HULL-FORM OPTIMIZATION OF A 66,000 DWT BULK CARRIER IN IRREGULAR WAVE CONDITION

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Abstract. This paper deploys optimization techniques to obtain the optimum hull form of a 66,000 DWT bulk carrier in calm water and in irregular head waves at sea state 6. Parametric modification functions for the bow hull-form variation are SAC shape, section shape (U-V type, DLWL type). Multi-objective functions are applied to minimize the values of wave-making resistance in calm water and mean added resistance in waves. WAVIS version 1.3 is used to obtain wave-making resistance in calm water condition. The modified Fujii and Takahashi's formula is applied to obtain the added resistance in short waves. The added resistance in long wave is obtained from the potential-flow solver based on the 3-D panel method. And the mean added resistance in irregular head waves is obtained by linear superposition of the wave spectrum and the response function. The PSO (Particle swarm optimization) algorithm is employed for the optimization technique. The resistance and motion characteristics in calm water, in regular head waves and in irregular head waves of the two hull forms are compared. It has been shown that the optimal brings 6.8% reduction in the mean added resistance at sea state 6.

1 INTRODUCTION

Currently shipbuilding companies are asked to develop new hull forms to reduce greenhouse gases. The recent IMO MEPC regulation on EEDI (Energy Efficiency Design Index) makes ship designers to have an interest in the prediction of speed loss due to a real sea condition. Since the added resistance in actual seas is mainly due to winds or waves, it is considered to be effective for the improvement of ship performance in actual seas to reduce the added resistance due to waves (R_{AW}). The powering performance of a future ship should be optimized not only for calm water but also in waves. The bow shapes of large and slow speed ships like very large crude carriers (VLCC) or bulk carriers (BC) are generally blunt. A ship with blunt bow can transport more cargo and easier arrangement on the deck than that with sharp one in equal displacement. This overcomes the demerit of the higher resistance. A ship with blunt bow is usually designed with a focus on lower resistance and higher propulsion efficiency in calm water. Moreover, the reduction of R_{AW} is also to be taken into account at operational condition.

The R_{AW} in short waves is an important factor especially for a large ship's performance, because the significant frequency of a sea wave spectrum coincides with this range. Guo and Steen (2011) revealed that the fore part of ship has dominant contribution on the R_{AW}, that is, the R_{AW} acts on the bow near the free surface dominantly. Many researches showed that the blunt bow shape provides larger R_{AW} (Blok, 1983; Buchner, 1996; Matsumoto, 2002; Hirota et al., 2005; Kuroda et al., 2012; Tvete and Borgen, 2012). A long and protruding bow (named as 'beak-bow') reduces the R_{AW}, but increases overall length (Matsumoto et al., 2000; Orihara and Miyata, 2003; Hirota et al., 2005). Hirota et al. (2005) showed the results of the favorable effect in waves to use 'Ax-bow' and 'LEADGE-bow'. The Ax-bow, a successor of the beak-bow, is to sharpen the bow only above design load waterline (DLWL). The Ax-bow reduces the wave reflection above the DLWL maintaining the same resistance in calm water (Guo and Steen, 2011; Sadat-Hosseini et al., 2013; Seo et al., 2013). The Ax-bow concept was installed on "Kohyohsan", a 172,000 DWT Cape size BC (Matsumoto, 2002). The LEADGE-bow is a straightened bow to fill up the gap between the Ax-bow and the bulb. The whole bow line including under the DLWL is sharpened. Due to this the bow was expected to reduce the added resistance in both ballast and full load conditions. Hwang et al. (2013) applied the design concepts of Ax- and LEADGE-bow to 300k DWT VLCC (KVLCC2). SEA-Arrow (Sharp Entrance Angle bow as an Arrow) is developed and applied to medium-speed ships such as LPG carriers (Ebira et al., 2004). However, in the case of a ship with relatively sharp bow, such as high speed fine ship, the Ax-bow does not reduce the R_{AW}. In such ships, bow flare angle is a useful design parameter. The R_{AW} increases with the bow flare angle (Fang, 1995; Orihara and Miyata, 2003; Kihara et al., 2005; Fang et al., 2013; Jeong et al., 2013). If the vessels encounter short waves most of the time, a sharper bow may be optimal. However, if the encountered waves are in the radiation regime the majority of the operating time a sharper bow is expected to be less, as the motion characteristics are most important in this range. The X-bow of backward sloping bow is developed for not only reducing the R_{AW} but also improving motion characteristics of offshore vessels (Ulstein Group, 2005). The STX bow consists of three parts, i.e., A, B and C (Tvete and Borgen, 2012). The upper bow portion, C, is stretched forward making it sharper. This makes it possible to reduce the flare angles. The middle part, B, comprises a blunt shaped surface of transition area. And the lower part, A, is kept more or less as conventional hulls to minimize the calm water resistance.

