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Study on Wave-Breaking Phenomena of Full Hull Forms with and without Protruded Bows

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***Abstract* - The purpose of the present paper is to investigate the effect of protruded bows on the wave resistance of slowly moving full hull forms. For this purpose, a new concept of cargo ship which is called Ultra Large Block coefficient Ship (ULBS) $C_b \geq 0.95$ is used as the basic ship and its bow is modified by adding a bulbous bow. Since ULBS is a very blunt ship and is designed to sail at low-speed, it will have large wave-breaking in front of the bow. As it is stated that the protruded bows are effective in reducing steepness of bow waves and also contribute to the reduction of wave breaking resistance, in the present study, a bulbous bow is considered as an example of flow control devices and is attached to ULBS models in order to reduce the wave-breaking at the bow of ULBS. Then, the wave making resistance coefficient, integration of the square of free surface elevations, and the square of free surface disturbance function $D(x,y)$-values which are related to the wave-breaking phenomena are calculated using Rankine source method and Baba's low speed theory respectively for ULBS models with protruded bows in full load and ballast conditions. The calculated results are compared with those of non-bulbous bow ULBS models. The wave making resistance coefficient results of ULBS models with bulb appear to reduce in the case of full load condition but increase in the case of ballast condition. The integration of square of free surface disturbance function and wave elevation values of ULBS models with bulb, increase for both full load and ballast conditions compared to those without bulb.**

***Keywords* –Bulbous Bow, Free Surface Disturbance function, Ultra Large Block coefficient Ship (ULBS), Wave -making Resistance, Wave-Breaking**

I. INTRODUCTION

Developing or improving ship designs is required for maximizing the cargo carrying capacity with low resistance due to increase in demands for efficient sea transportation. Hence, the green ship concepts of Ultra Large Block Coefficient Ship (ULBS) were proposed and study plans on ULBS had been introduced by Suzuki et.al [1].

As ULBS is an extremely blunt ship with block coefficient larger than 0.95 and L/B smaller than 5, investigation of flow fields around a ship is important to improve its hydrodynamic performances.

Wave-breaking usually occurs in front of the bow of slowly moving full ships. BaBa[2] found that resistance component due to wave-breaking occupies a considerable portion of the total resistance in the ballast condition(shallow draft) from wave and wake measurements of tanker models. From the analytical calculations of semi-submerged ellipsoids, Baba [3] showed that the steeper waves give higher peak value of free surface disturbance function $D(x, y)$ which can be used as a measure of wave-breaking inceptions. Thus, the correlation between wave-breaking and free surface disturbance function was investigated by experimentally and numerically [1],[4]. In the previous study [4], the wave-making resistance coefficient, free surface elevations were evaluated by means of a Rankine source method [5] and the free surface disturbance function $D(x, y)$ -values were evaluated using the method proposed by Hess and Smith [6] according to Baba's low speed theory [3] for an indicator of wave-breaking. For the practical goal of ULBS, various flow control devices such as bulbous bow (that reduces wave breaking resistance), tap type rudder (that keeps course stability), stern tunnel (that reduces flow separation behind the stern), etc., are introduced in order to reduce fluid resistance and improve hydrodynamic performances. A bulbous bow is considered as an example of flow devices for better hydrodynamic performances in the present study. Many research state that addition of bulb to the bow can reduce the total resistance of the ship, most of which are performed with low-speed, full ships. From experimental studies of tanker models with and without protruded bows, Eckert and Sharma (1970) and Taniguchi et al. [7] found that in the ballast condition, the protruded bow is very effective in reducing resistance component due to wave-breaking. The simple calculations suggest that a submerged sphere or a protruding bow works in cancelling $D(x, y)$ -values induced by a main body in front of the bow i.e., the protruding bow is effective in reducing steepness of the local bow waves.

In the present study, a bulbous bow for full hull form ULBS is designed by using a methodology of bulbous bow design by Kracht [9], and the wave-breaking phenomena of ULBS models with protruded bows is investigated. In order to investigate the effect of bulbous bow on wave resistance of full hull form ULBS, the numerical parameters related to wave-making resistance and wave-breaking phenomena from the previous study are evaluated for ULBS model with protruded bows for ballast and full load conditions.

