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Numerical Simulation for Improvement in Resistance Performance by Bulb Retrofit under Optimal Trim Conditions

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최적 트림 조건하에서 벌브개조를 통한 선박저항성능 개선 연구

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Abstract : *The International Maritime Organization has recently strengthened its marine environment regulations. The energy efficiency index has long been an important indicator of ship design, and now, energy efficiency is being enforced for existing ships as well as new ships. To increase the energy efficiency of existing ships, methods such as retrofitting the bow bulb, selecting an optimized trim during ship operation, and installing an energy saving device have been applied. In this study, the ship resistance was numerically simulated using computational fluid dynamics (CFD) under various bow and stern trim conditions. In addition, the bulb was redesigned to further improve the resistance performance under the selected trim conditions. When the improved bulb was applied, the effective horse power increased by approximately 5%. It is, however, necessary to verify whether the redesigned bulb can reduce ship resistance in waves.*

Key Words : *Existing ship, Energy efficiency, Resistance, Bulb, Trim optimization*

요 약 : 최근 국제해사기구의 해양환경오염규제가 강화되어 오고 있다. 선박의 에너지 효율지수는 선박의 설계관점에서 매우 중요한 지표이다. 더욱이 새롭게 건조되는 선박은 물론 기존 운항 선박에도 에너지 효율지수를 만족하도록 강화하고 있다. 이에 따라 운항되고 있는 기존선박의 에너지 효율지수를 높이기 위해 선수 벌브개조, 운항 중 트림 최적화, 에너지 절감장치등 다양한 방법이 적용되고 있다. 본 연구에서는 전산 유체역학을 이용하여 다양한 선수/선미 트림조건에서 선박의 저항성능을 계산하고 분석하였다. 이를 바탕으로 최적화 된 트림조건에서 선박의 저항성능을 더욱 개선하기 위해 선수 벌브의 형상을 재설계하였다. 그 결과 정수 중에서 개선된 벌브 형상을 적용한 경우, 유효마력이 약 5% 향상되는 것을 확인하였으며, 향후 파도 중에서 재설계된 벌브형상이 저항성능에 미치는 영향을 조사할 예정이다.

핵심용어 : 기존선박, 에너지 효율지수, 선박저항, 선수 벌브, 트림 최적화

1. Introduction

The shipping and shipbuilding industries have had difficulties of operating their business since the implementation of regulating CO_2 emission from ship by IMO and the occurrence of global financial crisis in the second half of 2008. Under this global recession, most shipping firms have started to operate their fleets in slow steaming aiming at improvement of profit ratio per unit transportation. Shipbuilding companies have also encountered new circumstance being required somewhat different concept of hull form design from existing, particularly suitable for slow steaming and EEDI (Pétursson, 2009; Park and Kim, 2014).

There have been many technologies called 'Green ship technology' presented by many engineers associated with maritime sector enable to comply with not only for IMO's environmental regulation but for saving fuel cost as well (Park et al., 2013; Sherbaz and Duan, 2014). It is well known that most green ship technology is nothing new, but rather one that has been developing by the combination of each individual technology existing already

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(Seo et al., 2015; Kim et al., 2019; Lee and Park, 2021). This paper covers verification of the effectiveness of the combination of trim optimization and bulb retrofit for a 6,800 TEU container ship under slow steaming in this study.

2. Numerical analysis

For the numerical calculation, flow direction is positive x-axis, starboard direction is positive y-axis and opposite direction of gravity is positive z-axis is used on a orthogonal coordinate system. The continuity and momentum equation are used as a governing equation (1), (2) and coordinate is x_i=(x,y,z). The governing equation can be simply expressed by using average and fluctuation velocity defined as $\mu_i = (\mu, v, w) = \overline{\mu_i} + \dot{\mu_i}$.

$$\frac{\partial \overline{\mu_i}}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \overline{\mu_i}}{\partial t} + \overline{\mu_j}\frac{\partial \overline{\mu_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\mu\frac{\partial \overline{\mu_i}}{\partial x_j} - \rho\overline{\dot{\mu_i}\dot{\mu_j}}\right) \tag{2}$$

Here, μ: viscosity coefficient, p: static pressure, ρ : density of water, $-\rho\overline{\dot{\mu_i}\dot{\mu_j}}$: Reynolds stress.

