the optimization process were obtained. Note that the constraints are checked at every evaluation in the optimization process, whereas not in the case of the parametric studies.

**Bow hull-form optimization**

The parametric modification functions used for the optimization of the bow were SAC shape, section shape (U-V and DLWL type), and bulb shape (bulb height and size).

Fig. 1 shows the value of $C_W$ by gradually increasing or decreasing the design parameter of the parametric modification function. The X-axis is the variation of the design parameter. When one design parameter is changed, the remaining parameters are fixed as zero (0). Note that zero at X-axis denotes the original hull-form since there is no variation of the design parameter. The unit of $\Delta X$ is station. $\Delta Y$ and $\Delta Z$ are non-dimensionalized by $B/2$ and $T$, respectively.

![Fig. 1 Characteristics of wave-making resistance coefficient through the parametric study.](image)

(a) SAC shape. (b) Section shape. (c) Bulb shape.

Table 2 shows the outcome of the parametric study. The ratio shown is that of the changed hull-form $C_W$ against that of original hull-form $C_W$. The original $C_W$ constitutes $0.4995 \times 10^{-3}$. 

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original $C_W$</th>
<th>Changed $C_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC shape</td>
<td>0.4995×10^{-3}</td>
<td>0.4996×10^{-3}</td>
</tr>
<tr>
<td>Section shape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulb shape</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2 Design parameter of parametric modification function to show minimum $C_W$ for the parametric study of bow hull-form.

<table>
<thead>
<tr>
<th>Parametric modification function</th>
<th>Design variable</th>
<th>Value</th>
<th>$C_W \times 10^3$ (ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC shape</td>
<td>$X_0$</td>
<td>15</td>
<td>0.4364 (87.4%)</td>
</tr>
<tr>
<td></td>
<td>$X_1$</td>
<td>20 (FP)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$X_{0C}$</td>
<td>16.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Delta X$ at $X_{0C}$</td>
<td>-0.125</td>
<td></td>
</tr>
<tr>
<td>Section shape</td>
<td>$Z_0$</td>
<td>0.35</td>
<td>0.4204 (84.2%)</td>
</tr>
<tr>
<td></td>
<td>$\Delta Y_{Max}$</td>
<td>-0.05</td>
<td></td>
</tr>
<tr>
<td>DLWL type</td>
<td>$Z_0$</td>
<td>0.30</td>
<td>0.4958 (99.3%)</td>
</tr>
<tr>
<td></td>
<td>$\Delta Y_{Max}$</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>Bulb shape</td>
<td>$Z_2$</td>
<td>0.50</td>
<td>0.4800 (96.1%)</td>
</tr>
<tr>
<td></td>
<td>$\Delta B_y$ at $Z_2$</td>
<td>0.044</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Z_2$</td>
<td>0.50</td>
<td>0.4891 (97.9%)</td>
</tr>
<tr>
<td></td>
<td>$\Delta B_S$ at $Z_{12}$</td>
<td>0.044</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 shows the SAC of the original and varied hull-form. The SAC modification function is the X-axis modification function of $f_1(X)$. $f_1(X)$ is expressed as a 6th-degree polynomial. The condition to compute the coefficient is $f_1(X_0)=0$, $f_1(X_1)=0$, $f_1'(X_0)=0$, $f_1'(X_1)=0$, $f_1(X_{0C})=\Delta X$, $f_1(X_{C1})=-\Delta X$. And $X_{0C}=0.5(X_0+X_C)$, $X_{C1}=0.5(X_C+X_1)$. What is noteworthy is that $\Delta X$ are inverses from $X_C$. $X_0(=15)$ is the location where the change starts (or the starting point of a parallel middle part), and $X_1(=20)$ is FP where the change ends. $X_C(=17.5)$ is fixed between $X_0$ and $X_1$ and SAC does not vary. $\Delta X$ is the variation at $X_{0C}(=16.25)$. The modified hull is generated from the new SAC using the Lackenby method (Lackenby, 1950). The volume at $X_{C1}(=18.75)$ decreases and its hull also becomes slender, as the SAC moves toward the stern by $\Delta X=0.125$, decreasing the wave-making resistance generated from the shoulder wave, also lowering the $C_W$ by 12.6%.