II. RANKINE SOURCE METHOD

The Rankine source method is a numerical calculation method for wave-making resistance acting on the hull surface and wave elevations based on the double model flow with a free surface effect [5]. The origin of the coordinate system is located in an undisturbed free surface at amidship. The x- axis is considered positive in the direction of uniform fluid velocity U towards the aft, the y-axis extends to starboard and the z-axis is vertically upward as shown in Fig. 1. The fluid is considered as inviscid and irrotational in Rankine source method. The total velocity potential ϕ is the sum of velocity potential due to double model flow, ϕ_0 and the perturbed velocity potential representing the effect of free surface, ϕ_1.

$$\phi = \phi_0 + \phi_1 \tag{1}$$

$$\phi_0(x,y,z) = Ux - \iint_{S_0} \sigma_0(x',y',z')\frac{1}{r_0}dz \tag{2}$$

$$\phi_1(x,y,z) = -\iint_{S_1} \sigma_1(x',y')\frac{1}{r_1}dx'dy' - \iint_{S_0} \Delta\sigma_0(x',y',z')\frac{1}{r_0}dS \tag{3}$$

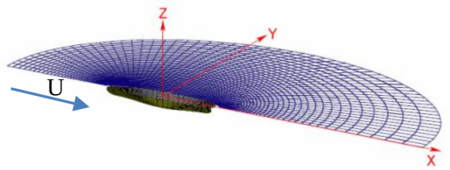

Fig. 1 Coordinate system and source panel arrangement

where S_0 is the hull surface of the double model , S_1 is the undisturbed free surface and

$$r_0 = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}$$

$$r_1 = \sqrt{(x-x')^2 + (y-y')^2 + z^2}$$

The velocity potentials in Eq.(3) are solved under the following hull surface boundary conditions on S_0 and Dawson's double model linearized free surface condition on S_1.

$$\frac{\partial \phi_0}{\partial n} = 0, \quad \frac{\partial \phi_1}{\partial n} = 0 \quad \text{on } S_0 \tag{4}$$

$$\phi_{0l}{}^2\phi_{1ll} + 2\phi_{0l}\phi_{0ll}\phi_{1l} + g\phi_{1z} = -\phi_{0l}{}^2\phi_{0ll} \quad \text{on } S_1 \text{ and } z=0 \tag{5}$$

The pressure on the hull can be calculated from Bernoulli's equation by neglecting the higher order terms of ϕ_0 and ϕ_1 . The equation can be expressed as follows:

$$p - p_0 =$$

$$\frac{1}{2}\rho\left(U^2 - \phi_{0x}^2 - \phi_{0y}^2 - \phi_{0z}^2 - 2\phi_{0x}\phi_{1x} - 2\phi_{0y}\phi_{1y} - 2\phi_{0z}\phi_{1z}\right) \tag{6}$$

The wave height of the free surface can be expressed as

$$\zeta(x,y) = \frac{1}{2g}\left(U^2 - \phi_{0x}^2 - \phi_{0y}^2 - 2\phi_{0x}\phi_{1x} - 2\phi_{0y}\phi_{1y}\right) \tag{7}$$

The wave-making resistance coefficient obtained by Rankine source method is defined by

$$C_w = \frac{R_w}{\frac{1}{2}\rho U^2 L^2}, \quad R_w = -\iint_S p n_x dS \tag{8}$$

where, R_w is wave making resistance, L is ship length between perpendiculars, ρ is the density of water and U is the design speed, n_x is the unit normal on a surface panel, dS denotes the area of panel on the hull surface. The integration of the square of free surface elevations can be evaluated by means of the Rankine source method using the elliptical panel arrangement on the free surface by Eq. (9).

$$I_{\zeta^2} = \int_0^{\infty}\int_{-0.5L}^{-\infty} \zeta^2(x,y)/L^2 dxdy \tag{9}$$

The free surface disturbance function $D(x,y)$ are evaluated by means of Baba low speed theory [3] using Hess and Smith method based on double model flow without a free surface effect[6].

$$D(x,y) = \frac{\partial}{\partial x}\left[\phi_{0x}(x,y,0)\,\zeta_0(x,y)\right] + \frac{\partial}{\partial y}\left[\phi_{0y}(x,y,0)\,\zeta_0(x,y)\right]$$

$$\zeta_0(x,y) = \frac{1}{2g}\left[U^2 - \phi_{0x}^2(x,y,0) - \phi_{0y}^2(x,y,0)\right] \tag{10}$$

$$I_{D^2} = \int_0^{\infty}\int_{-0.5L}^{-\infty} D^2(x,y)/U^2 dxdy \tag{11}$$

The value of numerical parameter I_{D^2} can be obtained by calculating the free surface disturbance function $D(x,y)$ using the mathematical procedures described by Akima [8].