The hull-form optimization to satisfy the objective functions taking the wave effect into account through the simulation-based design (SBD) has not been widely applied. Most of the objective functions are related to the seakeeping performances; Wigley and Series 60 with minimum bow vertical motion (Bagheri et al., 2014), SR175 container ship with minimum heave and pitch motions (Campana et al., 2009), ferry with minimum wave height in calm water and absolute vertical acceleration (Grigoropoulos and Chalkias, 2010), combatant ship DTMB 5415 with total resistance and seakeeping (Tahara et al., 2008; Kim et al., 2010).

In this paper, the hull-form optimization in calm water and in short wave through the SBD is proposed. The objective ship is a 66k DWT BC. Hull forms are varied by parametric modification functions. Two objective functions are taken into account; minimum wave-making resistance in calm water and mean added resistance ($\overline{R_{AW}}$) in short crested irregular head waves. The varied hull forms are coupled with the deterministic particle swarm optimization.

2 OBJECTIVE SHIP

The objective ship is 66k DWT BC. Two hull forms had been developed. The former, designed by DSME (Daewoo Shipbuilding & Marine Engineering Co., Ltd.) and KAIST (Korea Advanced Institute of Science and Technology), is initial hull form, which bow hull form is applied to the concept of LEADGE bow to reduce the R_{AW}. The body plan and side view of the initial hull forms are presented in Fig. 1. The principal dimensions at the full-load draft are listed in Table 1. The design speed (V_S) at the full-load draft is 14.5 knots and the Froude number (F_N)=0.170. The F_N is non-dimensionalized by the V_S and LPP.

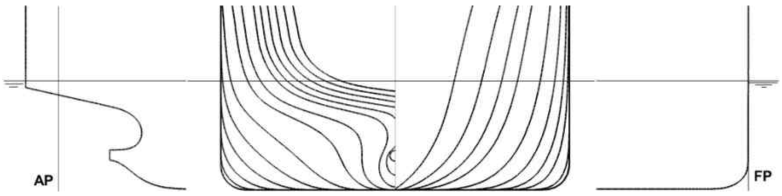


Figure 1: Body plan and side view of the initial hull form

Table 1: Principal dimensions of the initial hull form

Length overall [m]	LOA	200.0
Length between perpendiculars [m]	LPP	196.0
Length on waterline [m]	LWL	200.0
Breadth [m]	B	36.0
Draft [m]	T	11.2
Wetted surface area [m^2]	WSA	9,773
Displacement [m^3]	∇	64,472
LCB from midship (+: forward) [m]	LCB	5.27
Height of center of gravity [m]	KG	7.02
Water plane area [m^2]	WPA	6,501

3 PROBLEM FORMULATION

The mathematical formulation of the optimization problem is expressed as

$$Minimize\ [f_1(\bar{x}), f_2(\bar{x}), \cdots, f_K(\bar{x})] \tag{1}$$

Subject to the equality and inequality constraints

$$h_j(\bar{x}) = 0, \quad \mathrm{j} = 1, \cdots, \mathrm{p} \tag{2}$$

$$g_j(\bar{x}) < 0, \quad \mathrm{j} = 1, \cdots, \mathrm{q} \tag{3}$$

where $f_i(\bar{x})$ is the objective function, K is the number of objective functions, p is the number of equality constraints, q is the number of inequality constraints and $\bar{x} = (x_1, x2, \cdots, x_N) \subseteq S$ is a solution or design variable. The search space S is defined as an N-dimensional rectangle in $\Re^N$ (domains of variables defined by their lower and upper bounds):

$$x_i^{\ell} \le x_i \le x_i^{u},\ \ \mathrm{i} = 1, \cdots, \mathrm{N} \tag{4}$$

The constraints define the feasible area. This means that if the design variables vector $\bar{x}$ be in agreement with all constraints $h_j(\bar{x})$ (equality constraint) and $g_j(\bar{x})$ (inequality constraint), it belongs to the feasible area.

