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Ship Hull Form Optimization by Evolutionary Algorithm in Order to Diminish the Drag

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Abstract: This study presents a numerical method for optimizing hull form in calm water with respect to total drag which contains a viscous drag and a wave drag. The ITTC 1957 model-ship correlation line was used to predict frictional drag and the corrected linearized thin-ship theory was employed to estimate the wave drag. The evolution strategy (ES) which is a member of the evolutionary algorithms (EAs) family obtains an optimum hull form by considering some design constraints. Standard Wigley hull is considered as an initial hull in optimization procedures for two test cases and new hull forms were achieved at Froude numbers 0.24, 0.316 and 0.408. In one case the ES technique was ran for the initial hull form, where the main dimensions were fixed and the only variables were the hull offsets. In the other case in addition to hull offsets, the main dimensions were considered as variables that are optimized simultaneously. The numerical results of optimization procedure demonstrate that the optimized hull forms yield a reduction in total drag.

Keywords: optimization; evolutionary algorithms; drag; thin-ship theory

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1 Introduction

Finding an optimal ship hull in the stage of preliminary design that sometimes leads to a significant reduction of cost is an important issue for ship designers. Technique of hydrodynamic hull form optimization based on the analysis of Computational Fluid Dynamics (CFD) is a method for engineering design problems that can automatically improve the design of ship components. This type of optimization involves an iterative computations proceeding of improving hull form. Reducing the cost or merit function is the main goal of using this type of technique. The evaluation function represents the hydrodynamic efficiency of the ship. In general, a numerical optimization algorithm for the objective function, evaluates the hydrodynamic performance (objective function) by a reliable and appropriate method, called geometrical representation of hull surface. Also, the selection of the related design variables and constraints are considered to be the main four components needed to evaluate optimization problems in the field of ship hydrodynamics.

CFD is an important aspect of hydrodynamic optimization task involving simulating flow fields around the hull. CFD analysis was used as a replacement for towing tank experiments. In recent years, a considerable number of applications of CFD methods to hydrodynamic modification, especially for calculating calm water drag and wave patterns have been utilized in hydrodynamic optimization.

For a comprehensive and detailed ship hydrodynamic optimization all objective functions such as drag, stability, seakeeping, *etc*. must be considered, because it is clear that consideration of an objective function without the other ones gives unrealistic and impractical results.

In the ship hydrodynamics industry, experts and ship designers the most important and fundamental problem is the design of minimum drag ships satisfying given design requirements such as displacement, volume and speed. In this study, the hydrodynamic optimization hull form is obtained based on the main objective function to reach the minimum drag. A number of researchers have tried to utilize optimization techniques in order to minimize some user defined objective functions. Some researchers have considered several objective functions and some others only an objective function that are known as multi objective and single objective optimization respectively (Zhang, 2012 and 2009; Gammon, 2011; Kim *et al*., 2008; Dejhalla *et al*., 2001; Percival *et al*., 2001). One or more geometrical constraints, e.g. displacement, the main characteristics and hydrodynamic constraints of the ship's hull must be introduced to limit the changing of the hull. Several optimization algorithms have been utilized in studies of the hull form optimization.

At present, there are many optimization algorithms. The three algorithms consist of: steepest descent, conjugate gradient and sequential quadratic programming, which were all considered by Saha *et al*. (2004) and Peri *et al*. (2001). Today other types of optimization algorithms that are used more in hydrodynamic optimization are called EAs. This technique is one of the most popular and robust techniques for optimization problems. These algorithms may be divided into four categories: genetic algorithms (GAs), evolutionary strategies (ESs), evolutionary programming (EP) and genetic programming (GP). Among these algorithms, GA and EP are most widely used in hull shape modification problems. However, GP has been used very little as it relates to these specific problems. Genetic algorithm techniques for hull form optimization are used. Grigoropoulos *et al*. (2004) proposed a multi-objective optimization technique based on evolutionary strategies to optimize a hull form with respect to hydrodynamic performance. They used seakeeping and total

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drag in calm water as objective functions. Grigoropoulos and Chalkias (2010) selected a multi-objective optimization scheme for the hull form optimization with respect to its performance in calm and rough water. However, instead of the total drag the calm water performance is calculated via the maximum wave height of the waves generated by a sailing ship.

The CFD methods are used to obtain the hydrodynamic performance, the choice of methods depends on the problem conditions. Excessive computational requirements, lack of robustness or versatility due to limited range of applicability, preprocessing discretization requirements that are overly time consuming and hence too expensive for common applications are important factors that can restrict the practical usefulness of a CFD method for routine applications such as ship hull form optimization. Michell's thin ship theory is a simple CFD method that is used by Tuck and Lazauskas (1998). Chandraprabha and Molland (2006) employed slender ship approximation which is another simple CFD method. Potential flow panel methods based on Rankine sources and RANS based viscous flow methods are more sophisticated techniques. A combination of flow solvers based on potential flow, viscous boundary layer and RANS is presented by Janson and Larsson (1996). Ghassemi *et al.* (2010) applied the boundary element method (BEM) for determining the wave-making drag for Wigley hull and some other submerged bodies.

In this paper, the total drag in calm water is the only objective function. The calm water drag of ship is assumed to be composed of wave drag and viscous drag. The viscous drag may be divided into two parts: frictional drag and pressure drag due to viscosity effects. The frictional drag is calculated using the ITTC 1957 ship-model correlation line formula. The wave drag in calm water is estimated using the linearized thin ship theory. This theory is a low cost (less time consuming) and rapid method, therefore making this application an appropriate method for calculating wave drag as a hydrodynamic performance in the optimization of ship hull.

Evolutionary algorithms are stochastic in nature rather than deterministic as in classical optimization methods. These algorithms are based on the collective learning process within a population of individual, each of which represents a search point in the space of potential solutions to a given problem. The population evolves toward better and better regions of the search space. The advantages of evolutionary algorithms are: no presumptions with respect to problem space, widely applicable, low development and application costs, easy to incorporate other methods, solutions are interpretable, can be run interactively, accommodate user proposed solutions, and provide many alternative solutions and intrinsic parallelism, straightforward parallel implementations. The appropriate problems for the evolutionary algorithms are complex problems with one or more of the following features: many free parameters, complex relationships between parameters, mixed types of parameters (integer, real), many local optima, multiple objectives, noisy data, changing conditions (dynamic fitness landscape).

