Resistance Reduction Studies by Means of Increasing the Beam with Waterline Parabolization

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Abstract

It has been more than a decade since Calisal et al. (2002) proposed the concept of reduction of the resistance by increasing the beam. Although this is a controversial concept compared to the traditional approach which adopts that the coefficients of residual resistance vary with the beam to the power of 2. The authors, during the course of resistance reduction studies, have disclosed that the new present concept has the ability to reduce the resistance for the Froude number interval of 0.2 – 0.4. Accordingly, a review of the authors' previous work is presented here from the resistance point of view as well as from the seakeeping point of view. Moreover, the production cost due to increasing the beam is also examined and explained. The studies presented include mathematical, computational and experimental results.

Keywords: Hull form optimization, beam increment, waterline parabolization, wave resistance, cost analysis.

1. Introduction

Kent (1919) was the first one who focused on the relationship between the resistance and the beam together with parallel body length. Weinblum (1950) studied the relationship between wave resistance and beam and gave an empirical value of 1.6 to the power of the beam as a significant physical parameter relater with the wave resistance. Wehausen et al. (1961) calculated this power of beam as 1.8 by making use of Taylor Standard Series. It has been then become a general understanding among naval architects that the coefficients of residual resistance vary with the beam to the power of 2 within experimental error. But most of these and related studies, on which this understanding/conclusion is based, are for relatively slow-speed ships with Froude numbers less than 0.21.

In contrast to the common understanding mentioned above, Çalışal, Gören and Danışman (2002) discusses, for the first time, the resistance reduction potential of increasing the beam while smoothing the shoulders of ships for moderate and relatively higher Froude numbers. The variation of ship resistance for Froude numbers less than 0.2 with beam decrements was already confirmed mathematically by Çalısal et al. (2002). Nevertheless, the same study, which bases its mathematical justification on Michell's integral, shows that the new concept of parabolization of waterlines by increasing the beam (which leads to a decrease in parallel middle-body) decreases the wave resistance in the Froude number region, approximately, 0.2< Fn < 0.4. Here Gotman's (1998) work, which shows that ships with a mid-ship bulb have the least wave resistance, can also be cited as a support to the present concept.

This paper aims to show that the present concept is not a hull form dependent approach and to clearly identify the techniques and to describe the tools for proper applications of the present concept. A generalized analytical and numerical justification of the concept of increasing the beam is presented. One cross-channel passenger ferry, one heavy-lifter container ship and one Ro-Ro ferry are studied additionally for this purpose, and numerical results and experimental measurements –where available – are presented. Possible construction cost increase due to the beam increment is also examined and explained.

2. Theoretical background

During the preliminary steps of developing the present concept, we investigated mathematically the effect of the beam increment on the wave resistance by means of Michell's integral. Two numerical models were considered for this purpose and a simplification was made by adopting a wall-sided model #1 with a parallel middle-body in the interval –L/4 < x < L/4 with parabolic bow and stern waterlines. On the other hand, wall-sided model #2 has parabolic waterlines along the complete length of the hull. One form of Michell's integral can be given as:

$$R = \frac{4\rho g^2}{\pi c^2} \int_1^\infty \frac{\lambda^2}{\sqrt{\lambda^2-1}} [P^2(\lambda) + Q^2(\lambda)] d\lambda \qquad (1)$$

where

$$P(\lambda) = \iint f_x(x,y) \exp\left(\frac{g\lambda^2}{c^2} y\right) \cos\left(\frac{g\lambda}{c^2} x\right) dxdy \qquad (2)$$

$$Q(\lambda) = \iint f_x(x,y) \exp\left(\frac{g\lambda^2}{c^2} y\right) \sin\left(\frac{g\lambda}{c^2} x\right) dxdy \qquad (3)$$

The details of this formulation can be found in Wehausen and Laitone (1960). Here, c is the ship's speed, ρ is the water density and g is the gravitational acceleration. Since the waterlines are symmetric about the amidships in our numerical model, studying the effect of Q(λ) is adequate. Let Q(λ) be expressed as Q_1 and Q_2 for models #1 and #2, respectively. We assumed shallow draft to reduce the effect of the exponential term in P and Q functions. Q function includes the integrals for the bow and stern regions, but no contribution from the parallel middle-body of the model #1. Q_2, in addition to the integrals of the bow and stern regions, includes the integration, Q_{12}, along the parabolized mid-body at about the half-length for model #2. We then write:

$Q_2 = Q_1 + Q_{12}$, and thus;

$$Q_2^2 = Q_1^2 + 2Q_1Q_{12} + Q_{12}^2 \qquad (4)$$

It is clear that, depending on the sign of Q_1Q_{12}, wave resistance may either increase or decrease with the addition of parabolic waterlines which in turn increase the beam as compared to model #1 with a parallel middle-body. For various values of λ; Q_{12} is negative, causing the wave resistance to decrease. For this simplified numerical model, it was shown (Çalışal et al., 2002) that a decrease in wave resistance was obtained in the Froude number range of $0.2 < Fr < 0.5$.