In this study, the bow hull form is to be optimized, whereas the stern hull form remains fixed. The objective functions are to minimize wave-making resistance in calm water (R_W) and the $\overline{R_{AW}}$ in sea state (SS) 6 at V_M=1.292m/s. The constraints are principal particulars of LOA, B and T. The displacement is an inequality constraint, which is kept within ±1% of the initial value.

4 ESTIMATION OBJECTIVE FUNCTIONS AND HULL FORM VARIATION

The objective functions are to minimize the R_W in calm water and the $\overline{R_{AW}}$ in short crested irregular head waves.

The R_W may be obtained from the potential-flow solver which is utilized WAVIS v.1.3. The details and formulations of the numerical methodologies are well described in the works of Kim et al. (1998, 2000). In the present work, 1923 panels on the hull and 1815 panels on the free surface are used. This has been deemed appropriate to identify the proper trends of the objective functions. During the computation the ship is fixed to sink and trim, and the nonlinear free-surface boundary condition is applied.

The R_{AW} in short wave is primarily due to wave reflection. In the short wave range, the numerical methods based on the potential-flow theory may not be reliable since the R_{AW} due to ship motion is almost negligible and the R_{AW} due to wave reflection ($R_{AW}^{ref.}$) is dominant. Semi-empirical formula (Kuroda et al., 2008) is used in this work for calculation of R_{AW} in regular short wave.

The R_{AW} in regular long waves is mainly due to ship motion. The 3-D panel source distribution method based on the frequency-domain approach is used. The R_{AW} is obtained from the direct pressure integration. The details and the formulations of the numerical methodologies are extensively documented in Chun (1992).

The $\overline{R_{AW}}$ in short crested irregular head waves is calculated by linear superposition of the wave spectrum S(ω) and the response function of the R_{AW} (Strom-Tejsen et al., 1973).

$$\overline{R_{AW}} = 2\int_0^{\infty} \frac{R_{AW}(\omega)}{\zeta_a^{\ 2}} S(\omega) d\omega \tag{5}$$

ITTC wave spectrum is used;

$$S(\omega) = \frac{A}{\omega^5} \exp(-\frac{B}{\omega^4})\ \ [\mathrm{m^2 \cdot s}] \tag{6}$$

where ζ_a is wave amplitude, $A = 173 H_{1/3}{}^2 / T_1{}^4$, $H_{1/3}$ is significant wave height, $B = 691 / T_1{}^4$, and T_1 is the averaged period.

A designer-friendly parametric modification tool is adopted for modifying the hull form according to the classical naval architect's approach as well as the office design practice.

The parametric modification function is superimposed on the original hull (H_{old}) to obtain modified geometry (H_{new}):

$$H_{new}(X,Y,Z) = H_{old}(X,Y,Z) + r^{(\ell)}(X) \cdot s^{(m)}(Y) \cdot t^{(n)}(Z) \tag{7}$$

where $r^{(\ell)}(X)$, $s^{(m)}(Y)$ and $t^{(n)}(Z)$ are the parametric modification functions defined as polynomials along the X, Y and Z directions, respectively. The superscripts (ℓ), (m) and (n) are the orders of polynomials. Here, a local coordinate (X, Y, Z) is applied, where the positive X direction goes from the AP to the FP, and the positive Z direction is vertical from the hull bottom. The modified geometry is obtained using the perturbation with specific direction depending on the design parameters. Sectional area curve (SAC) and section shape of DLWL type are used as modification functions.

The SAC and section shape of DLWL parametric modification functions are;

$$X_{new} = X_{old} + r^{(6)}(X) \tag{8}$$

$$Y_{new} = Y_{old} + r^{(4)}(X) \cdot s^{(5)}(Y) \cdot t^{(1)/(3)/(2)}(Z) \tag{9}$$

Details are well documented in Park et al. (2015) and Kim et al. (2016).