In this study, the evolution strategy algorithm is used for single objective optimization of ship hull form moving at constant speed in calm water. In the field of hydrodynamic optimization of ship hull form the application of the evolution strategy as an optimization methodology is very limited and our study will examine a new study utilizing this methodology. The evolution strategies were invented in the early 1960s by Rechenberg (1973), Schwefel (1995), Beyer and Schwefel (2002) who were working on an application concerning shape optimization of a bent pipe and a flashing nozzle. The evolution strategies are a class of the large field of the evolutionary algorithms which implement a random search in the solutions space with the goal of optimizing some objective functions. These algorithms may be separated into three strategies based on its mutation: uncorrelated mutation with one step size, uncorrelated mutation with n step sizes and correlated mutations. In this study we utilize the well-known evolution strategy based on uncorrelated mutation with n step sizes. The step size is the standard deviation of Gaussian distribution which is used as a random variable in this algorithm. The survivor selection mechanisms which are used in this algorithm is (μ,λ) , μ is the number of parent and λ is the number of generated child (offspring) for the next generation. Recombination and mutation operators are applied on parents and offspring with a multivariate normal distribution in each generation. Each solution is evaluated by the objective function and one or more solutions depending on the survivor selection mechanism are selected as parents for the next generation. This trend will continue so until the end condition is satisfied.

In this study, after problem formulation and especially the explanation of linearized thin ship theory and a particular form of the optimization algorithm (evolution strategy), results of application of this methodology using two different examples of the Wigley hull are presented, in one example changing the hull offsets with fixed principal parameters of length, beam and draft, and in the other example allowing these parameters to change simultaneously with the hull offsets.

2 General problem formulation

In the early stages of conceptual design of a ship hull, it is necessary to specify the main particulars of a candidate design such as Length, Breath, Draught, Block coefficient, *etc*., because these parameters have significant influences on main elements of the ship, *i.e.* drag, maneuverability, final cost, stability, strength, displacement, seakeeping, *etc*.

This description can then be optimized with respect to important performance objectives. This paper focuses on determining the optimal hull form offsets and the optimal length, beam and draft simultaneously while satisfying specific constraints.

2.1 General formulation of optimization problem

The general mathematical form of a numerical constrained optimization problem has been represented here. Design variables and constraint conditions are used to characterize the problem. The role of design variables in hydrodynamic optimization problems is controlling the geometry of the hull during optimization procedure. Constraints are the values by which the design variables are restricted and may be separated in two types, equality and inequality constraints. A function being maximized or minimized by users is known as the objective function and the value of this function is a criterion to determine the efficiency of design optimization methodology. If in an optimization problem only one objective function is used, the optimization is known as single objective and if two or more objective functions are used, the optimization is known as multi objective. The standard formulation of an optimization problem mathematically is as follows:

$$\text{Optimize} \quad F(\bar{x})=\left[f_1(x),f_2(x),\ldots,f_m(x)\right] \qquad x\in\mathbb{R}^n$$

Subject to some equality and inequality constraints

$$h_i(\bar{x})=0 \quad i=1,\ldots,q$$
$$g_i(\bar{x})=0 \quad i=1,\ldots,p$$

where $f_i(\bar{x})$ is the objective function, m is the number of objective function, q is the number of equality constraints, p is the number of inequality constraints and $\bar{x}=(x_1,\ldots,x_n)\in\Im\subseteq\square$ is a solution or individual. The set $\square\subseteq\mathbb{R}^n$ defines the search space and the set $\Im\subseteq\square$ defines a feasible search space. The search space $\square$ is defined as an n-dimensional rectangle in $\mathbb{R}^n$ (domains of variables defined by their lower and upper bounds):

$$l(i)\le x_i\le u(i) \quad 1\le i\le n$$

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

In this study the only objective function is the total drag. Design variables vector includes the main parameters (length, beam, draft) and the hull offsets which are limited by the lower and upper bounds. The ship hull displacement also is an equality constraint.

2.2 Drag calculation

The total calm water drag of a ship at a given speed is the force required for the ship to move at that speed. The total drag is made up of two components: the viscous drag, due to moving the ship through a viscous fluid and the wave drag, due to moving the ship on the surface of the water. The wave drag resulted from energy dissipation in the formation of waves on the water surface. The total drag coefficient is:

$$C_T=C_v+C_w \tag{1}$$

where C_v is the viscous drag coefficient and C_w is the wave drag coefficient. The viscous drag is composed of frictional drag and pressure drag, i.e. $C_v=(1+k)\,C_f$.

and C_f is the frictional drag coefficient and k is the form factor which is determined by

$$\begin{gathered} k=0.6\sqrt{\nabla/L^3}+9\nabla/L^3, \\ 0.05\le k\le 0.4 \end{gathered} \tag{2}$$

The frictional drag coefficient is calculated by ITTC’57 as follows:

$$C_f=\frac{0.075}{\left(\lg Rn-2\right)^2} \tag{3}$$

where Rn is the Reynolds number given by

$$Rn=\frac{U\,L}{\nu} \tag{4}$$

where U is the ship speed, L is the ship length and ν is the kinematic viscosity.

2.2.1 Wave-making drag

When the body like ship moves in surface of water, the wave generated due to high pressure at the fore and aft part of it is called wave-making drag. There are some theories to determine the wave-making drag like Michell’s theory. This theory is valid only under certain restrictive conditions that the fluid is homogenous, incompressible, inviscid and hence the flow is irrotational, surface tension effects can be neglected, the slope of the hull surface relative to the center-plane is small (slender hull), the wave heights generated by the ship hull are small compared with their lengths, the ship does not experience any sinkage or trim and that the water infinitely deep and laterally unbounded. The coordinate system is depicted in Fig. 1.