Fig. 3 compares the original and U-V changed hulls. This is shown together with the parametric study of the stern in the following chapter. Section shape (U-V type) modification function calculates the variation of the breadth [$\Delta Y=f_2(X)+f_3(Y)+f_4(Z)$] by multiplying $f_2(X)$, $f_3(Y)$, $f_4(Z)$ which are the modification function of X-, Y-, Z-axis. Add this value to the original hull-form to generate the changed hull-form. $f_2(X)$ is the weighted function where the variation gradually increases from $X_0(=15)$ to $X_1(=20)$, and is referred to as a 4th-degree polynomial. The condition to compute the coefficient is $f_2(X_0)=0$, $f_2(X_1)=1$, $f_2'(X_0)=0$, $f_2'(X_1)=0$, $f_2''(X_1)=0$. $f_3(Y)$ is the weighted function expressed as a 5th-degree polynomial. The
condition to compute the coefficient is \( f_3(Y_0)=0, f_3(Y_1)=0, f_3(Y_2)=1, f_3'(Y_0)=0, f_3'(Y_1)=0, f_3'(Y_2)=0 \). The \( Y_0 \) is the center line of the hull, \( Y_1 = B/2 \) which stays the same even when the hull changes. \( f_4(Z) \) is divided into three; a 1st-degree polynomial is used at \( Z_0 \), a 3rd-degree polynomial between \( Z_0 \) and \( Z_1 \), and a 2nd-degree polynomial beyond \( Z_1 \). The conditions to compute the coefficient are \( f_4(Z_0)=0, f_4(Z_1)=\Delta Y_{\text{Max}}, f_4'(Z_1)=0, \) and \( f_4''(Z_1)=0 \). \( Z_0 (=0.35) \) is a fixed draft where no changes occur in the breadth, and \( Z_1 (=1.0) \) is \( T \). The value of \( Y_{\text{Max}} \) represents variation at \((X_1, Z_1)\), and this constitutes the design parameter as the polynomial changes accordingly. In the parametric study, the hull with a minimum \( C_W \) changes to one with a U-shaped section whose breadth decreased 0.05 at \((X_1, Z_1)\). The effect of the U-shape section is that the waterline shape grows larger in a draft smaller than \( Z_0 = 0.35 \), and leaner beyond this point as seen in Fig. 3. Such an outcome coincides with that of the SAC shape modification function previously outlined. In the full-load draft, the slender waterline shape decreases the \( C_W \) by 15.8%.

Fig. 3 Design parameters for section shape modification (U-V type).

Fig. 4 compares the original and DLWL changed hulls. This is shown together with the parametric study of the stern in the following chapter. Section shape (DLWL type) modification function computes the variation of the breadth \( \Delta Y = f_2(X) \cdot f_5(Y) \cdot f_6(Z) \) by multiplying \( f_2(X) \), \( f_5(Y) \), and \( f_6(Z) \) which are modification function of \( X \)-, \( Y \)-, \( Z \)-axis. Add this to the original hull-form to generate the changed hull-form. \( f_2(X) \) is the same as the modification function applied to the U-V type. \( f_5(Y) \) is the weighted function expressed as a 6th-degree polynomial. The conditions to compute the coefficient are \( f_5(Y_0)=0, f_5(Y_1)=0, f_5(Y_2)=0, f_5'(Y_0)=0, f_5'(0.5Y_0+0.5Y_2)=1, \) and \( f_5'(0.5Y_2+0.5Y_1)=-1 \). \( f_6(Z) \) is divided into three; using ‘0’ for below \( Z_0 (=0.3) \), a 3rd-degree polynomial between \( Z_0 \) and \( Z_1 (=1.0) \), and a 2nd-degree polynomial above \( Z_1 \). The conditions to compute coefficient were \( f_6(Z_0)=0, f_6(Z_1)=\Delta Y_{\text{Max}}, f_6'(Z_0)=0, f_6'(Z_1)=0, f_6''(Z_0)=0, \) and \( f_6''(Z_1)=0 \). There are no variations in the breadth below \( Z_0 \). \( \Delta Y_{\text{Max}} \) refers to the variation at \((X_1, Z_1)\), this constitutes the design parameter as the polynomial changes accordingly. In the parametric study, the minimum \( C_W \) hull grows slightly as the breadth increases 0.006 at \((X_1, Z_1)\). This counters the outcome of the section shape (U-V type). However, \( C_W \) decreases approximately 0.7% as the waterline shape of the bow bulb becomes slender though the shoulder wave is presumed to increase.