Thereafter, a series of studies were carried out to establish the validity of the present concept for various displacement type ships. The first attempt to show the effectiveness of the proposed concept was tested on a coaster tanker which indicates around 10 % of reduction in EHP. As a sequel study, Calisal et al. (2009) made a systematic investigation of ship resistance reduction by beam increments for a fishing vessel (UBC Series Hull). In this study, the beam was increased by 10 to 15 % of the beam by the step-by-step approach using add-on side-bulbs. The approach was controlled and evaluated first by Michell's integral and then by systematic experiments in the BC towing tank. The best alternative showed nearly 15 % reduction in total resistance in the targeted speed range of $0.3 < Fr < 0.4$. Moreover, the vessel's carrying capacity and static stability were also improved. The present parabolization concept was subsequently extended to a high speed NPL trimaran to determine whether resistance reduction using parabolic retrofitted side-bulbs could be achieved for a slender multi-hull vessel (Calisal et al., 2009). The Rankine source-panel method employing Dawson's (1977) algorithm was used to predict wave-making characteristics, an integral boundary layer solver and a RANS solver were used to calculate the viscous drag in the study in which a parametric search varying the size and the location of the bulbs was performed. Experimental validation of the results followed and 6 % reduction in total resistance is recorded. To provide a profound basis for the implementation of the present concept, Calisal et al. (2009) introduced a non-linear optimization technique to find the optimum shape and location of mid-ship bulbs. A Ro-Ro ferry hull is used as the baseline hull in this study and the optimization process studied achieved a reduction in total resistance around 10 %, as validated by the experiments. Both the resistance and seakeeping aspects of the concept were studied by Gould et al. (2010) using the same Ro-Ro hull form considered in the previous study. Although the advantages of the beam increment accompanied by the parabolization of waterlines are very obvious in terms of the resistance, it is not clear enough at this point to set an order of merit depending on seakeeping experiments, because the differences in seakeeping characteristics of the hulls in consideration remain within experimental error particularly for added resistance among the waves.

3. Computational study

Beam increasing design study basically requires 3 computational tools: i) a potential flow solver for calculating wave resistance characteristics, ii) a boundary layer flow solver or a viscous flow solver to check form factor variation, iii) a mathematical programming routine to determine the optimal position of the maximum beam increment.

3.1. Potential flow solver for wave resistance

In order to determine the wave resistance characteristics – such as wave resistance itself, wave elevations, dynamic trim and sinkage, pressure distribution on the wetted hull surface – a flow solver which is based on Dawson's (1977) algorithm is used. According to the present code, ITU-Dawson, the Rankine source distribution is made over the panels which represent the wetted surface area (WSA) of the ship hull under the loaded waterline (LWL) as well as on a portion of the free surface around the hull.

Impermeability condition is applied at the WSA of the ship. The free surface condition proposed by Dawson, quadratic in double-model potential and linear in perturbation potential, is imposed on the discretized free surface around the ship. The differentiation of the velocities in the free surface condition along the streamlines is performed by Dawson's 4-point backward differentiation scheme which numerically satisfies radiation condition within the free surface area around the ship. Wave resistance is then calculated by means of pressure integration over the WSA in the present study.

a. Boundary layer flow solver to check form factor variation

It is recommended that it is necessary to examine the viscous resistance of the parent and improved hulls to determine if there are form drag penalties due to the addition of a mid-ship bulb or due to an increase in the beam. Integral Boundary Layer (IBL) solvers are available and are more versatile in obtaining form factors as compared to the viscous (RANS) solvers. A commercially available IBL solver is used in the present design studies. RANS and IBL solvers predicted lower frictional drag than the ITTC correlation line and both solvers predicted approximately 1% increase in frictional resistance coefficient for the parabolized hull, (Calisal et al., 2009). This is an expected result caused by the growth of boundary layer thickness due to an increase in the fullness of the parabolized hull.

b. Mathematical programming routine

In the present approach, wave resistance is taken as the objective function. An unfavorable increase in the form drag is treated as a penalty in the optimization procedure. There are many general-purpose, gradient-based packages available to solve this shape optimization problem for minimum wave resistance. As for the geometric modeling; a rectangular patch is defined on the wetted surface of the hull on which the optimal position of the maximum beam increment is searched, (Calisal et al., 2009). Indeed, geometric modeling requires intricate work and in some cases a systematic search might be preferred to figure out the favorable position of the amidships bulb or of the position of maximum beam increment on the hull. Recently, an attempt by Gören et al. was made on determining the optimal shape of the design waterline by allowing an increase in the beam of ship based on mathematical programming.

4. Additional work

The present paper aims to show that the present concept is not a hull form-dependent approach. Thus, one cross-channel passenger ferry, one heavy-lifter container ship and a Ro-Ro ferry hull forms are additionally studied within the frame of the present concept for this purpose and the results are presented in the following. The possibility of a beam increase by a retrofit and the cost analysis was also discussed in the following chapters.