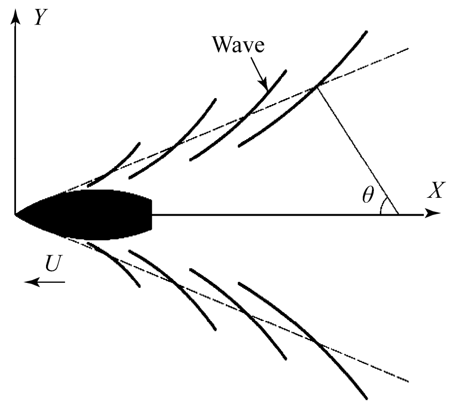

Fig. 1 Coordinate system of Michell's thin ship theory

Based on the energy flux far from the ship, the equation for the wave drag is

$$R_w = \frac{\pi}{2}\rho U^2 \int_{-\pi/2}^{\pi/2} \left|A(\theta)\right|^2 \cos^3(\theta)\mathrm{d}\theta \tag{5}$$

ρ is the density of water, θ is the angle between the direction of the moving ship and that of a propagating wave and $A(\theta)$ is the amplitude function specific to hull shape, sometimes also called the free wave spectrum and describes the far field ship waves. The amplitude function is the only term dependent on hull shape and can be calculated by experimental measurement or by approximation such as small disturbance theory. For a mono-hull based on Michell's thin ship theory the amplitude function is as follows:

$$A(\theta) = \frac{2}{\pi}(k_0 \sec^3\theta)\int_{-\infty}^{0}\int_{-\infty}^{\infty} Y_x(x,z)\mathrm{e}^{\mathrm{i}k_0 x\sec\theta}\mathrm{e}^{k_0 z\sec^2\theta}\mathrm{d}x\mathrm{d}z \tag{6}$$

Working with the hull offsets $Y(x,z)$ is usually preferred over working with the slope of the offsets $Y_x(x,z)$; hence this equation is integrated by parts including only the transom stern:

$$\begin{aligned} A(\theta) = {} & -\frac{2\mathrm{i}}{\pi}(k_0 \sec^2\theta)^2\int_{-\infty}^{0}\int_{-\infty}^{\infty} Y(x,z)\mathrm{e}^{\mathrm{i}k_0 x\sec\theta}\mathrm{e}^{k_0 z\sec^2\theta}\mathrm{d}x\mathrm{d}z + \\ & \frac{2}{\pi}(k_0 \sec^3\theta)\int_{-\infty}^{0} Y(x_s,z)\mathrm{e}^{\mathrm{i}k_0 x_s\sec\theta}\mathrm{e}^{k_0 z\sec^2\theta}\mathrm{d}z \end{aligned} \tag{7}$$

where $k_0=g/U_2$, g is the acceleration of gravity, $y=\pm Y(x,z)$ is the equation or offsets of the submerged hull and $Y(x_s,z)$ indicate the non-zero transom stern offsets. In this equation the offsets of bow are assumed zero, otherwise will be added a complexity to the equation. The wave drag coefficient follows by normalization according to:

$$C_W = \frac{R_w}{0.5\rho S U^2} \tag{8}$$

with S denoting the (static) wetted surface area.

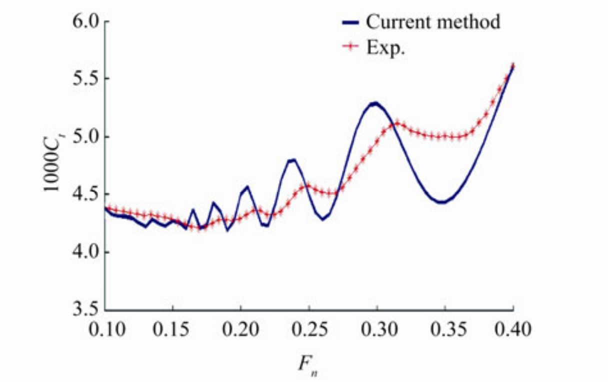

Fig. 2 Comparison of experimental drag coefficient with prediction for Wigley hull

The comparison of experiment (Ju, 1983), with current method for a Wigley hull (L/B=10 and L/T=16) is shown in Fig. 2. Using Michell's Integral for wave drag and the ITTC line with a form factor for viscous drag leads to rather good agreement. For the entire range of Froude number, errors between predictions and the experimental curve lie within about 12%. The current method used for calculating the total drag is relatively cost effective and less time consuming compared to other complex CFD methods and hence is a suitable method for the optimization. The total drag (objective function) is a function of the length, beam, draft and the hull offsets of the ship in the optimization process which must be minimized.

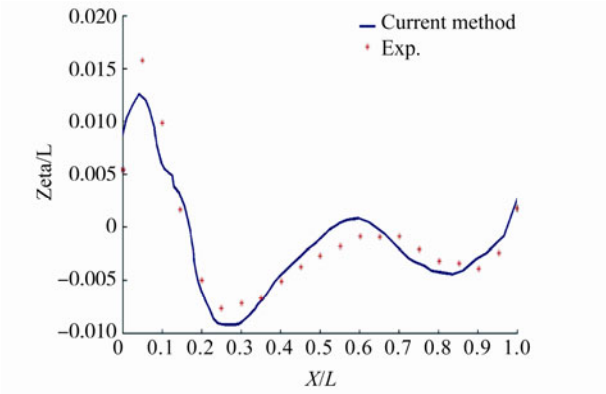

Fig. 3 Wave profile along Wigley hull

The integrand of above amplitude function is highly oscillatory, and special techniques are needed to evaluate the integrals. We use Filon's quadrature (Davis and Rabinowitz, 1984) to capture the rapid oscillations as $\left|\theta\right| \to \pi/2$. Conventional quadratures fail to capture the correct decay of the spectrum in this region (Tuck *et al*., 2002). A comparison of the calculated and measured (Kajitani *et al*., 1983) wave profile is made next to the Wigley hull for the initial and optimized hull are depicted in Fig. 3. The agreement of calculated wave profiles with the measurement is good but the bow wave elevation is underestimated for the Wigley hull.

3 Evolution strategies

Among the class of evolutionary algorithms, evolution strategies (ESs) are the most popular algorithms for solving continuous optimization problems, i.e. for optimizing real-valued function f defined on a subset of $\mathbb{R}^n$ for some dimension n, they can be applied to combinatorial problems as well. Evolution Strategies are inspired by the evolution theory (Darwinian Theory of biological evolution) by means of a process that is known as natural selection and the "survival of the fittest" principle. The common idea behind this technique is similar to other evolutionary algorithms: consider a population of individuals; the environmental pressure causes natural selection which leads to an increase in the fitness of the population. It is easy to see such a process as optimization. Consider an evaluation function to be minimized. A set of candidate solutions can be randomly generated and the objective function can be used as a measure of how individuals have performed in the problem domain (an abstract fitness measure) - the lower the better. According to this fitness, some of the better solutions are selected to seed the next generation by applying recombination and/or mutation operators to them. The recombination (also called crossover) operator is used to generate new candidate solutions (offspring) from existing ones, they take two or more selected candidates (parents) from the population pool and exchange some parts of the solutions to form one or more offspring. Mutation operator is used to generate one offspring from one parent by changing some parts of the candidate solution. Applying recombination and mutation operators causes a set of new candidates (the offspring) competing based on their fitness (and possibly age) with the old candidates (the parents) for a place in the next generation. This procedure can be iterated until a solution with sufficient quality (fitness) is found or a previously set computational time limit is reached. In other words, the end conditions must be satisfied. The composed application of selection and variation operators (recombination and mutation) improves fitness values in consecutive population. A general flowchart of evolution strategies is shown in Figure 4.

