



Evaluation of resistance increase and speed loss of a ship in wind and waves

Shaoze Luo^{a,b,c,*}, Ning Ma^{a,b,c,e}, Yoshiaki Hirakawa^{d,e}

^aSchool of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, China

^bState Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, China

^cCollaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai, China

^dSea & Air Control System Laboratory, Yokohama National University, Yokohama, Japan

^eInstitute of Advanced Sciences, Yokohama, Japan

Received 14 December 2015; received in revised form 7 April 2016; accepted 12 April 2016

Available online 27 April 2016

Abstract

Given the indication of the IMO's intent to the application of the EEDI and EEOI, the complete and precise total resistance of a ship and induced speed loss in wind and wave is primarily required. This paper proposed a practicable method to evaluate the total resistance in seaway. Besides the still water resistance, the added resistance due to waves is computed using panel method and the wind resistance is obtained using CFD with the verification of an open wind test and statistical formula. The speed loss is acquired in consideration of the matching of the hull, engine and propeller. A hull optimization method is consequently presented based on the proper resistance evaluation approach. The approach is validated available and the total resistance of a ship could be reduced after hull optimization.

© 2016 Shanghai Jiaotong University. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Keywords: Speed loss; Resistance increase; Wind; Wave; Hull form optimization.

1. Introduction

On the background of increasing focus on the reduction of the fuel consumption and demand of energy saving, there is a strong requirement for the complete and accurate evaluation of the resistance increase and speed loss of a ship in seaway instead of the previous simple power estimation in calm water. For this reason, the wind and waves factors contributing to speed loss should be properly considered.

The ship during voyage at actual sea will encounter external weather loads and thus causes the resistance increase, which result in speed reduction if the power never changes, or alternatively, requires an adequate power increasing in order to maintain a certain speed. It is of great importance to give

a valid estimation of added resistance considering a given sea condition.

Many studies concerning the added resistance and speed loss have been carried out in these years. Sverre Steen and Zhenju Chuang [14] have provided a method to measure the speed loss from model test and demonstrate the importance of friction correction. Journée [8] has developed a computer program to calculate speed and behavior of ship in seaway. Two factors including the natural speed reduction and voluntary speed reduction are considered. Full comparison between two methods of added resistance evaluation, one developed by Faltinsen, and the other by Salvesen, is performed by Matulja et al. [12, 11]. Pérez Arribas [1] also validated some prediction method against the experimental results of the seakeeping tests and made conclusions about the range of the application of these theories.

This paper defines the total resistance into three parts, still water resistance, added resistance due to waves and wind resistance. Each is evaluated with different methods. What is

* Corresponding author at: School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, China.

E-mail address: 624546581@qq.com (S. Luo).

more, a critical analysis and comparison for the wind loads has been carried out with statistical, computational and experimental data. Therefore, the resistance increase is predicted and the speed loss is gained in consideration of the interaction of the hull, engine and propeller in seaway. To obtain a better performance of a ship in wind and waves, the speed loss factor and EEOI as objectives are optimized using NSGA-II algorithm.

2. Methods

The added resistance, according to the load components, is divided into two parts, i.e. the wind resistance and the added resistance due to waves. In this paper, the ship is assumed advancing in head waves and the added resistance in waves is calculated with three dimensional panel method while the wind resistance is analyzed in several ways including statistical formulation, full CFD computation and open wind test in towing tank.

2.1. Wave added resistance

The resistance increase in regular waves is calculated with analytical method developed by Chen [2] and Newman [13]. The estimation in irregular waves is based on the linear hypothesis for the ship's response as well as the superposition principle for the components of waves and resistance spectra. Here the added wave resistance is approximated as second order drift force in head wave. The mean added wave resistance $\Delta\bar{R}_{AW}$ would be as follows:

$$\Delta\bar{R}_{AW} = 2 \int_0^{\infty} \frac{R_{AW}(\omega_e)}{\zeta_a^2} S_{\zeta}(\omega_e) d\omega_e \quad (1)$$

With $S_{\zeta}(\omega_e)$ the wave spectrum, ζ_a the significant wave height, ω_e the encountering frequency.

Chen's method includes the first-order and second-order potential theory of wave radiation and diffraction as well as the elimination of irregular frequencies, which is somehow accurate enough for engineering application.