4.1. Passenger ferry (PF)

First, the PF is taken into account (due to a project given by Istanbul Deniz Otobüsleri (IDO)), which is a cross-channel passenger ferry employed in the public marine transportation by IDO in Istanbul, (see Fig. 1 and Table 1 for cross-sections and main particulars, respectively). Despite the fact that the PF hull form has not a parallel middle-body, a beam increment is studied by the potential flow solver for minimum wave resistance by systematic search under the given design constraints. It is understood from the wave resistance analysis that about 5 % increment made to the beam (see Figure 2) acts like a (mid-ship) bulb and results in nearly 25 % reduction in wave resistance, Figure 3. This is confirmed by tow-tank experiments which point out around 12 % effective power reduction at the service speed of 15 kn, Fig. 4.

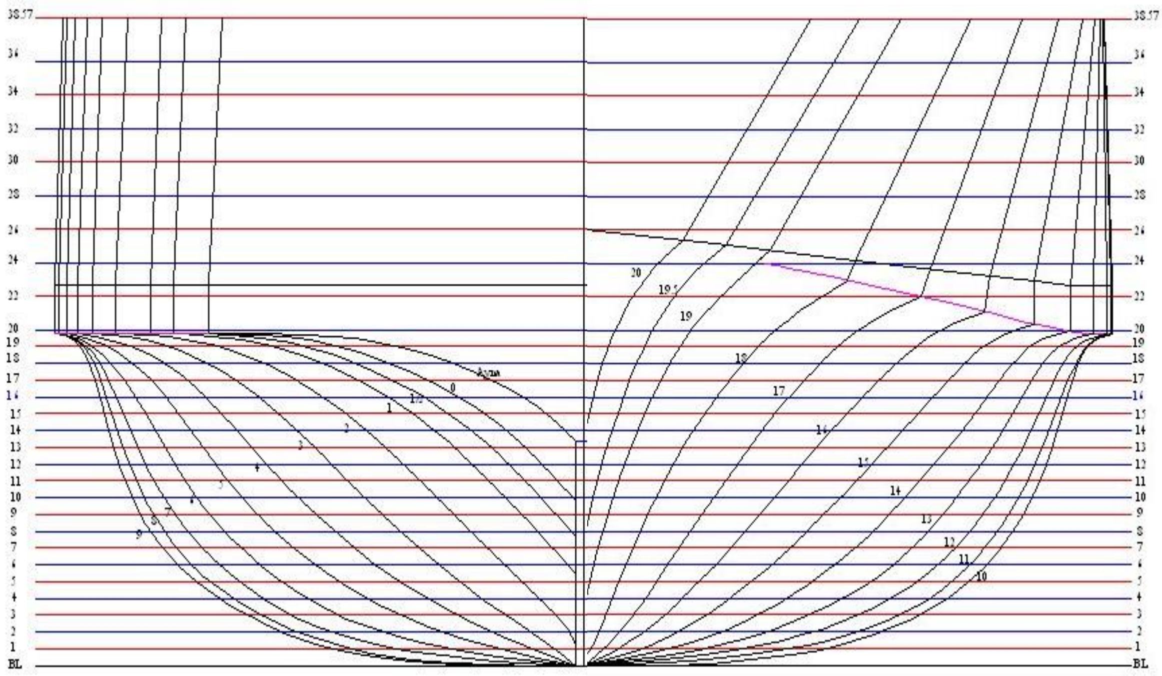


Figure 1. PF cross-sections.

Table 1. Main particulars of PF

Length between perp.	L_{BP} (m)	52.80
Length on waterline	L_{WL} (m)	55.02
Beam	B (m)	10.94
Draught (midship)	T (m)	2.35
Draught (AP)	T_A (m)	2.60
Draught (FP)	T_F (m)	2.10
Displacement Volume	∇ (m^3)	603.17
Service Speed	V (knot)	15

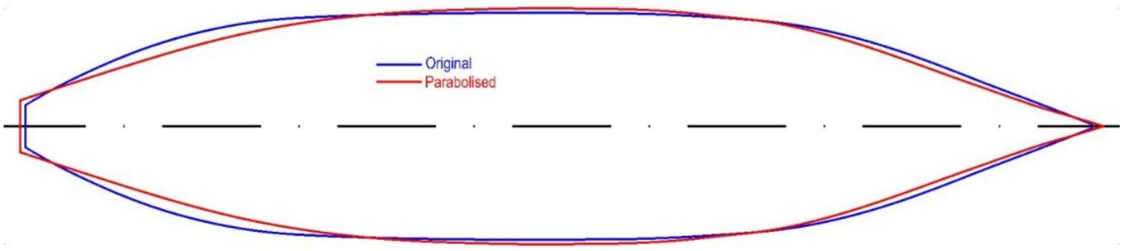


Figure 2. Beam increment at the loaded waterline.