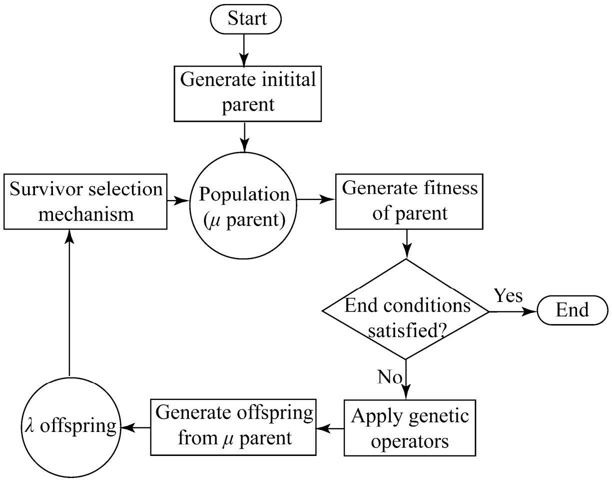

Fig. 4 General flowchart of evolution strategies

Variables in evolution strategies are divided into two categories: object and strategy variables. Standard representation of variables in evolution strategies is as real-valued vectors because ESs is usually used for continuous parameters. A form of an individual in ESs is as follows:

$$\left\langle x_1, \cdots, x_n \ \sigma_1 \ \cdots \ \sigma_{n_\sigma} \right\rangle$$

where x_i is the object variable and σ_i is mutation step size or standard deviation (strategy variable). A normal (Gaussian) distribution with zero mean and standard deviation σ in the mutation operator of ES is a major characteristic. A common approach of mutation operator is uncorrelated mutation with n step sizes. The advantage of this approach is that the fitness surface can be treated in different directions with different slopes. The mutation methodology for $i \in \{1, \cdots, n\}$ is as follows:

$$\sigma_i^{t+1} = \sigma_i^t \cdot \mathrm{e}^{\tau \cdot N(0,1) + \eta \cdot N_i(0,1)} \tag{9}$$

$$x_i^{t+1} = x_i^t + \sigma_i^{t+1} \cdot N_i(0,1) \tag{10}$$

where $\tau \propto 1/\sqrt{2n}$, $\eta \propto 1/\sqrt{2\sqrt{n}}$ and $N_i(0,1)$ are random numbers drawn from the standard normal distribution. Note that the $N(0,1)$ is drawn only once (Back *et al.,* 2000). Global intermediate recombination and global discrete recombination are typically two main types of recombination used in ES. One child $\bar{z}$ is produced from two parents $\bar{x}$ and $\bar{y}$ drawn randomly from μ parents for each position $i \in \{1, \cdots, n\}$ where

$$z_i = \begin{cases} (x_i + y_i)/2 & \text{(a)} \\ x_i \text{ or } y_i \text{ chosen randomly} & \text{(b)} \end{cases}$$

The global intermediate recombination (a) and the global discrete recombination (b) are preferred for use in the strategy variables and the object variables respectively. The (μ, λ) survivor selection scheme has advantages over its competitor, the $(\mu + \lambda)$ selection scheme (Eiben and Smith, 2003). The special characteristic of ESs lies in the self-adaptation of the standard deviation of the Gaussian distribution used in the mutation (Back and Schwefel, 1993).

Further to their robustness, ES:

- Can locate global optimum and escape from local optimums.
- Can locate feasible optimal solution, in constrained optimization problems.
- Use the values and parameters themselves, not a coding of them.

4 Optimization procedure

The procedure of optimizing a ship hull form in order to find a hull shape with minimum total drag is as follows. The optimization of hull form can be performed by evaluating the hull forms that are generated by variation operators and then selecting the best forms of lower drag in each generation.

The Wigley hull form is considered as initial hull form. Each chromosome (biologic name of a solution) in the optimization algorithm consists of ship offsets, length (waterline length), beam (in waterline) and draft. Because of large number of variables, the evolution strategy is a successful technique for the hull form optimization problems from a total drag point of view. The design constraints that were used for this study are that the optimizer allowed no change in the total displacement of the ship. In addition, sinkage and trim effects are not considered as a hydrodynamic design constraint. Some limits have been imposed on the principal dimensions and the hull offsets. In order to restrict the search space and to keep the optimal hull near the original one for comparison, the length, beam and draft are limited to a ±20 percent variation in the principal dimensions and the offsets points are limited to ±6 percent of the initial hull offsets for the case only the offsets values are changed and ±2 percent of the initial hull offsets for the case in which both the offsets values and the main dimensions are changed. Table 1 represents variation percent of variables used in test cases.

Table 1 Variation percent of variables used in test cases

Item	Variation percent			
Variables	Hull offsets	L	B	T
Offsets	±6	fixed	fixed	fixed
Main dimensions and offsets	±2	±20	±20	±20

The Wigley model is a popular and well-known model in ship hydrodynamics experiments. Many experimental and numerical results can be found in the literature for this model. We employed this model to compare numerical results. The standard Wigley hull is a mathematical displacement hull form, the geometric surface of which can be defined as:

$$f(x,y)=\frac{B}{2}\left[1-\left(\frac{2x}{L}\right)^2\right]\left[1-\left(\frac{z}{T}\right)^2\right]$$

where B is the ship beam, L is the ship length, T is the ship draft, $-L/2\leqslant x\leqslant L/2$ and $-T\leqslant z\leqslant 0$. The total drag which may be computed from equation (1) is the objective function of the optimization algorithm. The hull form optimization is performed at a single Froude number ($Fn=U/\sqrt{gL}$) of 0.316. The Froude number is based on waterline length. Table 2 demonstrates the main particulars of the Wigley hull.