2.2. Wind resistance

Fujiwara [5] has developed a new estimation method based on physical component models of the wind loads acting on ships, and this method is later modified for new ship forms such as large containerships. The modified method is more accurate in wind loads estimation of containership compared with Isherwood's [7] empirical formulas analyzed from a wide range of merchant ships. The longitudinal wind drag coefficient C_x then could be calculated from:

$$\begin{aligned} C_x(\Psi_A) = & C_{LF} \cos \Psi_A \\ & + C_{XLI} (\sin \Psi_A - \frac{1}{2} \sin \Psi_A \cos^2 \Psi_A) \sin \Psi_A \\ & + C_{ALF} \sin \Psi_A \cos^2 \Psi_A \\ & + \frac{A_{RC}}{A_{OD}} (C_{D1} \cos^2 \Psi_A + C_{D2} \sin \Psi_A \cos \Psi_A) \end{aligned} \quad (2)$$

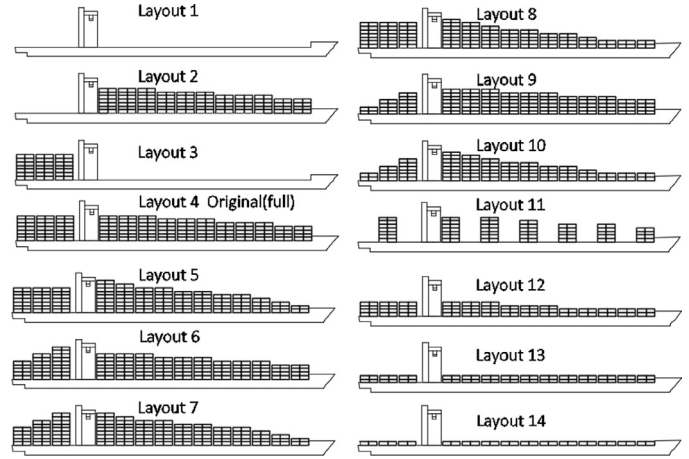


Fig. 1. Container layouts on the deck.

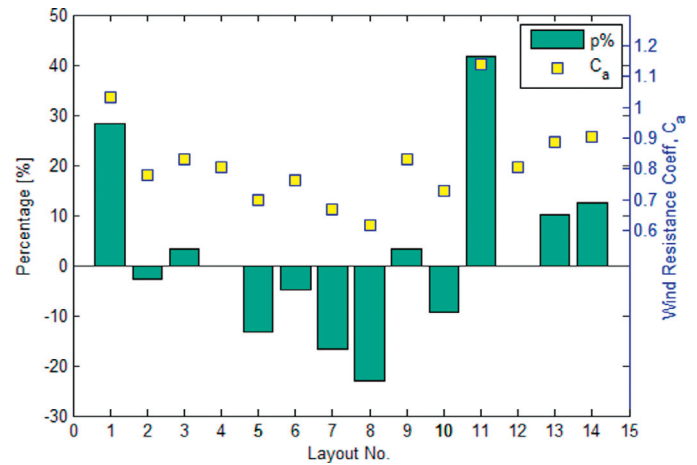


Fig. 2. Coefficient comparison in layouts.

With Ψ_A the angle of attack, C_{LF} the lift force part, C_{XLI} caused by the linear potential theory, and additional force C_{XLI} caused by the 3-dimensional flow effect. A_{RC} corresponds to the lack part area in the lateral projected area on the deck's fully imaged containers A_{OD} . C_{D1} and C_{D2} are the additional coefficients.

For more detailed and precise results, the author has carried out an open wind test in towing tank. The wind profile was studied and compared with other experiment results to validate the feasibility of the open wind test before wind drag of a scale model in different container layouts was measured. The series of the experiment with container layouts in Fig. 1 have been carried out in in Yokohama National University (hereafter simply YNU). The experiment results of the wind resistance coefficients in different layout are displayed in Fig. 2.

Computational calculation is also performed based on the same cases. The Realizable κ - ϵ turbulence model and standard wall function are adopted and the local refinement is applied to the region near the containers. Second order upwind difference scheme is used for relatively accurate and stable results.