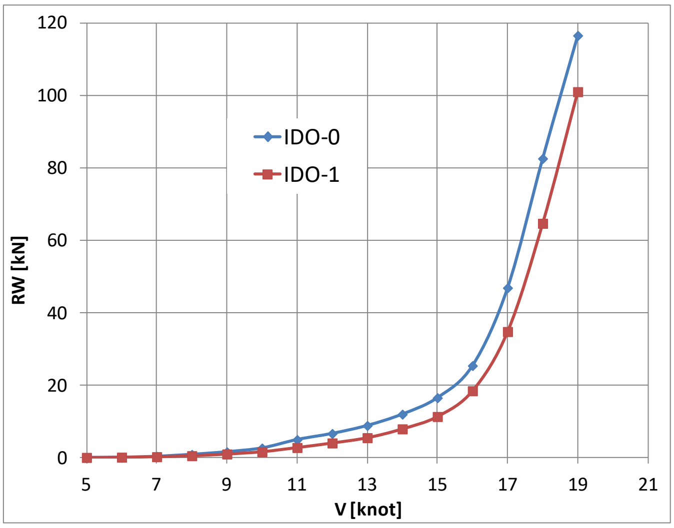


Figure 3. Computed wave resistances (Rw) for original (IDO-0) and for optimized (IDO-1) hulls.

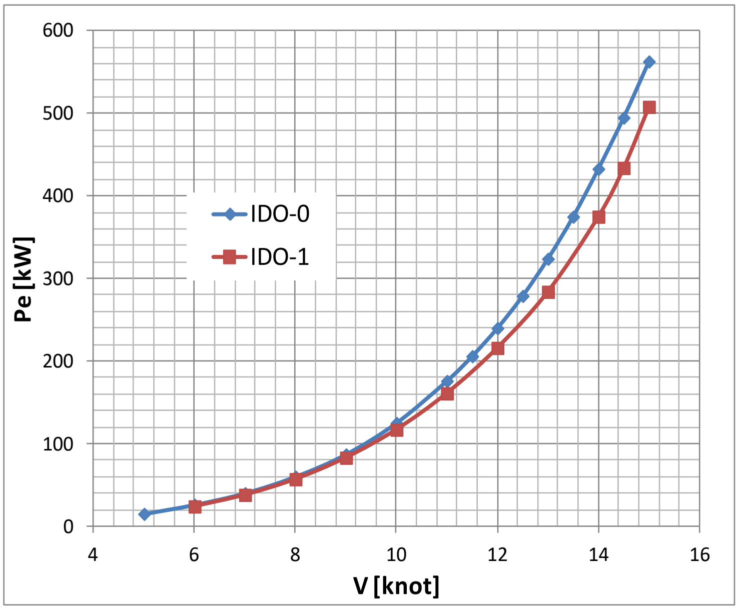


Figure 4. Experimental results for effective powers of the hulls.

4.2. Heavy-Lifter containership (HLC)

The owner and his designer of this HLC is faced with a stability problem due to the heavy gears which are to be installed on the deck of the ship. Thus, the problem turns out to be an ideal application of the present concept, since the owner/designer would like to resolve the stability problem by increasing the beam while not having a penalty from the resistance. Meantime, a new bulbous bow optimization is performed in addition to the beam increasing study. The potential flow solver for wave resistance and the boundary layer flow solver to figure out the change in the form factor are employed in the present hull form improvement study. The improved hull form – with a 6 % increase in the beam and a slight decrease in parallel midbody which allows the smoothing of the shoulders – as compared to the initial hull form is given in cross-sections in Fig. 5. The beam increment shows its effect after 13.5 knots (F_n = 0.26) which additionally reduces the wave resistance 12 % (at the design speed of 14.5 kn) as compared to the hull form with the new bulb design, Fig. 6. The effect of the beam increment accompanied by the smoothing of the shoulders can also be observed in Fig. 7 by comparing the wave elevations around the hull. It should be noted here that considerable percentage of the gain in wave resistance due to the increased beam is lost by a slight increase in wetted surface area and in turn by the frictional resistance and by a slight increase in the form factor as computational studies point out. But there is still a small amount of gain around 2 % in total resistance, according to the computational analysis, due to the increased beam with smoothed shoulders together with other advantages such as considerable gains in stability and in payload capacity.

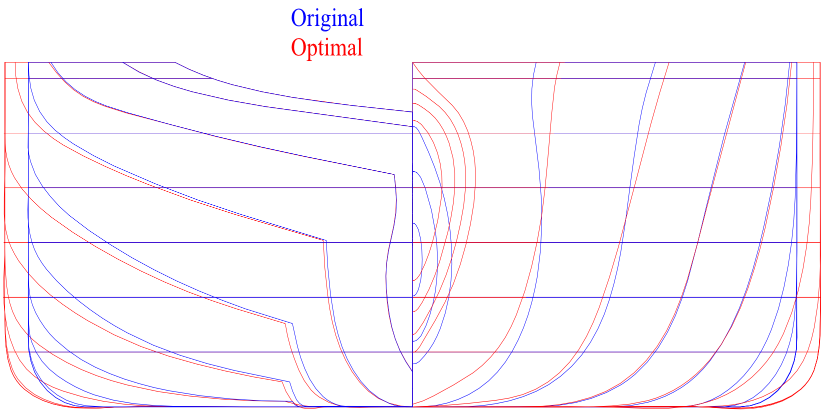


Figure 5. Cross-sections of the original (blue) and the widened/optimal (red) hulls.