Fig. 4 Design parameters for section shape modification (DLWL type).

Figs. 5(a) and 5(b) compare the original hull-form and that after the bulb height and size have been altered, respectively. The bulb-height modification function computes the variation in the height (\( \Delta Z \)) by multiplying \( f_7(X) \), \( f_7(Y) \), and \( f_7(Z) \) which are modification functions of \( f_{\text{BH}}(X, Y, Z) \). This is added to the original hull form to get the changed hull. The modification function in \( X \)-axis is weighted, and is the same as \( f_2(X) \) of section shape (U-V). The modification function in \( Y \)-axis is also
weighted, and is expressed as a 1\textsuperscript{st}-degree polynomial. The conditions to compute the coefficient are \( f_7(Y_0)=1 \) and \( f_7(Y_1)=0 \). The breadth limit does not change even when the local breadth does as above-mentioned. Modification function \( f_8(Z) \) is expressed as a 5\textsuperscript{th}-degree polynomial. The conditions to compute the coefficient are \( f_8(Z_0)=0 \), \( f_8'(Z_0)=0 \), \( f_8(Z_1)=\Delta BH_1 \), \( f_8'(Z_0)=0 \), \( f_8'(Z_1)=0 \), \( Z_0=0 \), \( Z_2(=0.5) \) is the height of the bulb-tip. \( \Delta BH \) denotes the variation at \( Z_2 \), and the variation of the bulb height differs accordingly constituting the design parameter. \( C_W \) of a varied hull-form with the \( \Delta BH \) 0.044 higher decreases approximately 3.9\%. The bulb-size modification function \( f_{BS}(X, Y, Z) \) computes the variation in height (\( \Delta Z \)) by multiplying modification functions \( f_2(X) \), \( f_7(Y) \), and \( f_9(Z) \). The varied hull-form is generated by adding this to the original form.

The modification functions in X- and Y- axis are equal to functions \( f_2(X) \) and \( f_7(Y) \) of the bulb height. The modification function toward Z-axis is expressed as a 6\textsuperscript{th}-degree polynomial \( f_9(Z) \). The conditions to compute the coefficient are \( f_9(Z_0)=0 \), \( f_9(Z_1)=0 \), \( f_9(Z_2)=0 \), \( f_9'(Z_0)=0 \), \( f_9'(Z_1)=0 \), \( f_9(0.5Z_0+0.5Z_2)=-\Delta BS \), and \( f_9(0.5Z_2+0.5Z_1)=\Delta BS \). \( Z_0 \) and \( Z_2 \) are mentioned above. \( \Delta BS (=0.05) \) is the variation amount at \( Z_{12}(=0.75) \), which is the midpoint of \( Z_1 \) and \( Z_2 \), whose value changes the variation of the bulb size, making it a design parameter. The \( C_W \) of a ship whose \( \Delta BS \) is 0.044 larger falls around 2.1\%. Note that the displacement of the bow bulb, which is one of the important parameters for hull-form design, is automatically taken into consideration, i.e., that of the optimized hull form increases by 7.04\% (from 347.8 \( m^3 \) to 372.3 \( m^3 \)).

![Fig. 5 Design parameters for bulb height and size modification.](image)

Such analysis allows the evaluation of what modification function impacts \( C_W \) the most prior to optimization. Applying the modification functions of SAC and section shape (DLWL type), the change of \( C_W \) show concave curves. In the cases of modification functions of section shape (U-V type) and bulb shape (bulb height and size); the \( C_W \) decreases linearly to become a U-shape and respectively higher, and larger.