5 HULL FORM OPTIMIZATION

The particle swarm optimization (PSO) algorithm is applied for the optimization technique, which is a gradient-free global optimization algorithm. The PSO assumed that each individual in the particles swarm is composed of three N-dimensional vectors, where N is the dimensionality of the search space. These are the current position ($\vec{x}_i$), previous best position ($\vec{p}_i$), and velocity ($\vec{v}_i$). A particle swarm is composed of Nv number of particles, the position of the number i particle is expressed as $\vec{x}_i = [x_{i1}, x_{i2}, \ldots x_{iN}]$ and so the velocity is $\vec{v}_i = [v_{i1}, v_{i2}, \ldots v_{iN}]$. The best position find by the number i particle is $\vec{p}_i = [p_{i1}, p_{i2}, \ldots p_{iN}]$and the best position find by the whole particles is expressed as $\vec{p}_g = [p_{g1}, p_{g2}, \ldots p_{gN}]$. The basic algorithm is simple as follows:

- Step 0 (Initialize): Distribute a set of particles inside the design space. Evaluate the objective function in the particles' position and find the best location (p_b). Note that the effective number and distribution of the initial particles significantly affect the results in the PSO algorithm.

- Step 1 (Compute particle's velocity): At the step k+1, calculate the velocity vector vi for each particle i using the equation:

$$v_i^{k+1} = \chi \left[w^k v_i^k + c_1 r_1^k \left(p_i^k - x_i^k \right) + c_2 r_2^k \left(p_g^k - x_i^k \right) \right] \tag{10}$$

where χ is a speed limit and w is the inertia of the particles controlling the impact of the previous velocities onto the current one. The second and third terms, with weights c_1 and c_2, are the individual and collective contributions, respectively and finally; r_1 and r_2 are random coefficients uniformly distributed in [0,1].

- Step 2 (Update position): Update the position of each particle

$$x_i^{k+1} = x_i^k + v_i^k \tag{11}$$

- Step 3 (Check convergence): Go to Step 1 and repeat until some convergence criterion (e.g. the maximum distance among the particles, a condition on the velocity) comes to a match.

Experimental results indicate that a large value of the inertia w promotes a wide exploration of the global search space. Hence w is initially set to a high value and then gradually decreased ($w^{k+1}=K \cdot w^n$, with $K < 1$) to facilitate the fine-tuning of the current search area. The details and formulations of the numerical methodologies are well described in the works of Kim et al. (2016). The set of parameters adopted in the computations are listed in Table 2.

Table 2: Particle swarm optimization parameters

PSO parameters		Present problem
Constriction parameter (speed limit)	X	1.0
Initial inertia weight	w^0	1.4
Decreasing coefficient for the inertia	K	0.975
Individual parameter	c_1	0.4
Social parameter	c_2	0.3

Fig. 2 shows the distributions of all the swarm particles and the Pareto optimal set. Distribution of the particles is concentrated around a certain point. Among swarm particles, optimal solution is chosen, that sum of the R_W and $\overline{R_{AW}}$ decrease is maximum. The optimal hull form (hereafter 'the optimal') is obtained at ΔXmax=-0.248 and ΔYmax=-0.0698 with ΔR_W=0.003N and $\Delta \overline{R_{AW}}$ =1.505N.

The R_W and $\overline{R_{AW}}$ in SS 6, and the displacement and wetted surface at model scale of the initial and the optimal are compared in Table 3. RR% is a percentage reduction ratio of the value of the optimal to that of the initial. Decreasing amount of the R_W is small. However, the decreasing amount of the $\overline{R_{AW}}$ is much greater than that of the R_W. Displacement of the optimal is reduced by 0.8%, which is within the inequality constraint ±1% of the original value. The WSA also shows the same tendency.

The body plans, the shape of DLWL and three-dimensional view at bow region of the initial and the optimal are displayed in Fig. 3. The cross-sectional shape is changed to U type and section shape of DWL is varied sharply in the bow region, forward of station 17. But remains unchanged aft of station 17.

The wave patterns in calm water around the initial and the optimal are displayed in Fig. 4. The divergent wave is clearly shown. The wave elevations near the fore-shoulder part of the optimal are a little lower than those of the initial. This is due to slender waterline at fore-shoulder part near design draft.