Table 2 Main particulars of the Wigley hull

Model type	L /m	B /m	T /m	S /m^2	Design Fn
Wigley	3.048	0.3048	0.1905	1.383	0.316

The process of optimization is performed by the evolution strategy. The offset points and principal dimensions can be represented by real-valued vectors in the limits as already mentioned. The global intermediate recombination and the global discrete recombination have been used in the strategy variables and the object variables respectively. The mutation operator with n step size (using normal distribution) has been applied to the individuals. The recombination rate has been 0.80, while the mutation rate has been 1 per one individual. The parent selection has been approached by a uniform random distribution. According to results of tests carried out by authors the (μ,λ) scheme has been considered as an appropriate survivor selection mechanism for test cases used the Wigley hull as mother model. If we don't use a way to smooth the hull, the generated hulls are wavy and impractical. Therefore, we have used a modification algorithm by means of cubic B-Spline surface to obtain fair hull forms in the optimization methodology.

5 Result and discussion

5.1 Wigley hull with fixed principal parameters

At first test a 3.048 m Wigley hull form with length to beam ratio L/B = 10 and length to draft ratio L/T = 16 is considered for optimizing with respect to the minimum total drag. This hull form is optimized in calm and deep water with infinite bounds. The optimization of hull form is carried out at Fn = 0.316 with the given restrictions on the main dimensions (the length, beam, and draft). The displacement is assumed to remain constant as a constraint. Because the main dimensions are fixed in this case and the only change is in the offsets of ship model, evaluating results are convenient with observing the initial and optimal hull forms.

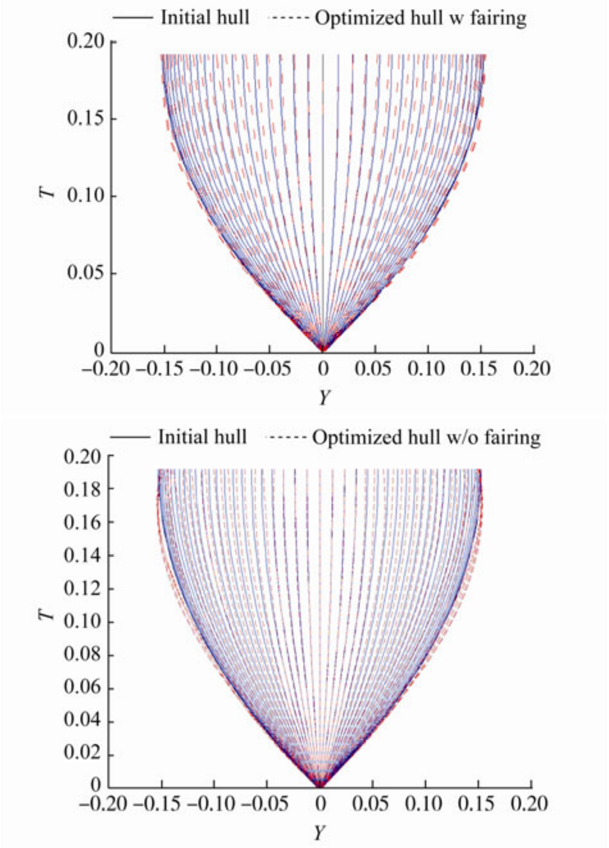

Fig. 5 Body plans of initial Wigley hull and optimal hull with fixed main dimensions

The variation interval in the hull offsets is between 94 and 106 percent of offsets values of the initial hull. Application of the evolution strategy technique generated optimal hull form with body-plan before and after hull fairing exhibited in Fig. 5. The single-speed optimization procedure improved the initial hull and produced a reasonable hull form.

140 hull forms in each generation are created and among them, the best 20 hull forms are selected to seed the next generation based on the fitness (the lower total drag the better). The obtained hull is smoothed by using cubic

B-Spline surface fitting. As can be seen in Fig. 5 the initial hull has not changed much and so the modified hull form is approximately covered by the initial hull form, specifically in the end sections of the hull. The sections area toward the amid-ships sections has decreased (contracting sections), toward the ends of the hull and in the amid-ship sections has increased (extending sections) and near the extreme ends of the hull has almost remained unchanged.

In all Figures and Tables R_{t0} is the total drag of the initial hull, R_f is the frictional drag, R_w is the wave drag and R_t is the total drag of the hull that have been optimized. The frictional drag coefficient calculating by equation (3) remains unchanged and its curve is straight line, because the values of the length, speed and kinematic viscosity in this case are constant during the optimization. The reduction percent of the total drag is about 11.4% at Fn=0.316.

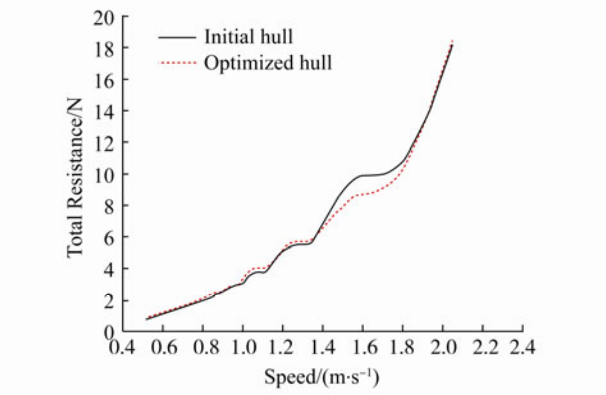

Fig. 6 The total drag for the initial Wigley hull and the optimized hull with fixed main dimensions

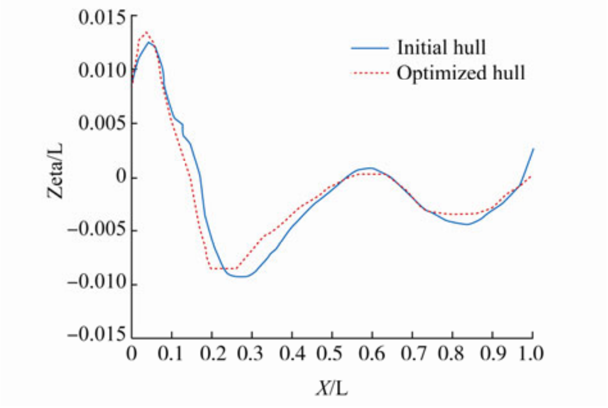

Fig. 7 Comparison of wave profiles along the Wigley hull with fixed main dimensions

If our objective function was the wave drag, its reduction percent would be 35.3% that is a considerable reduction. Table 3 indicates some parameters of the initial and optimized hulls. In all Tables plus and minus signs mean increase and reduction respectively.