Mesh generation and numerical calculation were carried out using CFD commercial code of the STAR-CCM+ v11.06. Trimmed mesh method has advantage to set mesh size small or large economically through the configuration control of mesh density in accordance with each flow characteristics is used. Total about 1.3 million number of grid with 6 prism layers for calculation of the flow near boundary layer are created as shown in Fig 1.

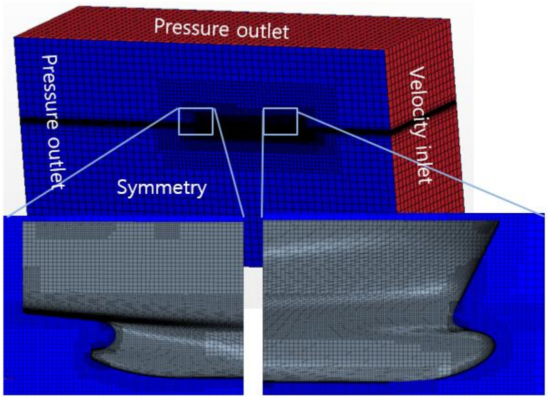


Fig. 1. Generated mesh for a 6,800 TEU container ship.

3. Trim optimization

To analyze changes in wave patterns and total resistance of model scale in slow steaming condition for a 6,800 TEU container ship, 40 % of DMCR (Derated Maximum Continuous Rating) is selected to confirm ship speed for this analysis through investigation about actual ship voyage data presented by a shipping company. Table 1 show the principal dimension of the 6,800 TEU container ship. The length between perpendiculars is 292 m, the breadth is 40 m and the draft is 12 m. Numerical simulations were performed at the model scale for comparison with the model test

Table 1. Principal dimensional parameters of the ship

Parameter	Value
Length between perpendiculars (L_{PP})	292 m
Molded breadth (B)	40 m
Design draught (T)	12 m
Displacement (▽)	85,435 m^3
Wetted surface area (WSA)	13,673 m^2
Scale ratio	40.214

Total 5 cases of trim condition which were available for an actual existing ship are considered to investigate optimum sailing position at each Froude number (Fn) presented in Table 2. Original design speed is Fn:0.255 and it is considered to compare resistance performance with those of in slow steaming. It was investigated from the actual ship voyage data that the most frequent ship speed is Fn:0.173 in slow steaming and Fn:0.163 and 0.183 are considered additionally for more accurate analysis on the resistance performance in the range of slow ship speed. The constraint for this analysis is decided as a volume below design draft for keeping same deadweight of all cases. In Table 2, + sign and - sign indicates bow trim and stern trim respectively. Fig. 2 shows the sketch for the draft change corresponding to each trim condition and it is noticed that the transom in -2 m stern trim is submerged partially.

Table 2. Trim and velocity conditions

Trim (m)	T_a / T_f [m]	Fn
+2	10.86 / 12.86	0.163 0.173 0.183 0.255
+1	11.43 / 12.43	
0	12.00 / 12.00	
-1	12.56 / 11.56	
-2	13.11 / 11.11	

Here, T_f : Draft by of bow, T_a : Draft by of stern,
Fn : Froude number

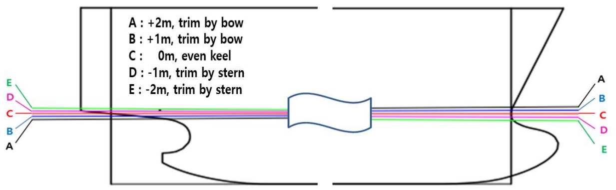


Fig. 2. Draft changes by trim variation.

Prior to full scope of calculation, a numerical analysis is carried out under Fn:0.255 due to only existence of model test result in that speed. The model test was conducted at Hyundai heavy industries. s a result it is verified that there is approximately 1 % of total resistance difference between EXP and CFD as shown in Table 3.