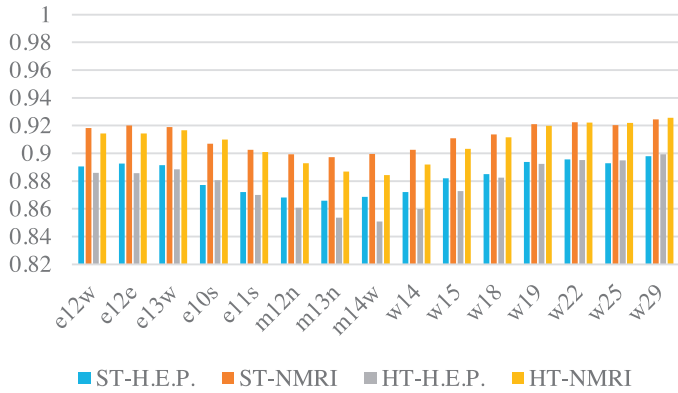


Fig. 3. Speed loss coefficient with wind resistance.

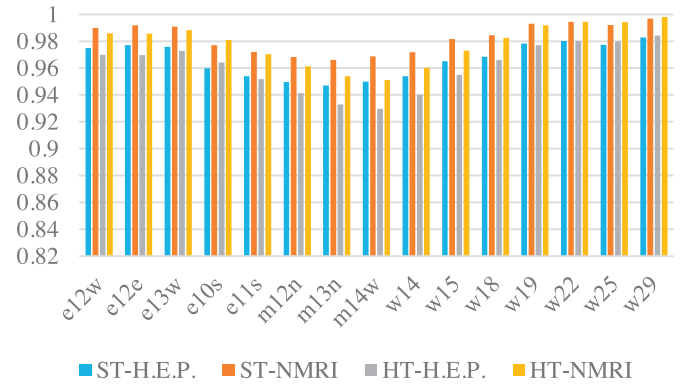


Fig. 4. Speed loss coefficient without wind resistance.

From a series of container layout cases, the difference of the wind drag force has been analyzed and simulated by CFD. It is proved that 1) open wind test is an effective measurement though it is simple; 2) through cross validation, the results are proved credible and CFD has the priority of the more detailed fluid field information and higher precision; 3) the wind drag can be reduced through configuration optimization. Through different methods, the wind resistance coefficients by CFD method is chosen to be applied in the evaluation of the resistance increase and optimal layout of the containers would be adopted during the optimization.

2.3. Speed loss

IMO proposed the EEDI/EEOI regulation, but no specified procedure for calculation of the speed loss coefficient is issued. There are several methods [9] nowadays to analyze the speed loss coefficient. One method is the widely used NMRI approach, where coefficient f_w is defined as the ratio of the speed in sea condition (V_w) to the reference speed in calm water (V_{ref}). Both speeds are defined at P_{EEDI} (75% MCR) and EEDI draft. Another method by FENG [4] takes into account the energy transmission among hull, engine and propeller as well as the hydrodynamic interaction, which may better guarantee the navigation performance of the ship in seaway. It is obvious that the speed loss coefficient is remarkably different whether the wind resistance is taken into account (Figs. 3 and 4).

3. Optimization

The total resistance that takes account the resistance increase for a specific sea state condition has been estimated by means of the above theories. Given the information of the engine and propeller, the speed loss coefficient could be computed through the NMRI approach or hull-engine-propeller (H.E.P.) matching method. Based on the Energy Efficiency Design Index formula recommended by IMO [6], the ship speed performance could be further evaluated.

3.1. Hull form transformation

For the purpose of ship performance optimization, a local modification of hull surface is applied by using radial basis function. The transformation can be easily achieved by arranging control nodes around the ship hull [10]. The radial basis function describes the surface as follows:

$$S(X) = \sum_{j=1}^N \lambda_j \phi(\|X - X_j\|) + p(X) \quad (3)$$

Where $X = (x, y, z)$ is the node on surface, ϕ is the basis function. Here Wendland's C2 function with compact support is chosen.

$$\phi(\|X\|) = (1 - \|X\|)^4(4\|X\| + 1) \quad (4)$$

Additional boundary condition is set:

$$\sum_{j=1}^N \lambda_j p(X_j) = 0, j = 1, \dots, N \quad (5)$$

The linear polynomial to recover the translation and rotation is defined as follows,

$$p(X) = c_1 + c_2x + c_3y + c_4z \quad (6)$$

Thus the values $\lambda = [\lambda_1, \lambda_2, \dots, \lambda_N]^T$ and $c = [c_1, c_2, c_3, c_4]^T$ can be obtained by solving the system. And the hull surface can be modified if different f is chosen.