III. Design of a Bulbous Bow

In the present study, in order to investigate the wave-breaking phenomena of full hull forms ULBS with and without protruded bows, a bulbous bow is designed based on a quantitative method developed for low-speed full hull form by Kracht [9],[10]. Kracht [9] classified bulbs into three types according to the shape of the bulb section at the forward perpendicular. These three types are Delta type, O type, and Nabla type. Δ, O and ∇, as shown in Fig. 2. The chosen bulb for ULBS models is O type because it is suitable for full as well as for slender ships.

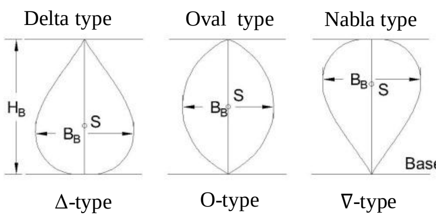

Fig. 2 Types of bulbs by Kracht [9]

According to Kracht [9] , three linear parameters, i.e., the length, breadth, and depth; and three nonlinear parameters, i.e., the area, lateral and volume, are used to describe the bulb form for all practical purposes. The six parameters are non-dimensionalized with ship particulars and are shown in Fig. 3 and Table 1. The bulb parameters defining bulbous bow for ULBS hull (C_b=0.9725) based on draft 0.1m are presented in Table 2.

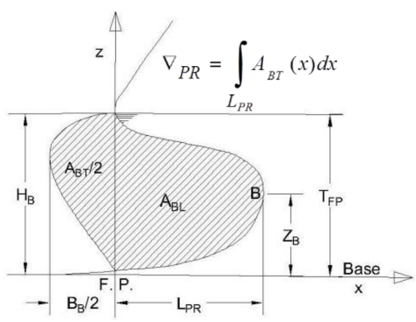

Fig. 3 Descriptions of linear and nonlinear bulb parameters by Kracht [9]

TABLE I

LINEAR AND NONLINEAR PARAMETERS FOR DEFINING BULBOUS BOW

Linear parameters		Non-linear parameters	
Breadth parameter, C_{BB}	B_B/B_{MS}	Cross section Parameter, C_{ABT}	A_{BT}/A_{MS}
Length parameter, C_{LPR}	L_{PR}/L_{PP}	Lateral Parameter, C_{ABL}	A_{BL}/A_{MS}
Depth Parameter, C_{ZB}	Z_B/T_{FP}	Volume parameter, $C_{\nabla PR}$	∇_{PR}/∇_{WL}

B_B : the maximum breadth of the bulb area A_{BT} ; B_{MS} : the maximum breadth of ship; L_{PP} : length betweenperpendiculars; ∇_{WL} is the displacement of ship .

TABLE II
BULB PARAMETERS FOR ULBS MODEL

Bulb parameters for ULBS					
Parameters	C_{BB}	C_{LPR}	C_{ZB}	C_{ABT}	H_B/L
Dimensions	0.300	0.020	0.375	0.150	0.042

IV. RESULTS AND DISCUSSIONS

In the present study, the full hull form ULBS is used as a basic ship and is modified by adding a bulbous bow. The particulars of ULBS models $(C_b \geq 0.95)$ are shown in Table 3. ULBS models with three different drafts, where d =0.1m, d =0.15m are taken as full load condition and d =0.05m is used as ballast condition. Froude number (Fnd) is defined based on draft of the model (d). The number of panels on one-half of the hull surface (without bulb) is 1701 and modified with bulb is 1804. The examples of hull surface panel distribution for ULBS models with and without bulb for three different drafts are shown from Fig. 5 to Fig. 8. The free surface is divided into 4800 quadrilateral panels. The free surface panel distribution starts from 1.5L upstream to 2.5L downstream (L=ship length) and 1.5L in transverse direction having the elliptical boundary, as shown in Fig. 9.

Then, the wave-breaking phenomena of ULBS models with and without protruding bows are investigated for the cases of full load and ballast conditions as shown in Table 4.

According to the previous study [4], the wave-making resistance coefficients and wave elevations of ULBS hulls with bulb are calculated by Rankine source method [5] and the distributions of free surface disturbance function values by the method proposed by Hess and Smith [6] according to Baba's low speed theory[3]. The comparisons of calculated results related to wave-breaking phenomena in the full load and ballast conditions are interpreted for ULBS models with and without protruded bows.