Table 3. Comparison of R_{TM} between EXP and CFD

Item	EXP	CFD	Difference [%]
R_{TM} [N]	70.082	69.337	1.06

Here, R_{TM} : Total resistance

Table 4 shows the summarized result from full scope calculation intended for this study. There is just 1 % of total resistance reduction at Fn:0.255 combined with +1 m of bow trim condition while it is decreased up to 3 % at Fn:0.173 combined with +1 m bow trim condition. In contrast, it is shown that there is increment for total resistance at every ship speed combined with all stern trims and maximum 6 % of increase is observed at Fn:0.163 combined with -2 m stern trim.

Table 4. Comparison of each resistance component for various trim conditions and ship speeds

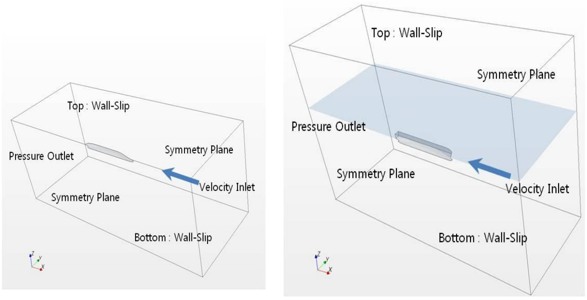
Fn	Trim (m)	Total resistance [%]	Pressure resistance [%]	Frictional resistance [%]
0.163	+2	99	88	101
	+1	99	93	100
	0	100	100	100
	-1	102	120	100
	-2	**106**	152	101
0.173	+2	98	89	99
	+1	**97**	91	98
	0	100	100	100
	-1	101	119	99
	-2	105	146	100
0.183	+2	99	88	101
	+1	99	89	100
	0	100	100	100
	-1	102	116	100
	-2	105	145	100
0.255	+2	100	95	101
	+1	99	96	100
	0	100	100	100
	-1	101	108	100
	-2	104	118	101

4. Form factor assumption in trimmed condition

To identify the cause of change in total resistance more specifically, additional study of separating total resistance into wave resistance and viscous resistance is required.

First, two different computational domains are devised. One is to ignore free surface effect for getting only viscous resistance component. Fig 3(a) shows the sketch of the composition of volume grid and boundary conditions for ignorance of free surface effect. In contrast, the other is the computational domain showing in Fig 3(b) is to consider free surface effect.

The formation of two domains below free surface level is exactly identical but they can be distinguished by just presence or absence of the grid above free surface.



(a) without free surface (b) with free surface

Fig. 3. Computational domain and boundary condition for considering w and w/o free surface.

Discrimination of computational domain by free surface grid allows wave making resistance component to be separated logically by the difference of total resistance calculated from two different domains. And then form factor, *k* can be also obtained by 1978 ITTC performance prediction method showing in Equation (3).

Equation (3) is a way to classify total resistance as wave making resistance and viscous resistance which can be separated into 3-D form resistance ($k \cdot C_{FM}$) and friction resistance presented by ITTC in 1957.

$$C_{TM} = C_{FM}(1+k) + C_W \tag{3}$$

Here, C_{TM} : total resistance coefficient

C_{FM} : friction resistance coefficient by model-ship correlation curve presented by ITTC in 1957

C_W : wave making resistance coefficient

k : form factor

To verify validity of this approach the results from CFD and EXP are compared in Table 5. The difference of form factor, *k* between CFD and EXP shows consistency as 4 % not only for Fn:0.173 but for Fn:0.255 as well. The gap and consistency are deemed to be acceptable for this study. Getting form factor by CFD also allows prediction of more reasonable effective power in full scale of a ship. In addition, assorting resistance components in compliance with ITTC 1978 method could give useful information to hull form designer to create their initial concept for a hull form development under slow ship speed. Further, it could help ship operator to do more accurate economic comparative evaluation corresponding to trim variation for their fleet.

Table 5. Form factor comparison between CFD and EXP at low and high speed

Fn	CFD			EXP	Difference [%]
	R_{TM} [N]		(1+*k*)		
	w/ free surface	w/o free surface			
0.173	30.9	29.2	1.062	1.105	4
0.255	67.6	59.5	1.063	1.105	4

Table 6 show the proportion and resistance components for various trim conditions at Fn:0.173 and Fn:0.255. The total resistance (R_t) of a ship consists of wave making resistance (R_{wav}) and viscous resistance (R_{vis}). R_t, R_{wav} and R_{vis} are created by the amount of increase and decrease on the basis of even trim under assumption that all values at each ship speed in even trim is 100 %.