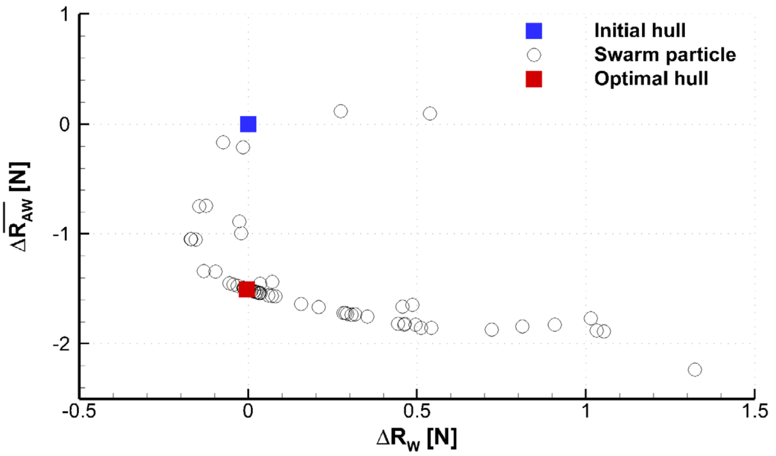


Figure 2: Swarm particles from multi objective optimization of initial hull

Table 3: Wave-making resistance in calm water, mean added resistance in SS 6, displacement and wetted surface at model scale

Hull form	Initial	Optimal	Diff.	RR%
R_W [N]	1.734	1.731	-0.003	-0.2
$\overline{R_{AW}}$ [N]	22.110	20.605	-1.505	-6.8
∇ [m^3]	1.750	1.736	-0.014	-0.8
WSA [m^2]	8.935	8.886	-0.039	-0.5

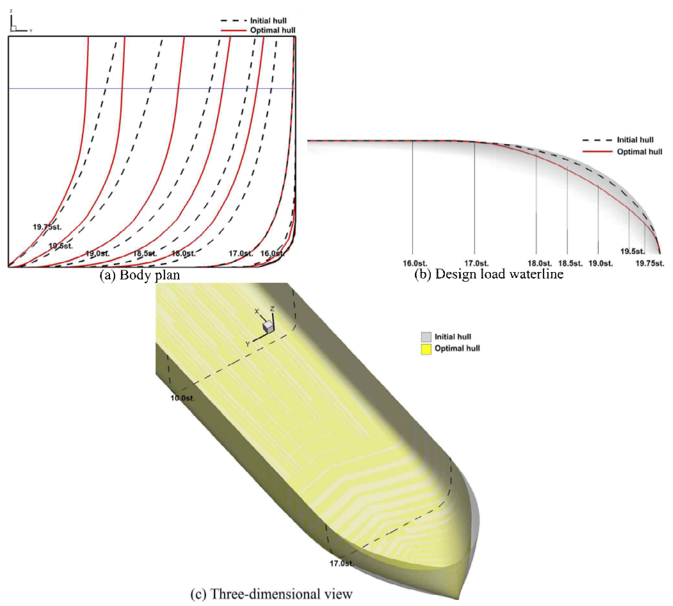


Figure 3: Swarm particles from multi objective optimization of initial hull

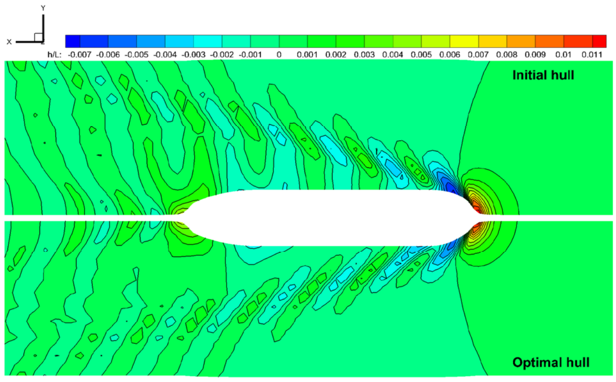
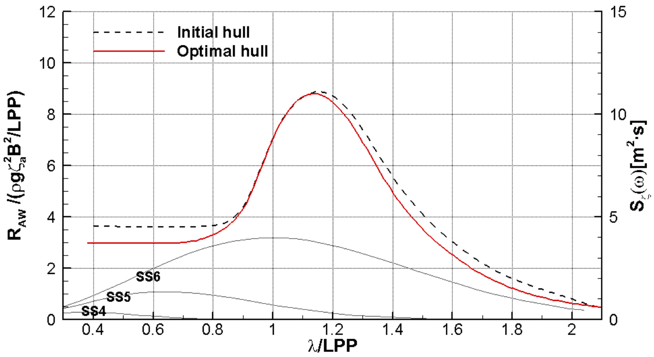
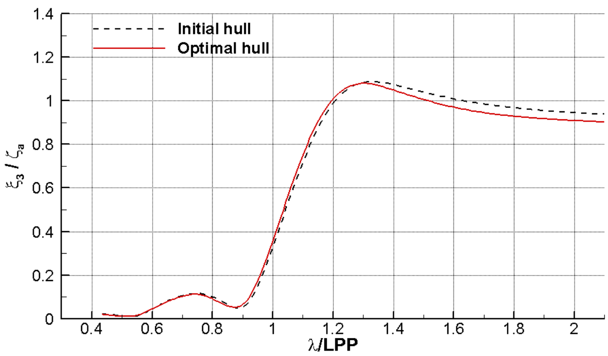