$$\begin{pmatrix} f \\ 0 \end{pmatrix} = \begin{pmatrix} \Phi & P \\ P^T & 0 \end{pmatrix} \begin{pmatrix} \lambda \\ c \end{pmatrix} \quad (7)$$

Figs. 5 and 6 show the control nodes distribution on the ship model. The fixed nodes are used to maintain the rest of the hull form that tends to be same with the origin; the movable nodes are spread around the bow for local modification.

3.2. Optimization algorithm

The performance optimization can be seen as a multiple-objective optimization problem. In this paper, Non-dominated Sorting Genetic Algorithm II is employed to globally search

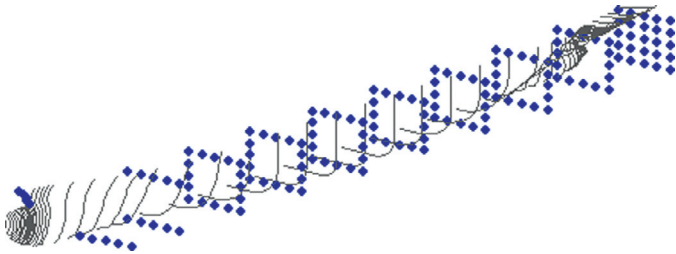


Fig. 5. Distribution of the fixed control nodes on the hull surface.

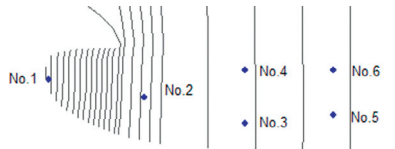


Fig. 6. Movable control nodes used as design variables.

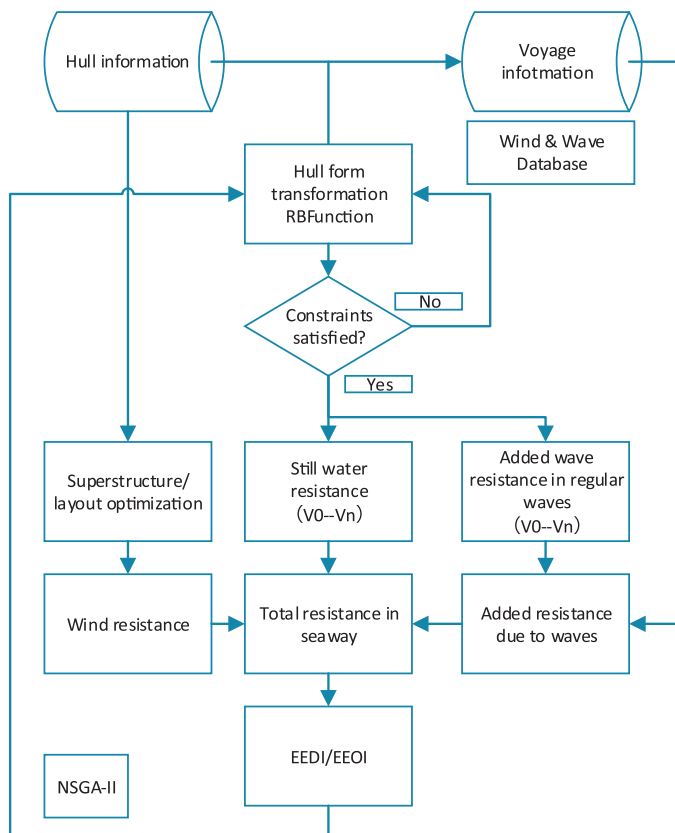


Fig. 7. Flow chart of optimization.

the Pareto solutions. The NSGA-II method (3) is able to find a much better spread of the solution and convergence in most problems. In this case, the hull form is optimized with EEDI index and weather speed loss coefficient as optimization objectives and less change in displacement as a constraint. The optimization flow chart is shown in Fig. 7. It is noted that the wind resistance optimization module is independent of NSGA-II optimization loop since the computational calculation by CFD is rather time consuming. Table 1 gives the variants and constraints in optimization procedure.