The proportion of the wave making resistance (P_{wav}) is about 6 up to 13 % corresponding to every trim variation combined low speed range (Fn:0.173) and about 12 to 18 % in design speed (Fn:0.255). Wave making resistance (R_{wav}) is increased in every stern and bow trim variation combined with all ship speeds compared to one of even trim. However the viscous resistance (R_{vis}) was rather decreased in all trim conditions

Total resistance (R_t) is maximally decreased by 3 % and 1 % under +1 m bow trim condition of Fn:0.163 and Fn:0.255. It was confirmed that the reduction in total resistance according to the trim change was all made by the decrease in viscous resistance. This trend is similar to the results of previous study (Park et al, 2013).

Table 6. Comparison of resistance components calculated by utilization of form factor

Fn	Trim [m]	$P_{wav.}$ [%]	$P_{vis.}$ [%]	R_t [%]	$R_{wav.}$ [%]	$R_{vis.}$ [%]
0.173	+2	9	91	98	168	94
	+1	8	92	**97**	148	**94**
	0	**6**	94	100	**100**	**100**
	-1	11	89	101	198	95
	-2	**13**	87	105	**249**	96
0.255	+2	17	83	100	105	95
	+1	16	84	**99**	104	**95**
	0	**12**	88	100	**100**	**100**
	-1	17	83	101	106	96
	-2	**18**	82	104	**107**	97

Here,

P_{wav} : Wave making resistance proportion occupied in total resistance of model scale(%)

P_{vis} : Viscous resistance proportion occupied in total resistance of model scale(%)

R_t : Percentage of total resistance change (%)

R_{wav} : Percentage of wave making resistance change (%)

R_{vis} : Percentage of viscous resistance change (%)

5. Bulbous bow retrofit

Recently, due to the exhaust gas regulation of ships, it is becoming more frequent to operate ships at low speeds. Accordingly, it is necessary to bulbous bow retrofit for suitable for low-speed operation. This section describes examination of the effectiveness of bulbous bow retrofit which is optimized at design draft and low speed, Fn:0.173. Table 7 shows analysis conditions. From ORG hull (original hull), very small amount of wetted surface area and volume is decreased in Reform type but it is permissible.

Table 7. Analysis conditions for bulbous bow retrofit

Trim [m]	T_a / T_f [m]	Fn	Model scale	
			WSA[m^2]	▽[m^3]
0 (Even)	12 / 12	0.173, 0.255	ORG:8.455 REFORM:8.439	ORG:1.314 REFORM:1.312

Fig 4, 5 shows the comparison of bulbous bow shapes. Herein, ORG means the original bulbous bow shape for a 6,800 TEU container ship and REFORM means the reformed bulbous bow shape for this study.

Two different ship speeds which are representative of the most frequent operating speeds among ship's slow (Fn:0.173) and high speed (Fn:0.255) conditions respectively are considered to investigate the effect on the bulbous bow retrofit.

Table 8 shows the total analysis cases and each result from CFD. Through precedent study on trim optimization and form factor prediction, it is pre-confirmed that the viscous resistance is the most dominant resistance component for reducing total resistance. Each resistance and power value indicates percentage difference to that of the model with ORG type. It was confirmed that the total resistance decreased by 2 % and the effective horse power (EHP) decreased by 4 % due to the modified bulbous bow under Fn:0.173. The improved REFROM type reduced the effective horsepower by about 4 % at low speed (Fn:0.173), but did not increase the effective horsepower at high speed. (Fn:0.255)

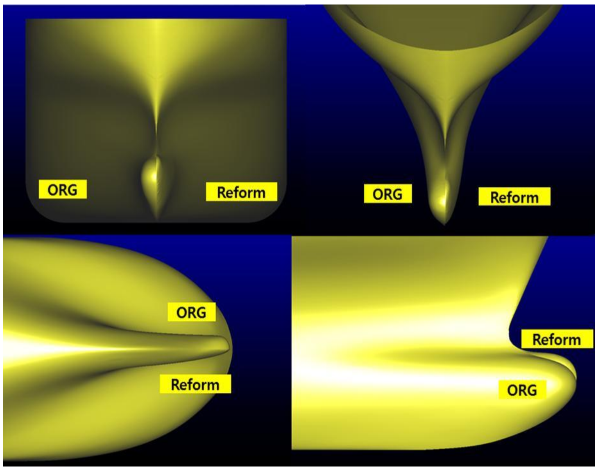


Fig. 4. Comparison of bulbous bow shape.