As a result, the modification functions to expect reducing \( C_W \) are in the order of section shape (U-V type), SAC shape, bulb size, bulb height and section shape (DLWL type). However, the parametric modification functions of bulb height and size are also taken into consideration for the optimization process, though their effects are small at the parametric studies. The design variables of the bulb height and size will affect hull-form variation at widely region since those of the other modification functions are taken into consideration together.

SQP is an efficient optimization algorithm only if the optimum is not a local optimum point. Fig. 6 presents \( C_W \) contour surface and the trace to find the optimization point where two design variables of SAC and section shape modification (U-V type) are used. The solid line on the contour surface denotes the (volume) constraint. The shapes of the contour surface and the constraint clearly show that the domain is convex. Thus, the SQP is a suitable algorithm because the descent always points around optimum solution at any point in the given feasible domain.

Table 3 shows the characteristics of the design variables of parametric modification functions for bow hull-form optimization. The value of \( C_W \) of the optimized bow hull-form constitutes 0.4321 \( \times 10^{-3} \). The optimized hull-form of the bow decreases the \( C_W \) by 13.5\%. 

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The most effective design parameters are $\Delta Y_{\text{Max}} (= -0.0334)$ of section shape (U-V type) and $\Delta B_{S} (= 0.05)$ of bulb size. $\Delta X (= -0.0005)$ of SAC, $\Delta Y_{\text{Max}} (= -0.0067)$ of section shape (DLWL) and $\Delta B_{H}$ of bulb height are relatively small. Note that the design variable of the SAC shape in the optimization is little changed. This may due to the optimal hull forms are already varied by changing the section shape of U-V type.

Figs. 7(a), 7(b) and 7(c) compare the body plans, side profiles, and waterlines, respectively, between the original and the optimized hull-form. Fig. 7(a) is shown together with the optimized hull-form of the stern in the following chapter. The characteristics of the optimized bow hull-form are the following: the section becomes a U-shape, the bulb size grows larger, and the full-load waterline becomes leaner.

### Table 3 Characteristics of the design variables of parametric modification functions for bow hull-form optimization.

<table>
<thead>
<tr>
<th>Parametric modification function</th>
<th>Fixed position</th>
<th>Range</th>
<th>Optimum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC shape</td>
<td>Xc=17.5</td>
<td>-0.5&lt;$\Delta X$&lt;0.5</td>
<td>-0.0005</td>
</tr>
<tr>
<td>Section shape</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-V type</td>
<td>Z0=0.35</td>
<td>-0.05&lt;$\Delta Y_{\text{Max}}$&lt;0.05</td>
<td>-0.0334</td>
</tr>
<tr>
<td>DLWL type</td>
<td>Z0=0.30</td>
<td>-0.05&lt;$\Delta Y_{\text{Max}}$&lt;0.05</td>
<td>-0.0067</td>
</tr>
<tr>
<td>Bulb shape</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulb height</td>
<td>Z2=0.50</td>
<td>-0.05&lt;$\Delta B_{H}$&lt;0.05</td>
<td>-0.0064</td>
</tr>
<tr>
<td>Bulb size</td>
<td>Z12=0.75</td>
<td>-0.05&lt;$\Delta B_{S}$&lt;0.05</td>
<td>0.0500</td>
</tr>
</tbody>
</table>

Fig. 6 Contour surface of $C_{W}$ and design variable history.

Fig. 7 Comparisons of body plans, side profiles and waterlines at full-load waterlines of bow.
Fig. 8 shows the comparison of wave profile (h) on the hull between the original and optimized hull-form at full-load draft. The h is non-dimensionalized by LPP. This is shown together with the full-load waterline. The h of the bow optimized hull-form becomes lower at the shoulder region.