Fig. 10 and Fig. 11 show the comparison of distributions of free surface $D(x, y)$ -values along the waterline of the ULBS models with and without bulb for drafts (d =0.1m, d =0.15m). The distributions of free surface $D(x, y)$ -values along the waterline of ULBS models with and without bulb are almost the same in the case of draft 0.1m, but increase a little in the case of draft 0.15m compared to those without bulb. The rate of change in $D(x, y)$ -values increases with increase in Froude number and draft of ULBS models with and without bulb.

TABLE III

PARTICULARS OF ULBS MODEL [4]

ULBS Models $(C_b \geq 0.95)$			
Length : L (m)	1.500		
Breadth : B (m)	0.300		
Depth : D (m)	0.2500		
Draft : d (m)	0.1000	0.1500	0.0500
Block coeff : C_b	0.9725	0.9741	0.9674
Midship coeff : C_m	0.9950	0.9967	0.9899
Bilge radius : R (m)	0.0187		

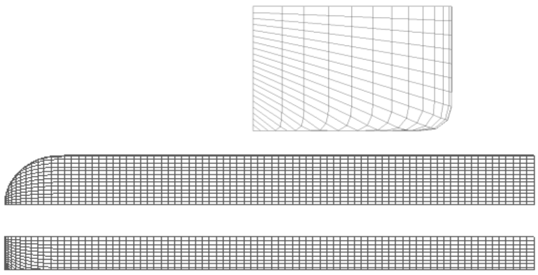

Fig. 5 Hull surface panel arrangement of ULBS model (C_b = 0.9725) without bulb (d =0.1m)

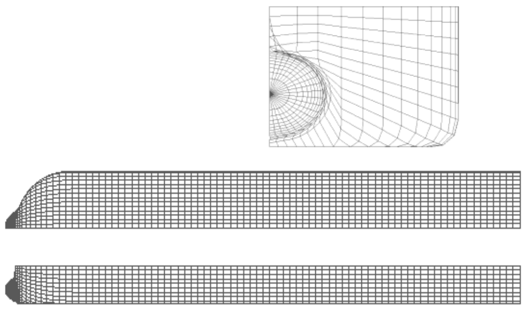

Fig. 6 Hull surface panel arrangement of ULBS model (C_b = 0.9725) with bulb (d =0.1m)

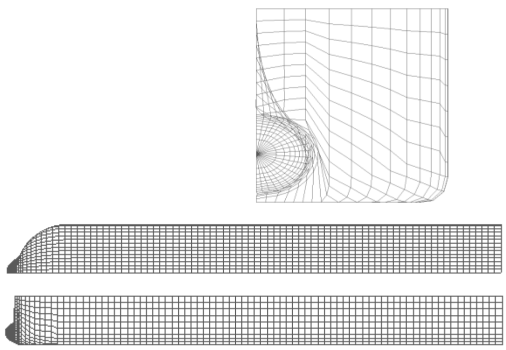

Fig. 7 Hull surface panel arrangement of ULBS model (C_b = 0.9741) with bulb (d =0.15m)

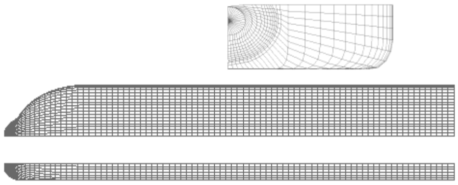

Fig. 8 Hull surface panel arrangement of model (C_b = 0.9674) with bulb (d =0.05m)

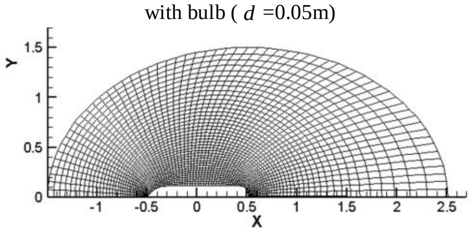

Fig. 9 Elliptical type free surface panel arrangement of ULBS model

TABLE IV

CALCULATION CASES FOR ULBS WITH AND WITHOUT BULB

Condition	Draft(m)	Fn			Fnd		
Full Load	0.10	0.103	0.129	0.155	0.4	0.5	0.6
	0.15	0.126	0.158	0.19			
Ballast	0.05	0.073	0.091	0.110			

Fig. 12 shows the comparison of wave-making resistance coefficients of the ULBS models with and without bulb for drafts (d =0.1m, d =0.15m). The wave-making resistance coefficients C_w -values of the models with bulb reduces in both cases of draft 0.1m and 0.15m compared to those without bulb. This is probably due to the bulbous bow's interference effect which is based on the change of wave distribution around the bow i.e., the waves created by bulb interfere with those created by the hull and reduce wave-making resistance. On reduction of wave making resistance, the effect of bulb is more significant in the case of draft 0.1m.