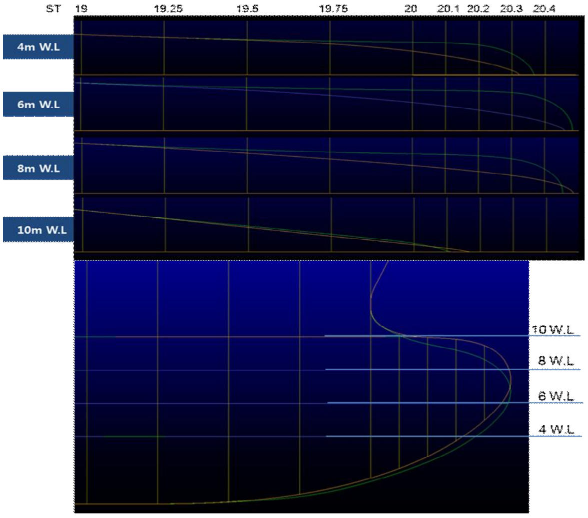


Fig. 5. Comparison of waterline shape.

Table 8. Comparison of resistance performance

ITEM	T_a / T_f [m]	Fn	R_t [%]	R_{wav} [%]	R_{vis} [%]	P_{eff} [%]
ORG	12/12	0.173	100	100	100	100
REFORM			98	175	94	96
ORG		0.255	100	100	100	100
REFORM			100	106	94	100

For this reason the bulbous bow shape is reformed by the view point aiming at reducing stagnation area in bulbous bow end and improving negative pressure distribution around the bulbous bow as shown in Fig 6.

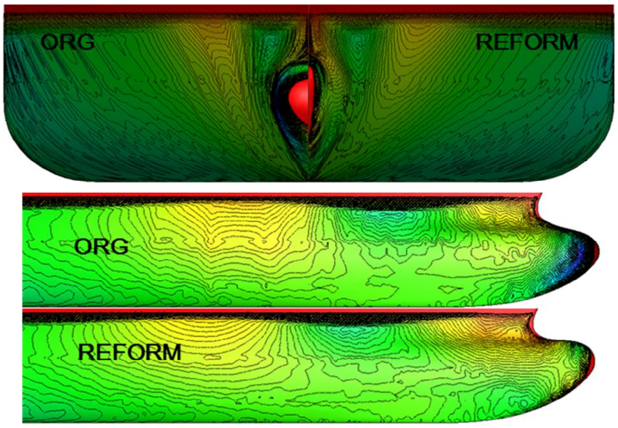


Fig. 6. Comparison of pressure contour on the hull surface between ORG and REFORM (even trim condition at Fn:0.173).

6. Synergy of optimum trim and bulbous bow retrofit

The combination study of trim optimization and bulbous bow retrofit is conducted in order to estimate feasible figure of total resistance and EHP reduction for a general container ship approximately. The total resistance was increase in all condition under trim by stern. Therefore, additional calculations were carried out only under trim by bow condition such as Table 9.

Table 9. Analysis conditions for the REFROM type with modified bulbous bow

Trim [m]	T_a / T_f [m]	Fn	Model scale	
			WSA[m^2]	▽[m^3]
+2	10.86/12.86	0.173, 0.255	ORG:8.353 REFORM:8.338	ORG:1.314 REFORM:1.312
+1	11.43/12.43		ORG:8.402 REFORM:8.386	
0	12/12		ORG:8.455 REFORM:8.439	

For all results shown in Table 10, which is arranged based on relative comparison with the even keel result of ORG type. When comparing to the results of trim optimization described in Table 4, the optimum trim condition showing the least total resistance and EHP values among all analysis cases of REFORM differs from that of ORG as shown in Table 10.