**Stern hull-form optimization**

The parametric modification functions used for the optimization of the stern were SAC and section shape (U-V type, DLWL type). The grids were generated using WAVIS code for the original hull-form. The number of grid cells is approximately 0.3 million (186×40×40). The grids for the changed hull-form are re-arranged according to the algebraic scheme (Tahara et al., 2004; Kim et al., 2007b). The parametric study for stern hull-form optimization is carried out in the same way as that for the bow. Fig. 9 shows the effects of the design parameters on the objective function of $C_{VPM}$. The effect of the parametric modification functions on the objective function is in the order of section shape (U-V type), SAC shape, and section shape (DLWL type).

Table 4 shows the outcome of the parametric study. The ratio shown is that of the changed hull-form $C_{VPM}$ against that of original hull-form $C_{VPM}$. The original $C_{VPM}$ constitutes $0.6841\times10^{-3}$.

![Diagram of wave profiles on the hull between original and optimized hull-form at full-load draft.](image)

**Fig. 9 The characteristics of viscous pressure resistance coefficient through the parametric study.**

**Table 4** Design parameter of parametric modification function to show minimum $C_{VPM}$ for the parametric study of stern hull-form.

<table>
<thead>
<tr>
<th>Parametric modification function</th>
<th>Design variable</th>
<th>Value</th>
<th>$C_{VPM} \times 10^3$ (ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC shape</td>
<td>$X_0$</td>
<td>0.5</td>
<td>0.6809 (99.5%)</td>
</tr>
<tr>
<td></td>
<td>$X_1$</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$X_{oc}$</td>
<td>2.375</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Delta X$ at $X_{oc}$</td>
<td>-0.094</td>
<td></td>
</tr>
<tr>
<td>Section shape</td>
<td>$Z_0$</td>
<td>0.45</td>
<td>0.6202 (90.7%)</td>
</tr>
<tr>
<td>U-V type</td>
<td>$\Delta Y_{Max}$</td>
<td>0.061</td>
<td></td>
</tr>
<tr>
<td>DLWL type</td>
<td>$Z_0$</td>
<td>0.40</td>
<td>0.6836 (99.9%)</td>
</tr>
<tr>
<td></td>
<td>$\Delta Y_{Max}$</td>
<td>-0.009</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 10 shows the SAC of the original and varied hull-form. The only difference between the stern and the bow SAC modification function is the starting and ending point. $X_0 (=0.5)$ is the location where the change starts, and $X_1 (=8.0)$ ends where the parallel middle part starts. $X_C = 4.25$. The volume at $X_{OC} (=2.375)$ decreases and its hull also becomes more slender, as the SAC moves toward the bow by $\Delta X = 0.094$, slightly decreasing the $C_{VPM}$ by 0.5%.

From the parametric study of section shape (U-V type), as shown in Fig. 3, the section becomes a V-shape, that is, leaner and flatter at the region below and above $Z_0 = 0.45$, respectively. This decreases the $C_{VPM}$ by a considerably large value of 9.3%.

From the parametric study of section shape (DLWL type), as shown in Fig. 4, the shape of waterline slightly becomes slender. However, the decreasing of the $C_{VPM}$ is negligible.

Therefore, the section shape (U-V type) may be the most effective modification function to reduce the $C_{VPM}$.

SQP is also applied for the optimization algorithm. Table 5 shows the characteristics of the design variables of parametric modification functions for stern hull-form optimization. The value of $C_{VPM}$ of the optimized stern hull-form constitutes $0.6272 \times 10^{-3}$. The optimized hull-form of the stern decreases the $C_{VPM}$ by 8.3%.

Fig. 7(a) compares the body plans between the original and the optimized hull-form. The characteristics of the optimized stern hull-form are the following: bow waterline becomes leaner; bow section becomes U-shape; bulb size grows larger; stern section becomes V-shape.

![Fig. 10 Design parameters of SAC shape modification for stern region.](image)

**Table 5** Characteristics of the design variables of parametric modification functions for stern hull-form optimization.