Table 1
Variables and constraints.

| ID | Lower limit | Upper limit |
|--------------------------|-------------------|-----------------|
| $(Disp-Disp_0)/Disp_0$ | -4% | 4% |
| $(B_m-B_{m0})/B_{m0}$ | -1% | 1% |
| $P_{m1}: (fx, fy, fz)$ | (-0.05, 0, -0.05) | (0.05, 0, 0.05) |
| $P_{m2-6}: (fx, fy, fz)$ | (0, -0.05, 0) | (0, 0.05, 0) |
| $P_f: (fx, fy, fz)$ | (0, 0, 0) | (0, 0, 0) |

Table 2
Information of 3100TEU containership.

| Loa/m | B/m | Design draft/m | Displacement/t | Service speed/kn | CSR/kW |
|-------|------|----------------|----------------|------------------|--------|
| 214.2 | 32.2 | 11.9 | 54621.8 | 22.5 | 28,728 |

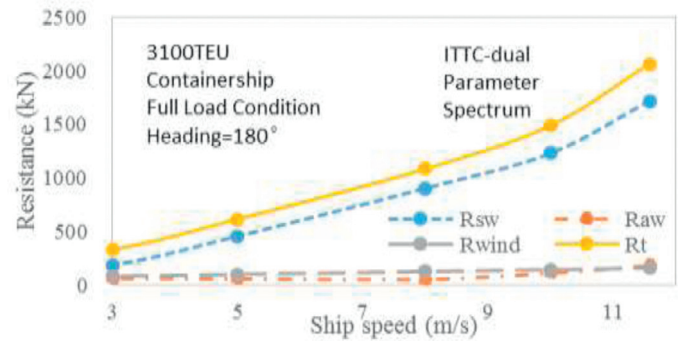


Fig. 8. Total resistance predicted in BF6.

Here in Table 1, $Disp_0/Disp$; the displacement before /after optimization, B_m/B_{m0} ; breadth before/after optimization. P_m and P_f mean movable and fixed control points, respectively.

4. Results

4.1. Total resistance

In this study, a conventional 3100TEU containership is taken as an initial hull, major information is presented in Table 2. The representative sea condition are granted level 6 on the Beaufort Scale. The resistance component of the containership including the resistance increase in seaway is shown in Fig. 8. It results that the major contribution to the total resistance is due to the resistance in calm water. The contribution due to weather condition amounts to 16.7% of the total resistance at design speed, which indicates that the resistance increase cannot be neglected and the real speed loss of the ship advancing in seaway should be properly treated and covered.

4.2. Optimization

The layout of the containers on the deck is rearranged to reduce the wind resistance in seaway. The wind resistance coefficient of the optimal solution, layout 8, declines from 0.8041 to 0.6181, a decrease of 23.1 percent, compared with that of the original layout (see layout 4 in Fig. 1). It is

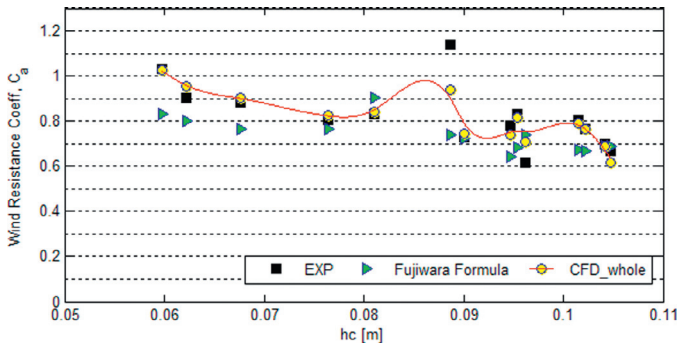


Fig. 9. Wind resistance coefficient in layouts with different vertical center position h_c .