4.3. BC Ro-Ro ferry

The present work on British Columbia's Ro-Ro hull is a continuation of the previous work of Calisal et al. (2009). Both the potential flow solver and the viscous flow solver is utilized in connection with the Sequential Programming algorithm to optimize the position and geometry of the side bulb. The original form and the improved form obtained by increasing the beam can be compared in Fig. 8. Table 2 gives the main particulars of both forms for comparison. Note that as a design requirement the displacement is kept constant for the fixed draft. Comparison of the free surface wave deformations caused by the parent and by the optimized (with amidships bulb) hulls given in Fig. 9 pinpoints the relative

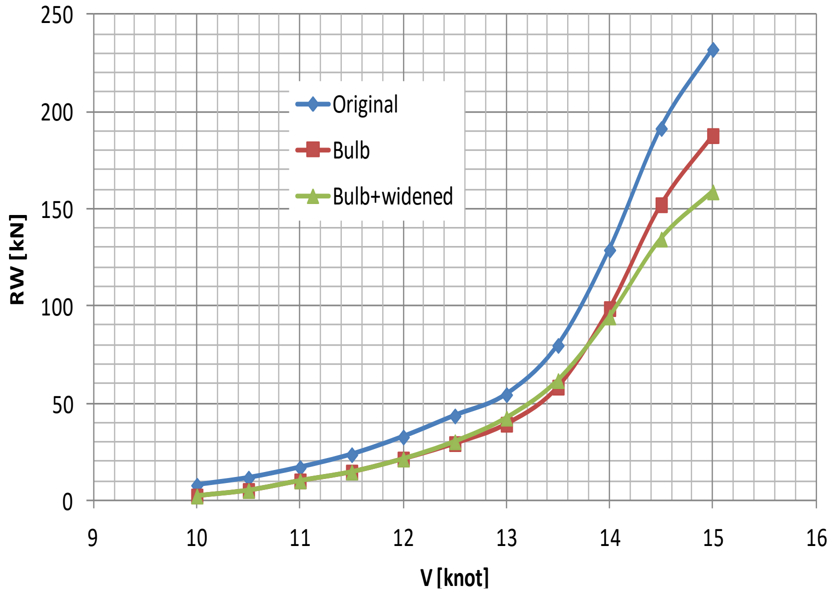


Figure 6. Computational wave resistances of the original and of the improved hulls.

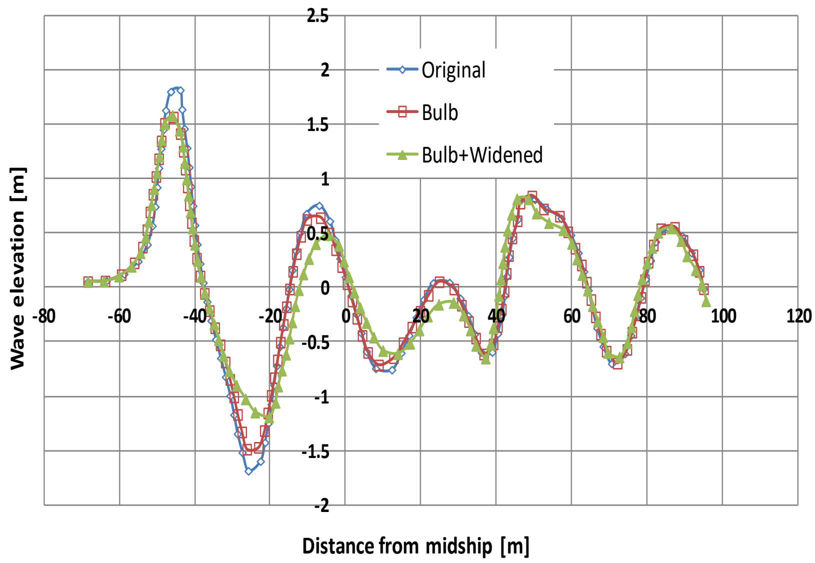


Figure 7. Wave elevations around the hull (V = 14.5 kn).

resistance reduction performance of the improved (optimized) hull with a mid-ship bulb. In Fig. 10, one can observe the wave resistance reduction capacity of the optimized hull (with mid-ship bulb) which is able to reduce the wave resistance (coefficient) by 18 % according to the computational results and by 20 % according to the experimental results. Computed form factors, (1+k), for the parent hull and for the optimized hull are found to be 1.305 and 1.290 (at Reynolds number of $5.35x10^6$), respectively. Form factors obtained from the experiments are 1.28 and 1.24 for the parent and for the optimized hulls, respectively. The decrease in the form factor may be attributed to the finer entrance and run of the optimized hull to keep the displacement constant despite an increase in the beam. Thus the resultant reduction in total resistance according to the experimental analysis at Fr = 0. 33 is about 11%.