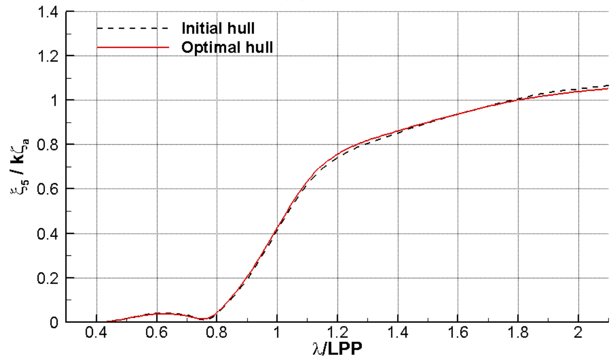
Figure 4: Comparison of wave patterns in calm water at design speed



(a) Added resistance coefficient



(b) Heave



(c) Pitch

Figure 5: Added resistance coefficients and motion RAOs in head sea

Fig. 5 displays the RAOs of the non-dimensional added resistance, heave and pitch motions, where ξ_3, and ξ_5 are heave and pitch amplitudes, and k is wave number. ITTC wave spectra are appended at Fig. 6(a). In short λ (λ/LPP<0.8), the non-dimensional R_{AW} is nearly constant. The the non-dimensional R_{AW} increases as λ increases before the peak value. After the peak value, the the non-dimensional R_{AW} decreases as λ increases. The peak value occurs around λ/LPP=1.0~1.2. There is little difference in the heave and pitch amplitude.

The R_W, R_{AW} at λ/LPP=0.5 and $\overline{R_{AW}}$ at SS 4-6 of the initial and the optimal are compared in Table 4. The optimal is greatly enhanced in the resistance performance in waves. However, the R_W of the optimal is reduced by 0.2%. The R_{AW} is also reduced by 15.1%. The $\overline{R_{AW}}$ at SS 6 of the optimal is reduced by 6.8%; and the SS 4 and 5 are similar showing the RR%=4~8%.

Table 2: Particle swarm optimization parameters

	Wave condition			R_W, R_{AW}, $\overline{R_{AW}}$ [N]			
		$H_{1/3}$ [m]	T_1 [sec]	Initial	Optimal		
				Value	Value	Diff.	RR%
Calm water (R_W)	-	-	-	1.734	1.731	-0.003	-0.2
Regular wave (R_{AW})	λ/L=0.5	-	-	5.865	4.982	-0.883	-15.1
Irregular wave ($\overline{R_{AW}}$)	SS 4	0.056	0.916	0.705	0.676	-0.029	-4.1
	SS 5	0.098	1.206	6.047	5.544	-0.503	-8.3
	SS 6	0.150	1.495	22.110	20.605	-1.505	-6.8

6 CONCLUSIONS

- A practical hull-form optimization technique to minimize the values of wave-making resistance in calm water and mean added resistance in short crested irregular head waves at sea state 6 has been introduced. The hull form including above design load waterline is readily varied using the parametric modification functions for the SAC and the section shape of DLWL. The Pareto optimal set has been obtained using the deterministic optimization technique of PSO.
- The optimal of a 66,000 DWT bulk carrier features more slender at fore-shoulder part. The optimal brings 0.2% reduction in the wave-making resistance and 6.8% reduction in the mean added resistance at sea state 6 in comparison with those of the initial hull form. There is little difference in the heave and pitch amplitude.
- Designer friendly hull-form variation and optimization techniques by taking resistance performances of not only in calm water but also in waves into account at shipyard are developed. Hull form designer will easily acquire objective information and save hull-form development period.

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