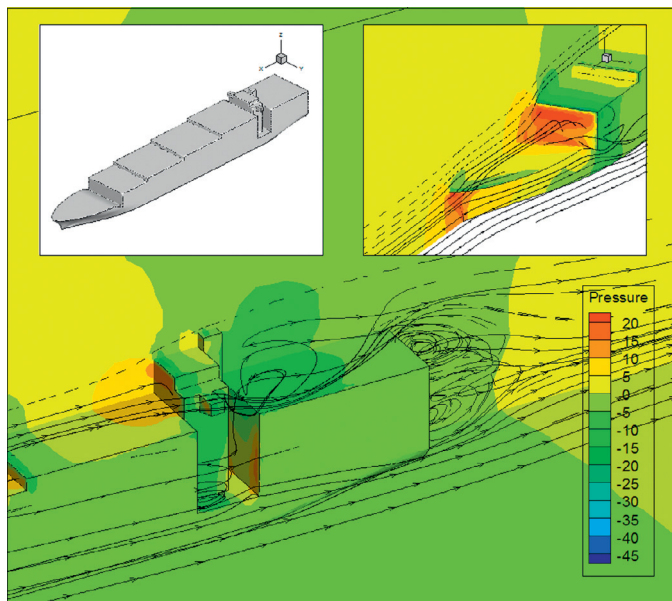


Fig. 10. Simulated flow field and pressure distribution (Layout 4).

observed that the wake behind the bridge and container is much smoother in layout 8 than that in layout 4 in Figs. 10 and 11. The streamlined arrangement can meliorate the pressure both on the windward and leeward side. The results in Fig. 9 also demonstrates a relationship between the wind resistance coefficient and the vertical center position h_c , which would offer some beneficial advice in arranging the containers with proper vertical center position.

According to the optimal wind resistance coefficient, the contribution due to the wind resistance reduction on the ship performance is remarkable and the EEDI has been lowered from 24.1221 to 23.7601 while the weather speed loss coefficient has been raised from 0.8695 to 0.8828.

For hull form optimization based on NSGA-II method, the design variables are related to the movable control nodes on the hull surface, which partially modified the hull form to meet better ship performance. The EEDI index and speed loss as objectives are weighted mean value on the basis of the ship voyage. Results of the design variables and history plots are shown in Table 3 and Fig. 12, respectively. The optimization

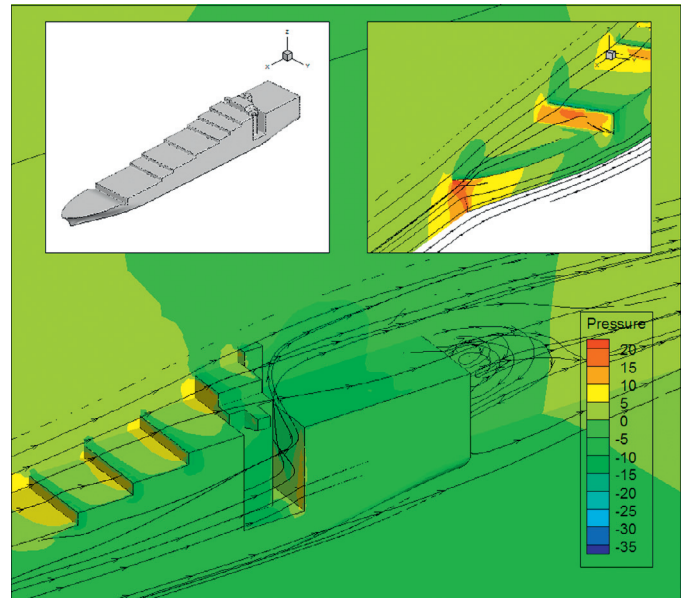


Fig. 11. Simulated flow field and pressure distribution (Layout 8).

Table 3
Best design parameter values.

| Objectives | NSGA-II | Origin |
|------------|------------|------------|
| f1x | 9.656E-03 | -1.259E-02 |
| f1z | 2.047E-02 | -1.282E-02 |
| f2y | 3.414E-02 | 1.881E-02 |
| f3y | -3.601E-02 | 1.672E-02 |
| f4y | -1.038E-02 | 3.622E-02 |
| f5y | -8.139E-03 | -4.693E-02 |
| f6y | 4.964E-02 | 4.631E-03 |

objectives f_w and EEDI are gradually improved especially in early stage and it appears mild after 500 runcounters.

In comparison with initial hull, the optimal hull exhibits small change in the displacement and the variant is within 0.2%. The EEDI index is reduced by 6.21% due to hull form optimization while the speed loss coefficient f_w is raised by 6.83% as well. The local surface modification improves the ship performance on the premise of little change in the displacement remarkably. It can be observed from Fig. 13 that the modified bulb is slightly stretched forward while the waterline length remains unchanged, which mainly helps to diminish the wave making resistance by improving the interaction between bow and stern wave system.