A recent study of Gören et al., which aims to base the present design concept fully on mathematical programming, shows computationally and experimentally that the methodology presented is capable of obtaining very favourable wave resistance characteristics. In this respect, Fig. 11 comperatively pinpoints the drastic cancellation of the wave system accomplished by the optimal hull which comprises a beam increment determined by mathematical programming.

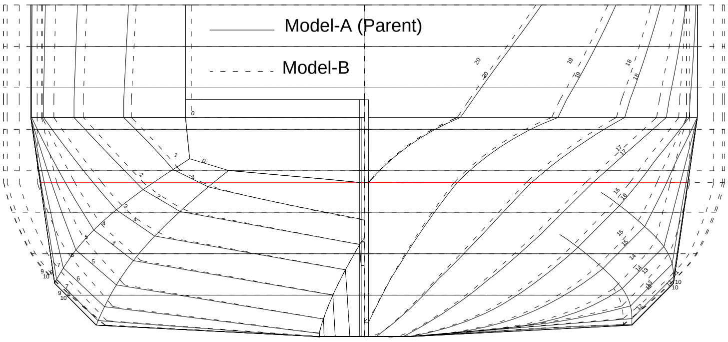


Figure 8. The parent form (Model-A) and the improved (widened) form (Model-B).

Table 2. Main particulars of the forms.

	Form (M318-A)	Optimized Form (M318-B)
L_{WL} (m)	38.75	38.75
B (m)	10.886	12.116
T (m)	2.6	2.6
WSA (m^2)	450.29	437.108
Displacement (ton)	679	679
C_B	0.602	0.534
C_P	0.659	0.626

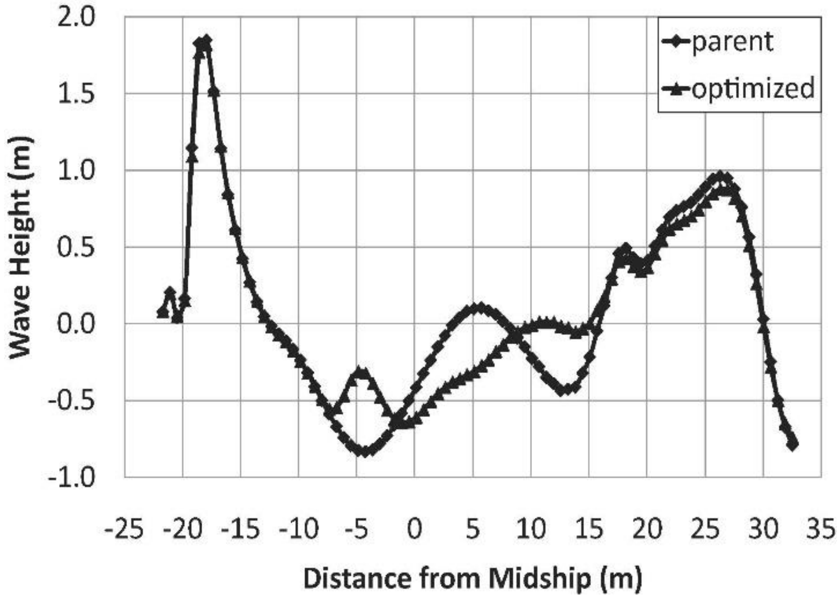


Figure 9. Comparative wave deformations around the hulls (V=13kn).