Fig. 6 shows comparison of the total drag for the optimal hull and the initial Wigley hull within a speed range. It can be seen that the total and wave drags for the optimal hull are decreased at a speed range centered where the single speed optimization process is implemented (Fn = 0.316) and nearly remains fixed at other speeds. Therefore, the optimized hull can conduct effectively only in the restricted range and after it slightly.

Table 3 Initial and optimized hulls for Wigley with fixed parameters

Model type	L/m	B/m	T/m	S/m^2	R_f/R_{t0}	R_w/R_{t0}	R_t/R_{t0}
Initial hull	3.048	0.305	0.190	1.38	0.634	0.34	1
Optimized hull	3.048	0.305	0.190	1.41	0.646	0.22	0.886
Variation percent	-	-	-	+1.95%	+1.95%	−35.3%	−1.4%

From Table 1 it can be realized that the Wigley hull form indicates a difficult hull for which to make any effective improvements, but it is remarkable that in this case the main dimensions were fixed. Fig. 7 shows a comparison of the wave profile at a longitudinal cut next to the hull for the initial and the optimized hull. The optimized hull creates a slightly larger bow wave and lower stern wave than the initial hull. The former is due to increased steepness of the bow wave and the latter is due to a reduction of the transverse wave system.

5.2 Evolving Wigley hull by changing main dimensions

In order to perform the optimization of hull for minimizing the total drag of the ship, which is a key factor in the hydrodynamic design of hull, and to determine the preliminary design parameters to satisfy the design requirements given by the owner or client, it is necessary the candidate solutions generated are permitted to vary by changing the offsets of hull form and the main dimensions. The 3.048 Wigley hull is considered for single speed optimization of hull form at Fn = 0.316 that the displacement of hull is assumed as a constraint. The offsets values of the hull are changed in the limits between 98 and 102 percent of initial offsets values and the main dimensions in the limits between 80 and 120 percent of the main dimensions of the initial hull. The process of optimization is run by producing 140 hulls of each algorithm of iteration and then by selecting the best 20 hulls among them as parent hulls of the next iteration. Fig. 8 shows body-plan of the optimal hull form with and without hull fairing generated by use of the evolution strategy optimization technique and body plan of the initial Wigley hull.

As can be seen in this Figure the beam of the optimized hull is wider than the beam of the initial Wigley hull and the draft of the optimized hull has decreased significantly. During the run of the optimization algorithm in addition to the hull offsets the length, beam and draft of the hull are changed. The length of the hull is rapidly decreased in the initial evaluations. In other words the initial hull is longer than the optimized hull. The changes in the main dimensions of the hull are to achieve minimum drag and match the constraint for the displacement.

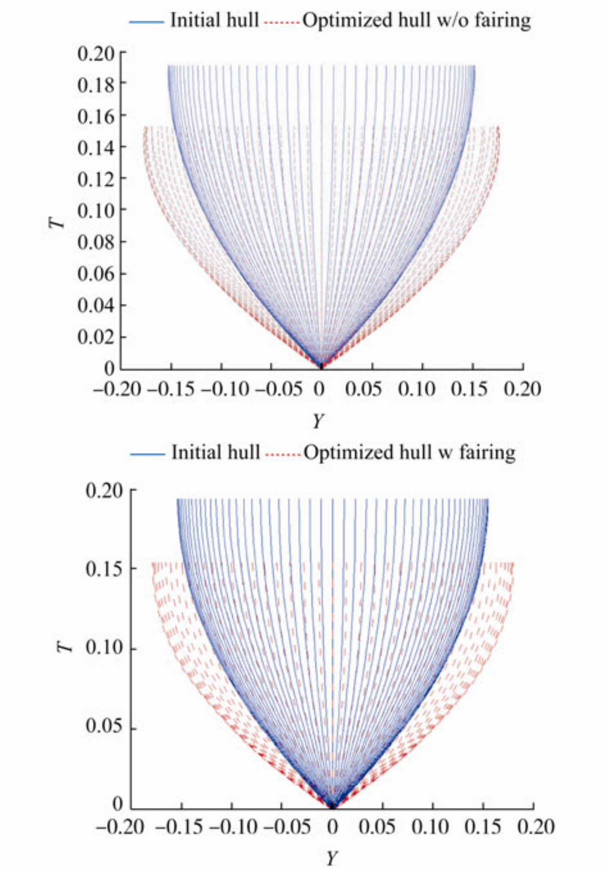

Fig. 8 Body plans of original Wigley hull and optimal hull with changing main dimensions

The frictional drag doesn’t remain unchanged. This is due to changes in the length and the wetted surface of the hull during the optimization process.

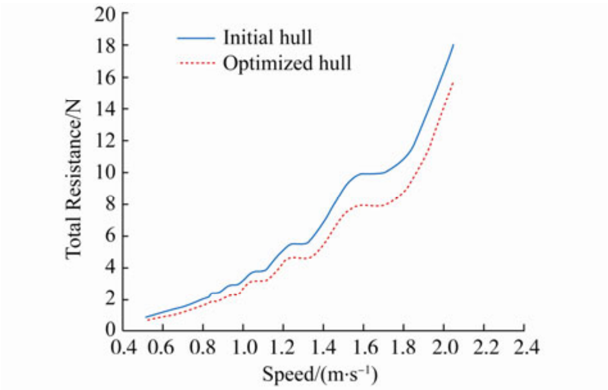

Fig. 9 The total drag for the initial Wigley hull and the optimized hull with changing main dimensions

Usually convergence changes of a parameter such as total drag and main dimensions of the hull in evolutionary algorithm are the same, so that in the early phase of the optimization process the parameter is decreased quite quickly allowing reduction trends to continue with less slopes until the algorithm converged to an optimal value. The frictional drag, wave drag and total drag are reduced approximately 19.6%, 25% and 19.3% respectively. The reduction in the wave drag is considerable. Table 4 shows some parameters of the initial hull and the optimized hull for this case. As can be seen in this Table the reduction percent obtained for the wave drag is more than the reduction percent for the frictional drag. The reason for this is that the optimization procedure (ES) affected the wave resistance more than the frictional resistance.