Table 10. Comparison of resistance performance corresponding to each trim condition of REFORM type

TYPE	TRIM	Fn	R_t [%]	R_{wav} [%]	R_{vis} [%]	P_{eff} [%]
ORG	+2	0.173	98	168	94	96
REFORM			97	141	94	95
ORG	+1		97	148	94	95
REFORM			97	152	94	95
ORG	0		100	100	100	100
REFORM			98	175	94	96
ORG	+2	0.255	100	105	95	100
REFORM			99	104	95	100
ORG	+1		99	104	95	98
REFORM			99	105	94	99
ORG	0		100	100	100	100
REFORM			100	106	94	100

This is obviously derived from fluid flow around fore body changed by bulbous bow retrofit. In addition, it also influences the tendency of the wave making resistance increase of REFORM type. For REFORM type, wave making resistance value in +2 m bow trim is lower than that of +1 m bow trim. Contrary to this result, for ORG shows larger value in +2 m than +1 m.

Even though the least wave making resistance, total resistance and EHP values are shown in +2 m bow trim of REFORM in Fn:0.173, the quantitative deduction is not greater than our initial expectation for significant synergy of trim optimization and bulbous bow retrofit.

However, it is confirmed that following two important possibilities allow us to see somewhat larger resistance deduction from this study.

First, larger viscous resistance deduction can be expected by reducing of bulbous bow volume that should be done by reduction of total stagnation area in the bulbous bow end and negative pressure around it.

Another is to optimize bulbous bow shape under optimum trim condition not even keen. For the bulbous bow of REFORM, it is optimized under even keel condition only. The reason that there is no significant effect in +1 m or +2 m bow trim even though it indicates 2 % of total resistance deduction compared to that of ORG in even keel condition is that the reformed bulbous bow shape is not appropriate for trimmed conditions.

7. Conclusion

It is investigated that the shipping company has operated the container ship in slow steaming due to rise of oil price and for countermeasure against environmental regulations tightened by IMO and other companies are not much different from this. Particularly it is indicated that 40 % of DMCR is proven as the most frequent portion among the voyage data.

The numerical calculation is conducted under slow steaming, Fn:0.163, 173, 183 and design ship speed condition, Fn:0.255. It can be expected that the results from this study can give hull form designer and ship operator many useful information which show the resistance performances changed by appearance of slow steaming concept as comparing to those of original design speed.

Total resistance decrease when compared with even trim basis is indicated that there is only 1 % confirmed as a maximum figure among the results of all bow and stern trims combined with design speed. In contrast, for slow steaming condition 3 % deduction is observed in +1 m bow condition and for all stern trim conditions, it is increased 1 % up to 5 %. Particularly in -2 m stern trim, it is indicated the highest increase value at 5 %.

The portion of wave making resistance in total resistance is about 6 % up to 18 % according to trim variation in slow steaming condition and for design speed it is indicated 12 % up to 18 %. Herein the highest increase corresponding to each speed is shown at each -2 m stern trim. It is also proven that the wave making resistance in every bow and stern trim condition is larger than one of even trim condition. The cause of total resistance decrease in all bow trim conditions seems to be by viscous resistance deduction.

The bulbous bow retrofit is conducted for even keel and slow steaming condition. This result is verified to be due to the effect by diminishment of stagnation area and negative pressure around the bulbous bow aiming at decrease of viscous resistance.

Total resistance decrease when compared with the even trim basis of ORG type in the design speed (Fn:0.255) is indicated that there is just maximum 1 % in +1 m bow trim of both types among all bow trims.

In contrast, for slow steaming condition 3 % deduction is observed in +2 m bow trim of REFORM type. This result shows a tendency different from that of trim optimization only. There is a little synergy at bout 1 % in +2 m bow trim in contrast with no synergy in +1 m bow trim.

For better synergy by those of combination, it can be only expected by more drastic reduction of bulbous bow volume in order to reduce viscous resistance as much as possible. One more key point is that the bulbous bow retrofit is preferable to be conducted in optimum trim condition that should be chosen before the bulbous bow retrofit.

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