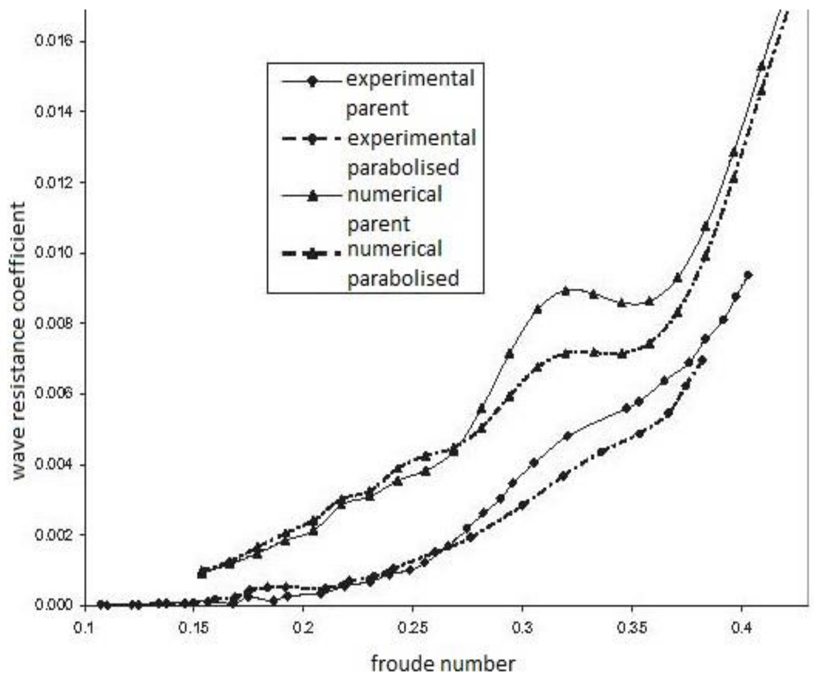
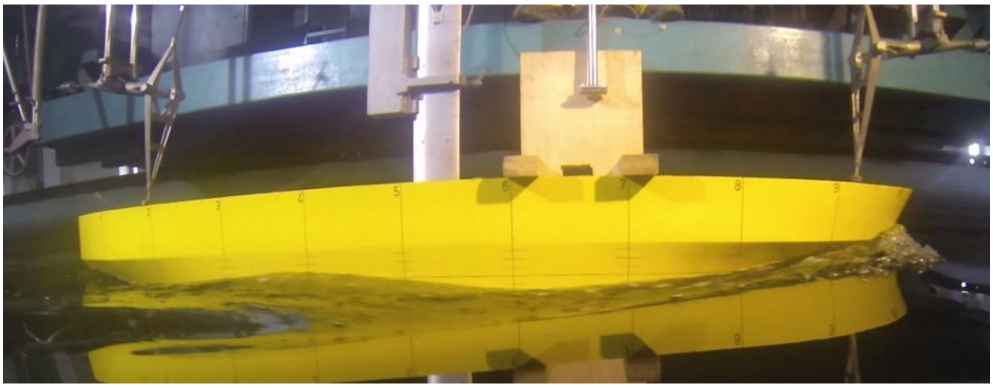


Figure 10. Computational and experimental coefficients of wave resistance for the both parent and parabolised hull forms



(a)

(b)

Figure 11. Wave elevation around the periphery of the original form (a) and of the optimized form (b) at Fr = 0.33 (BC Ferry Hull), Gören et al.

5. Additional construction cost of beam increase by a retrofit

The above given studies and calculations proved that it is possible to reduce the resistance up to 10% and sometimes more than 10 % by the beam increase. Such a considerable amount of saving may pave the way to apply beam increase on a working ship hull. Deli et al. (2016) studied a platform support vessel and obtained around 6 % reduction in the total resistance. They also conduct a cost analysis for a retrofit application. For PODAC (Product Oriented Design and Construction) cost modelling used in the preliminary design, the price of the total ship is taken as a function of displacement, speed and a complexity factor. A complexity factor is necessary to normalize the data and achieve better equations, because the cost data available to the IPT (Insurance Premium Tax) changes as the ship type changes. For the complexity factor, the IPT used is derived from a Size Factor and Ship Type Factor (STF) (see; Ennis et al., 1997).

For the platform supply vessel in consideration, the values of an oceangoing naval tug are taken into account and accordingly ship type factor is taken as 1.00. Fig. 12 shows the savings data for 60 months of the time period with different ship type factors.

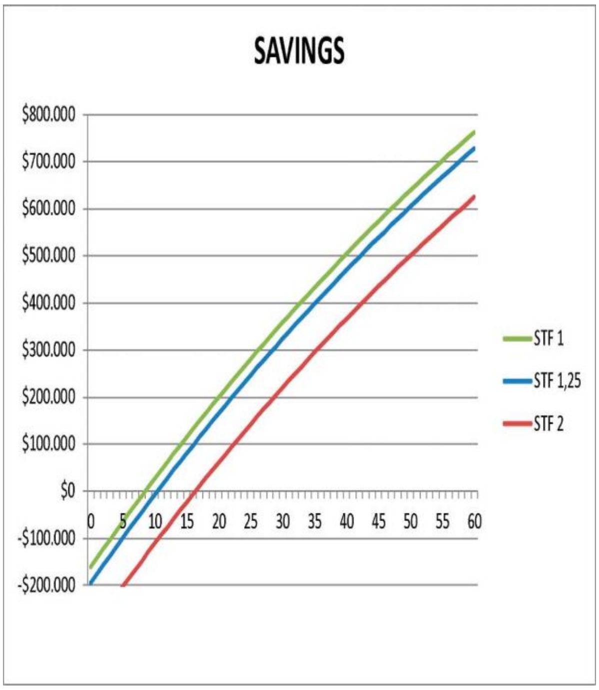


Figure 12. The savings data for 60 months of time period with different ship type factors (Deli et al., 2016).