Table 4 Initial and optimized hulls for Wigley with changing parameters

Model type	L/m	B/m	T/m	S/m^2	R_f/R_{t0}	R_w/R_{t0}	R_t/R_{t0}
Initial hull	3.048	0.305	0.190	1.38	0.634	0.34	1
Optimized hull	2.684	0.353	0.152	1.13	0.53	0.255	0.807
Variation percent	-12%	+16%	-20%	-18.1%	-19.6%	-25%	-19.3%

Comparing the hydrodynamic performance of the initial hull form with the optimized hull form for the total drag for a range of the speed is shown in Figure 9. As can be seen in this Figure although the hull form has been optimized for a single speed ($V = 1.73$), the total drag of the optimal hull form is less over the broad range of the speed. As the speed increases, the difference between the total drags of original and optimized hull forms (drag reduction) increases. The wave profile of the initial and the optimized hull at a longitudinal cut next to the hull is compared (see Figure 10). The optimized hull creates a slightly larger bow wave and lower stern wave than the initial hull which leads to lower wave resistance.

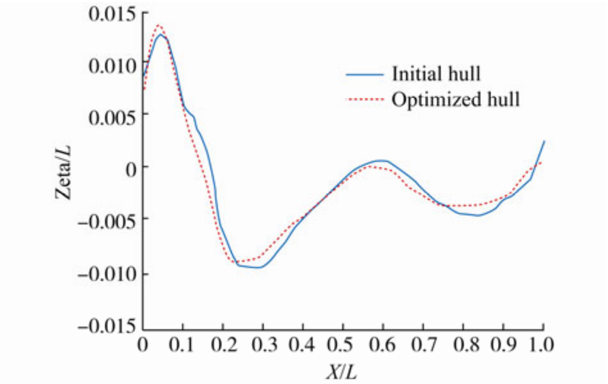

Fig. 10 Comparison of wave profiles along the Wigley hull with changing main dimensions

It should be noted that the optimization performed in the single speed ($Fn = 0.316$) and the optimal hull forms aren't same for all Froude numbers. For example the other optimal Wigley hull forms with changes in hull offsets and main dimensions simultaneously at $Fn = 0.25$ and $Fn = 0.408$ are shown in Figure 11. Tables 5 and 6 present characteristics of initial and optimized hulls at these Froude numbers. As can be seen from Tables the length and wetted surface of the hull are reduced and the hull beam is increased at $Fn = 0.25$

opposed to those at Fn = 0.408. The hull draft is decreased at both Froude numbers and the reduction percent of total resistance is 17.4% and 29% respectively. The higher reduction percent of the wave and total resistance at Fn = 0.408 is due to higher increase of the length to beam ratio.

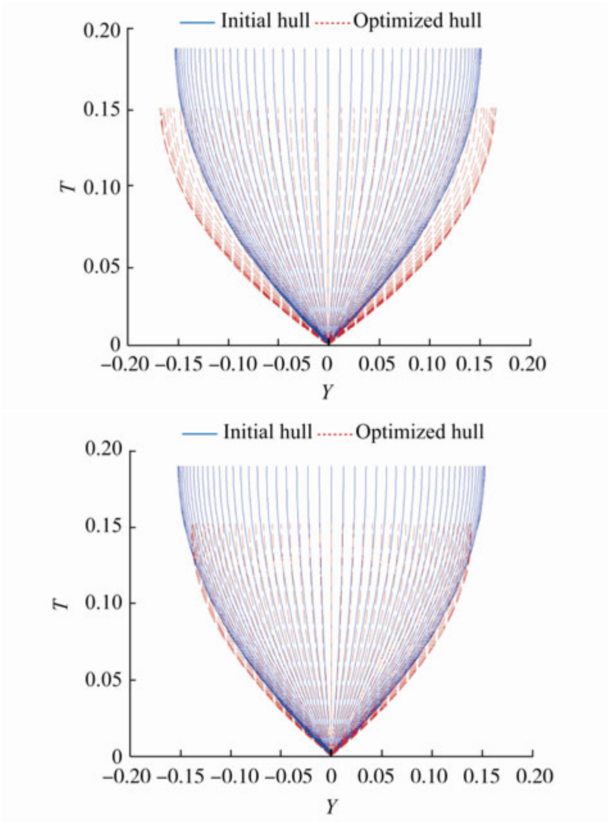

Fig. 11 Body plans of original Wigley hull and optimal hull with changes in hull offsets and main dimensions at Fn = 0.408 (bottom) and Fn = 0.25 (top)

Finally the results of optimization technique for a case (the Wigley hull form with changing principal parameters) were validated by an independent numerical prediction method. Fig. 12 shows a comparison between the wave resistance coefficient of optimized hulls calculated by corrected Michell's Integral used in this study and boundary element method (BEM) used in Ghassemi *et al.* (2010). The agreement of calculated wave resistances well with the BEM is rather good, especially close to Fn = 0.316. The thin ship theory overestimates the wave resistance. One of the main reasons for the difference between the current method and BEM is due to the absence of nonlinear effects. Since the BEM is a time consuming method, efforts to compute the wave resistance, we were conducted utilized utilizing the corrected Michell's Integral, which is a fast method. We will try to use the BEM which is more accurate than the current method for hull form optimization problems in our future studies.

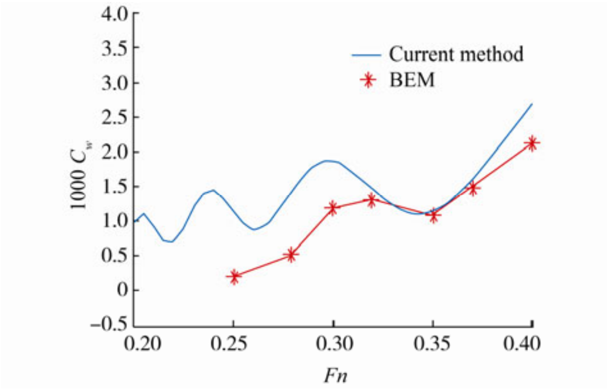

Fig. 12 Comparison of wave resistance coefficient of optimized Wigley hull

Table 5 Initial and optimized hulls for Wigley with changing parameters at Fn = 0.25