<table>
<thead>
<tr>
<th>Parametric modification function</th>
<th>Fixed position</th>
<th>Range</th>
<th>Optimum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC shape</td>
<td>$X_C = 0.2125$</td>
<td>$-0.3 &lt; \Delta X &lt; 0.3$</td>
<td>-0.018</td>
</tr>
<tr>
<td>Section shape</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U-V type</td>
<td>$Z_0 = 0.45$</td>
<td>$-0.07 &lt; \Delta Y &lt; 0.07$</td>
<td>0.03385</td>
</tr>
<tr>
<td>DLWL type</td>
<td>$Z_0 = 0.40$</td>
<td>$-0.07 &lt; \Delta Y &lt; 0.07$</td>
<td>-0.06269</td>
</tr>
</tbody>
</table>

![Fig. 11 Comparison of axial velocity contour and velocity vector between original (left) and optimized (right) hull-form.](image)
Fig. 11 presents the axial velocity contour and velocity vector on the propeller plane. The dashed circle denotes propeller radius. The optimized hull-form presents larger low-speed region at the upper side, and high-speed region at the lower side. This well-represents the effect of the V-shape at the stern as shown in Fig. 6(a), that is, leaner and flatter sections at lower and upper sides, respectively. The nominal wake fractions of the original and optimized hull-form are 0.436 and 0.383, respectively.

The computation was done on Intel (R) Core (TM) i5-2320, CPU 3.00 GHz, Ram 4.00 GB. The computational times per one evaluation using the potential and viscous codes are 1.43 and 63.64 minutes, respectively. And the time consumed was 1.46 hours for the bow and 35.0 hours for the stern. That is the reason why the optimization is conducted with the bow and stern separated.

VALIDATION USING MODEL TEST

The resistance and self-propulsion tests were conducted at a towing tank of KRISO to evaluate the speed-power performance of the optimized hull-form. The scale ratio is the same as that of the computations. During the resistance tests, the model was provided with no appendages. The model-test results are analyzed to a full ship scale according to the two-dimensional model-ship performance analysis method based on the ITTC-1978.

Table 6 shows the comparison of principal dimensions and resistance characteristics between the original and optimized hull-form at the design speed. \( C_{TS} \), \( C_R \) and PE (=\( R_{TS} V_S \), \( R_{TS} \): total ship resistance) are total and residual resistance coefficients, and effective horse power, respectively. \( C_A \) (model-ship correlation allowance) is -0.00027. The optimized hull-form decreases the PE by 1.7%. The difference between \( C_{TS} \) and PE is due to the change of the wetted surface.

Table 6 Comparison of principal dimensions and resistance characteristics between the original and optimized hull-form at \( V_S=16.0 \) knots.

<table>
<thead>
<tr>
<th></th>
<th>Displacement ( (m^3) )</th>
<th>Wetted surface ( (m^2) )</th>
<th>LCB % LPP</th>
<th>( C_{TM} \times 10^3 )</th>
<th>( C_R \times 10^3 )</th>
<th>( C_{TS} \times 10^3 )</th>
<th>PE ( (kW) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>158,127</td>
<td>17,985</td>
<td>2.98</td>
<td>3.620</td>
<td>0.621</td>
<td>1.824</td>
<td>9,463</td>
</tr>
<tr>
<td>Optimized</td>
<td>158,069 (99.96%)</td>
<td>18,087 (100.57%)</td>
<td>2.96 (99.33%)</td>
<td>3.575 (98.8%)</td>
<td>0.579 (93.2%)</td>
<td>1.781 (97.6%)</td>
<td>9,301 (98.3%)</td>
</tr>
</tbody>
</table>

Fig. 12 shows the comparison of PE for various ship speeds between the original and optimized hull-form. The decrease in PE becomes larger at the higher velocity region than the design velocity.

![Fig. 12 Comparison of effective power for various ship speeds between the original and optimized hull-form.](image)
The principal particulars of propeller are the following.

Table 7 Principal dimensions of propeller.