6. Conclusion and discussion

It has been shown that the systematic application of the waterline parabolization concept, in which the parallel middle-body of the vessel is expanded outward with locally parabolic waterlines, is able to reduce the wave resistance of displacement type ships at moderate Froude numbers. The promising capacity of this concept or of the "increased beam" or the side bulb in reducing effective power requirements for small craft at moderate and relatively higher speeds was proposed in Calisal et al. (2009). This paper provides evidence of the existing potential in reducing the fuel consumption of a large class of ships such as fishing vessels, yachts, ferry boats, container ships, etc. The numerical and experimental evidence given in this paper suggests that the parabolization concept can be applied successfully, as a retrofit or in original designs for significant fuel savings for different types of ships. During the application of the concept, the main focus of attention was the wave resistance first. Subsequently, attention was also directed to the changes in form factor for viscous resistance, to the impact of parabolization on seakeeping, added resistance, etc. The attempt in here is to share the design experience and experimental evidence collected at the Istanbul Technical University and the University of British Columbia to design more fuel efficient ships and to encourage the application of the concept.

During the course of the studies of the present concept, the authors also took into account the two issues. One of them is the question of how the beam increments affect the viscous resistance and in particular form resistance. For the cases reported in this paper or studied by the authors, no major increase in the viscous resistance was observed.

The second concern was on the possible increase in the construction cost of the ship frames for parabolized hulls. Of course, with the inclusion of parallel middle body there exists substantial savings in the construction cost of the frames and plates. A recent case study by Deli et al. (2016) on a platform supply vessel showed that the extra investment for an increase in the beam covers itself within shorter than 9 to 16 months of operation at the given conditions which is very reasonable.

The general hull form optimization methods usually suggested that the beam of the ship was to be kept constant or less than a maximum value as the expectation was that the ship-wave resistance was to increase with the square of the beam value. The experience gained and published earlier by the authors suggest that, in the formulation of the hull form optimization the beam of the ship should be a free variable within the concept of parabolization as described above. This new formulation is expected to provide hull forms with less fuel consumption or lower energy efficiency design indices EEDI of IMO.

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References

Calisal, S.M., Vyselaar, D., Klaptocz, V. and Goren, O. (2009). “A resistance reduction study of a trimaran using waterline parabolization”, Marine Technology, Vol. 46, No. 2, 91-98.

Calisal S., Tan, J., Sireli, M. and Goren. O. (2009). “A systematic investigation of ship resistance reduction by beam increment for small craft”, The Journal of Ocean Technology, Vol. 4, No 3, 57-72.

Calisal, S.M., Danisman, D.B., Goren, O., Gould, K., Maurice, P. and Klaptocz, V. (2009). “Reduction of wave resistance of displacement vessels by waterline parabolization”, SNAME Annual Meeting, Providence, Paper No. 2009-053.

Calisal, S.M., Goren, O. and Danisman, D.B. (2002). “Resistance reduction by increased beam for displacement-type ships”, Journal of Ship Research, Vol. 46, No. 3, 208-213.

Dawson, C.W. (1977). “A practical computer method for solving ship-wave problems”, Proceedings, 2nd Int. Conf. on Numerical Ship Hydrodynamics, Berkeley, 30-38.

Deli, O., Goren, O., Calisal, S. (2016). “Parabolization and Structural Integrity of Side Bulb Applied Platform Supply Vessel Hull Form”, Proceedings of PRADS2016, 4th – 8th September, Copenhagen, Denmark.

Ennis, K. J., Dougherty, J. J., Lamb, T., Greenwell, C. R., Zimmermann, R. (1997). “Product-Oriented Design and Construction Cost Model”, SNAME Ship Production Symposium, April 21-23, New Orleans, Louisiana.

Goren, O., Calisal, S.M. and Danisman, D.B. “Mathematical programming basis for ship resistance reduction through the optimization of design waterline”, submitted for publication to the Journal of MS&T.

Gotman, A. (1998). “The comparative criterion in deciding on the ship hull form with least wave resistance”, Proceedings, Colloquium EUROMECH 374, Poitiers, 277-284.

Gould, K., Calisal, S.M., Mikkelsen, J., Goren, O., Okan, B. and Kim, Y-T. (2010). “Powering and seakeeping characteristics of a displacement hull form with waterline parabolization", Proceedings, ASME 29th Int. Conf. on Ocean & Arctic Eng. (OMAE), Shangai, Paper No. 2010-20951.

Kent, J.L. (1919). "Model experiments on the effect of the beam on the resistance of mercantile ship forms", Transactions, Institute of Naval Architects, Vol. LXI, 311-319.

Weinblum, G.P. (1950). "Analysis of wave resistance", Davit W. Taylor Model Basin, TMB Report 710, Washington, 27.

Wehausen, J.V., Reichtert,G. and Gauthey, J.R. (1961). "On the resistance of ships", Institute of Engineering Research Series, Series 82, Issue #21, iii+55.

Wehausen, J.V. and Laitone, E.V. (1960). "Surface Waves", Handbuch der Physik, W. Flugge, (Ed.), Vol. 9, SpringerVerlag, Berlin, 446-778.