The relation between Fnd and the integration of square of free surface disturbance function values I_{D^2} of ULBS models with and without bulb are shown in Fig. 13. The calculated I_{D^2} -values with bulb are almost the same as those without bulb in the case of draft 0.1m, but increase a little in the case of draft 0.15m. Fig. 14 shows the comparison of $D(x,y)$ -values along the waterline of models with and without bulb in the ballast condition (d =0.05m). The maximum and minimum $D(x,y)$ -values drastically increase with bulb in the region near the bow compared to those without bulb.

Fig. 15 shows the comparison of numerically calculated wave resistance coefficient C_w of ULBS models with and without bulb in the ballast condition. C_w values of ULBS models with bulb increase disntctly in various speeds except Fn=0.155 compared to those without bulb. The calculated I_{D^2} -values of ULBS models with and without bulb in ballast condition is shown in Fig. 16. The I_{D^2} -values drastically increase with bulb compared to those without bulb. The enormous increase of C_w and I_{D^2} values in the case of ballast condition (d =0.05m) is due to steepening of waves (steeper waves give higher peak value of $D(x,y)$). This is probably because present bulbous bow is generated by bulb parameters based on draft 0.1m. Hence, it may not help to acheive the bulb's effect in the cases of draft 0.15m. and 0.05m. The wave-breaking effect including energy loss due to breaking of too-steep bow waves, gives main contribution to the total bulb effect of full ships. The amount of effect depends on the well-distributed bulb volume in longitudinal direction near to the free surface which influences the momentum deflection. Moreover, it is probably because of the range of integral domain of I_{D^2} since only the region near the bow is integrated and $D(x,y)$ is varied rapidly near the bow in case of full hull forms. Thus, detailed free surface panel should be considered to get the accurate results of I_{D^2} .

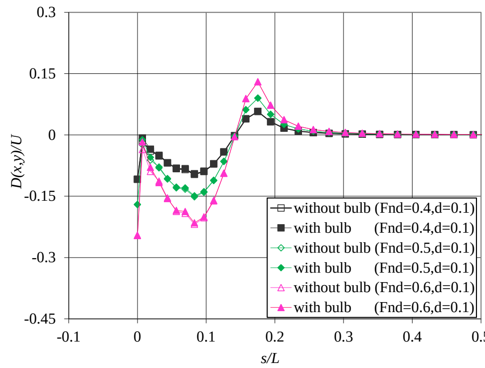

Fig. 10 Comparison of D(x, y) -values along the waterline of the ULBS model with and without bulb(C_b = 0.9725, d =0.1m)

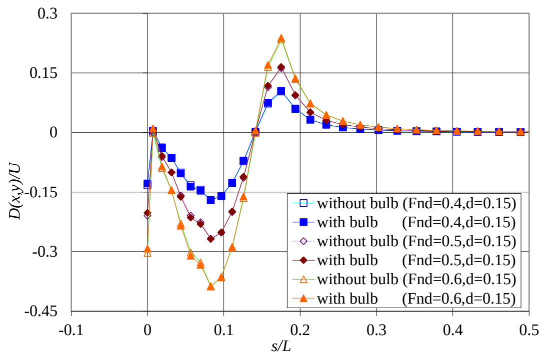

Fig. 11 Comparison of $D(x,y)$ values along the waterline of ULBS model) with and without bulb (C_b = 0.9741, d =0.15m)

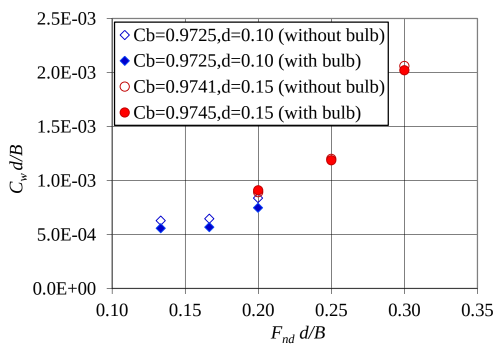

Fig. 12 Comparison of wave-making resistance coefficient values of ULBS models with and without bulb (d =0.1m, d =0.15m)