The whole optimization procedure consists of the container layout reconfiguration and hull form modification, which both improve the ship performance through increasing the energy efficiency. These two modules reduce the resistance increase due to wind and waves, respectively. The optimal solution (Fig. 14) would have a modest engineering reference for the new ship design or ship rebuilt (Table 4).

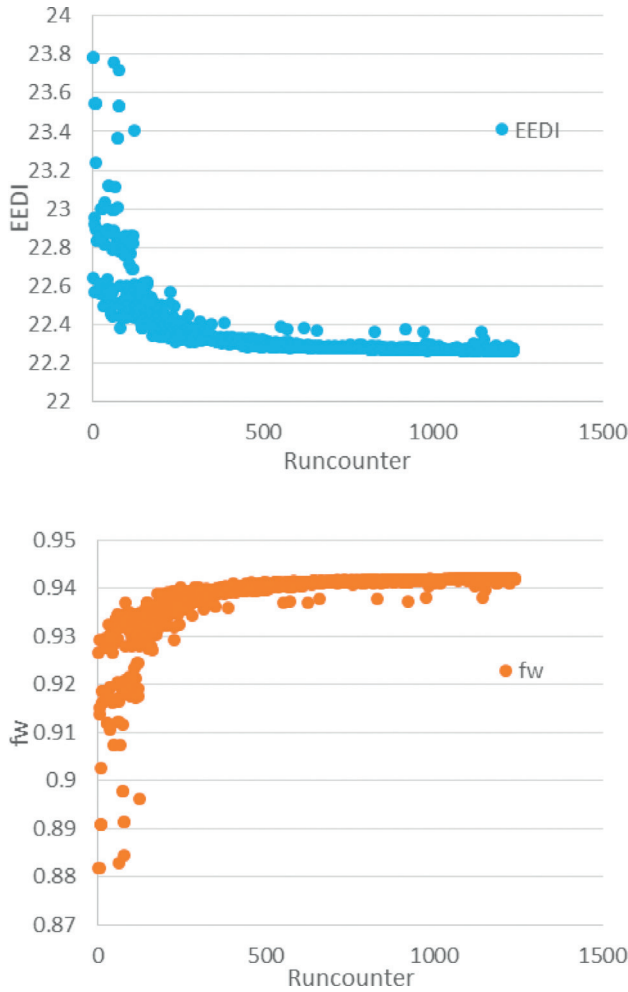


Fig. 12. Objectives history Plots (Up: EEDI; Down: fw).

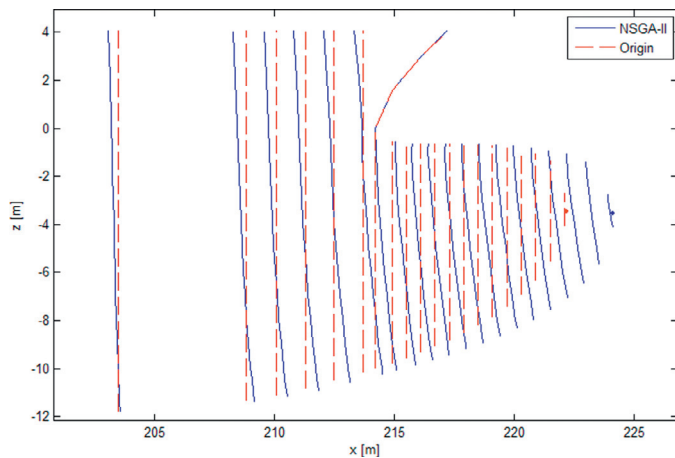


Fig. 13. Hull form optimization (side view).

5. Conclusion

Total resistance of a containership including the resistance increase due to wind and wave which cannot be neglected in seaway is calculated. Furthermore, a practicable method is proposed to estimate the added resistance due to waves and

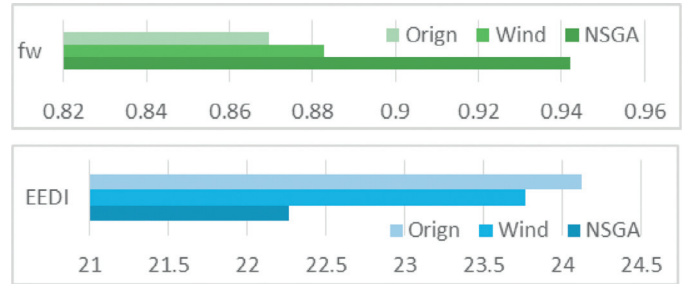


Fig. 14. EEDI and fw optimization results.