<table>
<thead>
<tr>
<th>No. of blade</th>
<th>Z</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>Dp</td>
<td>8.7 m</td>
</tr>
<tr>
<td>Area ratio</td>
<td>EAR</td>
<td>0.43</td>
</tr>
<tr>
<td>Pitch at 0.7 R_p (P/D)_0.7R</td>
<td>0.7076</td>
<td></td>
</tr>
<tr>
<td>Skew</td>
<td>19.96 deg.</td>
<td></td>
</tr>
<tr>
<td>Rake</td>
<td>0.00 deg.</td>
<td></td>
</tr>
<tr>
<td>Hub/Dia ratio</td>
<td>HDR</td>
<td>0.1550</td>
</tr>
<tr>
<td>Chord length at 0.7 R_p</td>
<td>0.2309 m</td>
<td></td>
</tr>
<tr>
<td>Thickness at 0.7 R_p</td>
<td>0.0154 m</td>
<td></td>
</tr>
<tr>
<td>Section type</td>
<td>KH18</td>
<td></td>
</tr>
</tbody>
</table>

The differences between the two- (or using C_A method) and three-dimensional (or form-factor method) analysis methods are towing force at self-propulsion point (F_{DO}) and wake prediction in full ship scale (w_{TS}), expressed as

\[ F_{DO} = 0.5 \cdot \rho_m \cdot S_m \cdot V_m^2 \cdot (C_{FM} - C_{FS} - C_A) \]  
(4)

\[ w_{TS} = (t + 0.04) + (w_{FS} - t - 0.04) \frac{C_{FS} + C_A}{C_{FM}} \]  
(5)

Table 8 shows the comparison of self-propulsion factors and propulsion characteristics between the original and optimized hull-form. The V-shape of the optimized stern hull-form decreases the w_{TS} by 10.6%. This coincides with the wake characteristics in Fig. 11. This decreasing w_{TS} induces higher J by 4.5%, \( \eta_O \) by 3.0% and \( \eta_D \) by 0.41 rpm. Even if \( t \) declines by 11.8%, \( \eta_{H} = \frac{(1-t)}{(1-w_{TS})} \) only decreases by 1.2% due to the increase in w_{TS}. The increasing \( \eta_R \) by 0.3% has little impact. As a result, the optimized hull-form increases \( \eta_D \) by 2.0% and improves PD by 3.7%.

Table 8 Comparison of self-propulsion factors and propulsion characteristics between the original and optimized hull-form at \( V_S = 16.0 \) knots.

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advance ratio</td>
<td>J</td>
<td>0.468</td>
</tr>
<tr>
<td>Thrust deduction fraction</td>
<td>t</td>
<td>0.238</td>
</tr>
<tr>
<td>Wake fraction</td>
<td>w_{TS}</td>
<td>0.322</td>
</tr>
<tr>
<td>Hull efficiency</td>
<td>( \eta_H )</td>
<td>1.123</td>
</tr>
<tr>
<td>Relative rotative efficiency</td>
<td>( \eta_R )</td>
<td>1.007</td>
</tr>
<tr>
<td>Propeller open-water efficiency</td>
<td>( \eta_O )</td>
<td>0.628</td>
</tr>
<tr>
<td>Propulsive efficiency</td>
<td>( \eta_D )</td>
<td>0.711</td>
</tr>
<tr>
<td>Deliverer power (kW)</td>
<td>PD</td>
<td>13,318</td>
</tr>
<tr>
<td>Propeller rotating speed (rpm)</td>
<td>n</td>
<td>82.25</td>
</tr>
</tbody>
</table>
Fig. 13 shows the comparison of PD and n for various ship speeds between the original and optimized hull-forms. The PD decline becomes larger at the higher velocity region than the design velocity, whereas n increases slightly at whole speed region.

CONCLUSIONS

This paper presents a practical hull-form optimization procedure through simulating the manual work of the ship yard. Using parametric modification functions, the initial hull form is easily deformed according to the variations of the design parameters, which are familiar to a ship designer as design variables. The technique of optimizing the bow and the stern hull-forms separately without altering neither, and combing the two sets of results is practical. Objective functions are the minimum values of wave-making and viscous pressure resistance coefficient for the bow and stern. The result of model test shows that the optimized hull-form brings 1.7% reduction in effective power in addition to 3.7% reduction in delivered power. This work will contribute to hull-form designing in a shipyard to be reflected in the objective information, to reducing the development period through automation, and enhancing the speed performance. Hull-form optimization taking self-propulsion conditions into consideration is suggested for further research.

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REFERENCES