Model type	L/m	B/m	T/m	S/m^2	R_f/R_{t0}	R_w/R_{t0}	R_t/R_{t0}
Initial hull	3.048	0.305	0.190	1.38	0.75	0.22	1
Optimized hull	2.887	0.337	0.152	1.19	0.65	0.15	0.826
Variation percent	-5.3%	+10.6%	-20%	-13.8%	-13%	-32%	-17.4%

Table 6 Initial and optimized hulls for Wigley with changing parameters at Fn = 0.408

Model type	L/m	B/m	T/m	S/m^2	R_f/R_{t0}	R_w/R_{t0}	R_t/R_{t0}
Initial hull	3.048	0.305	0.190	1.38	0.51	0.47	1
Optimized hull	3.658	0.28	0.152	1.41	0.50	0.24	0.71
Variation percent	+20%	-8.1%	-20%	+2.2%	- 2%	- 49%	-29%

5 Conclusions

A numerical optimization technique for optimizing hull forms in calm water was presented based on hydrodynamic performance of the hull based on total drag. The evolution strategy which is one of the evolutionary algorithms was linked to a simple CFD tool for estimating the total drag of a ship at constant speed based on Michell's thin ship wave drag theory and ITTC 1957 friction drag formula. The standard Wigley hull form has been considered as initial hull to optimize the hull forms having the same displacement as a constraint. The single speed optimization was conducted to derive optimal hull form based on offsets and optimal length, beam and draft in two cases. In a case the evolution strategy technique was run where the main dimensions were fixed and the only variables were the hull offsets. In the other case in addition to hull offsets, the main dimensions were considered as variables that were optimized simultaneously. An upper and a lower limit were imposed on the main dimensions of length, beam and draft. By comparing the achieved results from the optimization process with initial hull forms it became clear that an optimal hull form with improved characteristic for total drag can be obtained as demonstrated in the Figures deduced from two test cases. Finally the results were validated by the BEM. The obtained reduction percent especially in wave drags is considerable comparing with other papers. Evolution strategies using in this study are effective and robust techniques for hull form optimization. This optimization program could not be considered as a fully developed practical tool for early stages of ship design. A comprehensive concept design tool should be considered other important objective functions such as seakeeping, maneuverability, propulsion, weights and etc. Furthermore, to get better results, it is necessary to utilize a powerful method for solving three-dimensional flow around the hull, as well as evaluating the results by experiments to validate the optimization process.

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References

Back T, Fogel DB, Michalewicz EZ (2000). Evolutionary Computation 1: Basic Algorithms and Operators, Institute of Physics, Bristol (UK).

Back T, Schwefel HP (1993). An overview of evolutionary algorithms for parameter optimization. *Journal of Evolutionary Computation*, **1**(1), 1-23.

Beyer HG, Schwefel HP (2002). Evolution Strategies: A Comprehensive Introduction. *Journal of Natural Computing*. **1**(1), 3-52.

Chandraprabha S, Molland A F (2006). A numerical prediction of wash wave and wave drag of high speed displacement ships in deep and shallow water. *Conference on Mechanical Engineering*, Thailand.

Davis PJ, Rabinowitz P (1984). *Methods of Numerical Integration, 2nd ed*., Academic Press, New York.

Dejhalla R, Mirsa Z, Vukovic S (2001). Application of Genetic Algorithm for Ship Hull Form Optimization. *International Shipbuilding Progress*, **48**(2), 117-133.

Eiben AE, Smith JE (2003). *Introduction to evolutionary computing, 1st ed*., Springer, Natural Computing Series.

Gammon MA (2011). Optimization of fishing vessels using a Multi-Objective Genetic Algorithm. *Journal of Ocean Engineering*, **38**(10), 1054-1064.

Ghassemi H, Iranmanesh M, Aardeshir A (2010). Simulation of free surface wave pattern due to the moving bodies. *Iranian Journal of Science & Technology, Transaction B: Engineering*, **34**(2), 117-134.

Grigoropoulos GJ, Chalkias DS, Tikkos C (2004). Multi-objective hull form optimization of high-speed vessels. *Intl. conf. HIPER*.

Grigoropoulos GJ, Chalkias DS (2010). Hull-form optimization in calm and rough water. *Journal of Computer-Aided Design*, **42**(11), 977-984.

Janson C, Larsson L (1996). A method for the optimization of ship hulls from a resistance point of view. *21st Symposium on Naval Hydrodynamics*, Trondheim, Norway.

Ju S (1983). Study of total and viscous drag for the Wigley parabolic ship form. IIHR Report, no. 261, p. 35.

Kajitani H, Miyata H, Ikehata M, Tanaka H, Adachi H (1983). Summary of the cooperative experiment on Wigley parabolic model. *Proceedings of the Workshop on Ship Wave Resistance Computations*, Japan, 5–35.

Kim H, Yang C, Löhner R, Noblesse F (2008). A Practical Hydrodynamic Optimization Tool for the Design of a Monohull Ship. *Proc. ISOPE Conf*., Vancouver, Canada.

Percival S, Hendrix D, Noblesse F (2001). Hydrodynamic optimization of ship hull forms. *Journal of Applied Ocean Research*, **23**(6), 337-355.

Peri D, Rossetti M, Campana EF (2001). Design optimization of ship hulls via CFD techniques. *Journal of Ship Research*, **45**(2), 140-149.

Rechenberg I (1973). *Evolution strategie: Optimierung Technisher Systemenach Prinzipien des Biologischen Evolution*. Fromman-Hozlboog Verlag, Stuttgart.

Saha GK, Suzuki K, Kai H (2004). Hydrodynamic optimization of ship hull forms in shallow water. *Journal of Marine Science and Technology*, **9**(2), 51-62.

Schwefel HP (1995). *Evolution and Optimum Seeking*. New York, Wiley Interscience.

Tuck EO, Lazauskas L (1998). Optimum hull spacing of a family of multihulls. The University of Adelaide, Adelaide, Australia, Dept. Applied Mathematics Technical Report.

Tuck EO, Scullen DC, Lazauskas L (2002). Wave patterns and minimum wave drag for high-speed vessels. *Proc. of 24th Symposium on Naval Hydrodynamics*, Fukuoka, Japan.

Zhang BJ (2012). Research on optimization of hull lines for minimum resistance based on rankine source method. *Journal of Marine Science and Technology*, **20**(1), 89-94.

Zhang BJ (2009). The optimization of the hull form with the minimum wave making resistance based on rankine source method. *Journal of Hydrodynamics*, **21**(2), 277-284.

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