Table 4
Optimization objectives comparison.

| Objectives | NSGA-II | Rwind opt | Origin |
|------------------------------------------------|---------|-----------|---------|
| EEDI/g (t nm) ⁻¹ | 22.2613 | 23.7601 | 24.1221 |
| ΔEEDI/% | -6.213 | -1.500 | |
| (EEDI-EEDI ₀)/ EEDI ₀ % | -7.714 | -1.500 | |
| Fw | 0.9422 | 0.8828 | 0.8695 |
| Δfw/% | 6.832 | 1.530 | |
| (fw-fw ₀)/ fw ₀ % | 8.361 | 1.530 | |
| Disp/t | 54716.1 | 54621.8 | 54621.8 |
| (Disp-Disp ₀)/Disp ₀ % | 0.173 | - | |

wind resistance, so that the speed loss can be evaluated by using either NMRI approach or H.E.P. method. It is proved that the computational method is a simple and accurate method to evaluate the wind resistance, and it is validated by means of open wind test in towing tank.

To achieve better ship performance, the hull surface is locally modified by using radial basis function interpolation in total resistance evaluation loops. The EEDI and speed loss coefficient are optimized as objectives while the control nodes around surface are set as design parameters. Optimal Pareto solution can be obtained by NSGA-II algorithm. It demonstrates that the ship performance in seaway has a potential to be optimized once the resistance increase and speed loss are well evaluated.

Acknowledgments

The author wishes to much appreciate Prof. Y. HIRAKAWA from Yokohama National University for invaluable help with the open wind test in YNU’s towing tank. Also thanks Mr. H. TAKAYAMA for the expertise assistance and advice in the experiment.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.joes.2016.04.001](https://doi.org/10.1016/j.joes.2016.04.001).

References

[1] F. Pérez Arribas, Ocean Eng. 34 (7) (2007) 946–955.
 [2] Xiao-Bo Chen, in: Proceedings of Keynote Lecture of 6th International Conference on HydroDynamics, Perth, Australia, 2004.

- [3] Kalyanmoy Deb, et al., *IEEE Trans. Evol. Comput.* 6 (2) (2002) 182–197.
- [4] Pei-Yuan Feng, Ning Ma, Gu Xie-Chong, *J. Shanghai Jiaotong Univ.* 46 (8) (2012) 1248–1262.
- [5] Toshifumi Fujiwara, et al., in: *Proceedings of the Nineteenth International Offshore and Polar Engineering Conference, International Society of Offshore and Polar Engineers*, 2009.
- [6] IMO, *Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships*, Report No. IMO MEPC 66, 2014, 3–5.
- [7] Isherwood, R. M (1973). *Wind Resistance of Merchant Ships*. RINA Supplementary Papers 115.
- [8] J.M. J Journée, *Prediction of Speed and Behaviour of a Ship in a Sea-Way*, Delft University of Technology, 1976.
- [9] Kim, Yonghwan, Dominic Hudson, and Pepijn de Jong (2014). "Sea-keeping Committee."
- [10] Hyunyul Kim, Chi Yang, *J. Hydrodyn. Ser. B* 22 (5) (2010) 520–525.
- [11] Dunja Matulja, et al., *Brodogradnja* 62 (3) (2011) 259–264.
- [12] Matulja, Dunja, and Jasna Prpić-Oršić (2010). *Methods for Estimation of Ships Added Resistance in Regular Waves*. Simpozij Sorta 2010. Hrvatska znanstvena bibliografija i MZOS-Svibor.
- [13] J. N Newman, in: *Proceedings of the 23rd International Conference Offshore Mechanics & Arctic Engineering, Vancouver, Canada, 2004*.
- [14] Sverre Steen, Zhenju Chuang, in: *Proceedings of the third International Symposium on Marine Propulsors, smp'13, 2013*.