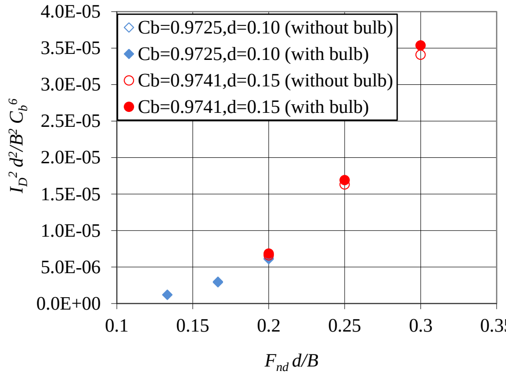

Fig. 13 Comparison of $Fnd - I_{D^2}$ curve of models with and without bulb in full load condition(d =0.1m, d =0.15)

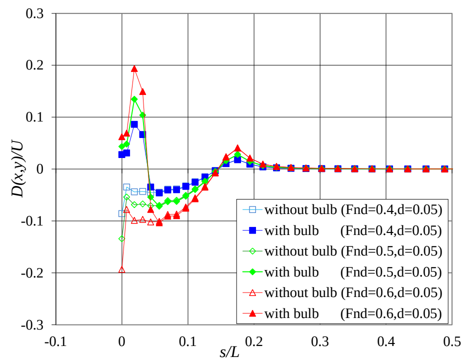

Fig. 14 Comparison of $D(x, y)$ - values along the waterline of the ULBS model with and without bulb (C_b = 0.9674, d=0.05m)

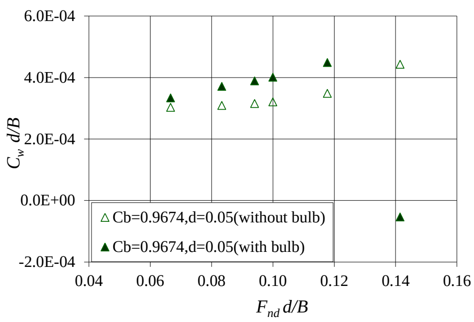

Fig. 15 Comparison of wave resistance coefficient (C_w) for models without and with bulb in the ballast condition(d =0.05m)

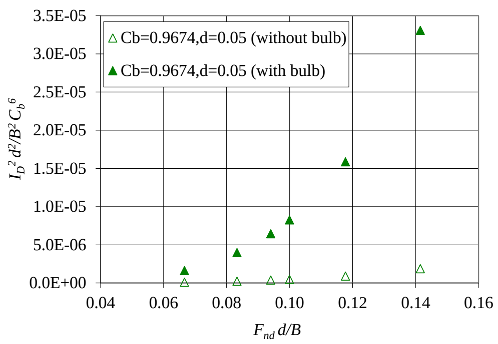

Fig. 16 Comparison of $Fnd - I_{D^2}$ curve of models without and with bulb in the ballast condition ((d =0.05m)

V. Conclusions

In this study, the effects of a bulbous bow upon wave resistance of Ultra Large Block coefficient Ship (ULBS) model have examined from various numerical parameters related to wave-breaking phenomena. The reduction of wave-making resistance coefficient C_w in full load condition is achieved due to the effect of bulb which expresses the resistance change due to interfering free waves systems of main hull and bulb. However, the effect of the reducing wave-breaking at bow might not be achieved for both full load and ballast conditions since wave-making resistance coefficient and integration of square of disturbance function values I_{D^2} increase significantly with bulb. It can be concluded that increase of peak $D(x, y)$ -values with bulb in the ballast condition is due to inadequate design of bulb for unconventional full hull form (ULBS). The flow field analysis tools which employ linearized free surface conditions are not capable of accounting for the bulb effects on non-linear wave-breaking phenomena. The presented design mechanism of bulb is a simple elliptical bulb based on design parameters by Kracht and this can be used as the prior step to numerical optimization of bulbous bow design for full hull forms . In this work, there is no specific treatment in generating bulbous bow for full hull form ULBS. In future works, CFD and SQP (non-linear programming) methods can be used to optimize full hull form ULBS hull with bulbous bow for minimum wave-breaking.

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