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Optimizing the Seakeeping Performance of Ship Hull Forms Using Genetic Algorithm

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ABSTRACT: Hull form optimization from a hydrodynamic performance point of view is an important aspect of ship design. This study presents a computational method to estimate the ship seakeeping in regular head wave. In the optimization process the Genetic Algorithm (GA) is linked to the computational method to obtain an optimum hull form by taking into account the displacement as design constraint. New hull forms are obtained from the well-known S60 hull and the classical Wigley hull taken as initial hulls in the optimization process at two Froude numbers (Fn=0.2 and Fn=0.3). The optimization variables are a combination of ship hull offsets and main dimensions. The objective function of the optimization procedure is the peak values for vertical absolute motion at a point 0.15LBP behind the forward perpendicular, in regular head waves.

1 INTRODUCTION

Prediction of Ship performances in calm and rough water is one of the most important concerns for naval architects, already at the earliest design stage. From this point of view seakeeping performance is one of the most important performances in the ship hull form optimization. It is possible to achieve considerable improvements in terms of habitability, operability and survivability by means of changes in hull form even when displacement and main dimensions have been fixed.

It is worth noting that for a comprehensive and detailed ship hydrodynamic optimization all objective functions such as resistance, 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.

Some researchers have considered two or three objective functions for optimizing hull form and some others only one objective functions. For example Gammon (2011) uses three objective functions in his study, Biliotti et al. (2011) and Grigoropoulos and Chalkias (2010) utilize two objective functions in their work and many researcher use only one objective function (Han et al., 2012, Zakerdoost et al., 2013, A. Scamardella and V. Piscopo, 2014).

Zhang (2009 and 2012), Kim et al. (2009 and 2008) and Saha et al. (2004) employed different types of the Nonlinear linear programming (NLP) as optimization techniques. Evolutionary Algorithm (EA) and Artificial Neural Networks (ANN or NN) offer effective method for conducting optimization and data analysis. EA techniques may be separated into Genetic Algorithm (GAs), Evolutionary Strategies (ESs) and Evolutionary Programming (EP). However at present Genetic Algorithm (GA) and evolution strategies (ESs) are most widely used in hull shape modification. In this work, the term GA is used to solving optimization problem. Day and Doctors (2001) studied hull form optimization using a GA technique in which the objective was to minimize resistance. Jun and Kuniharu (2004) presented a single-objective optimization algorithm based on genetic algorithm to improve hull form of a catamaran.

Due to the importance of seakeeping performance, seakeeping optimization has become a popular research topic for the last three decades.

Bales (1980) optimized a destroyer-type hull form, in head seas and at various speed, on the basis of analytical predictions, subsequently deriving by some regression formulas correlating relevant performances to form parameters, the optimum hull. Griogoropoulos and Loukakis (1988) developed a numerical method, based on a nonlinear direct search algorithm to minimize RAO peak values in head regular waves. Similar studies have been also carried out by Hearn et al. (1991), who developed an inverse design procedure, based on the optimum hull nonlinear direct search process. Kukner and Sariöz (1995) optimized the seakeeping qualities of a high speed vessel, generating by the Lackenby method (Lackenby, 1950), several derived hulls having different form parameters as regards the parent ones. Peacock et al.(1997) defined a mathematical model based on a multi-objective research algorithm for displacement mono-hulls. Sariöz and Sariöz (2006) proposed a new optimization procedure, based on a nonlinear problem solved by direct search techniques. Campana et al. (2009) proposed a new optimization technique for the heave motion of the S175 container ship, adopted by the ITTC Seakeeping Committee as a benchmark test, considering two different optimization procedures, namely a filled function based algorithm and a Particle Swarm Optimization method. Diez and Peri (2010) presented a new approach for the robust optimization of a bulk carrier conceptual design, subjected to uncertain operating and environmental conditions, so extending the standard deterministic formulation for design optimization to take into account the uncertainty related to design variables, operating conditions and computational results of the simulations. Finally Özüm et al. (2011) investigated the seakeeping qualities of fast ships, systematically varying both main dimensions and hull form parameters. Anyway, in almost all cases, optimization procedures were based on the assumption that the optimum hull is found when the vertical plane motions and absolute vertical acceleration in regular head waves due to combined pitch, heave motions, is minimized.

In this study, after problem formulation and especially the explanation of strip theory and a particular form of the optimization algorithm (genetic algorithm), results of application of this methodology using two different cases of the Wigley hull and the S60 hull are presented, and in both ones allowing principal parameters of length, beam and draft to change simultaneously with the offset of hull surface. It should be noted that the current design procedure is restricted to the minimization of vertical plane motions and roll is not included for the following reasons:

- The sensitivity of roll motion to weight distribution characteristics which are generally not available at the early stages of design.
- Difficulties in predicting nonlinear roll damping.
- The fact that excessive roll can always be reduced by changing heading to head or bow seas.

2 OPTIMIZATION PROBLEM AND GA

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:

$$\text{Optimize} \quad F(\bar{x})=\left[f_1(x),f_2(x),\ldots,f_m(x)\right] \qquad x\in\mathbb{R}^n \tag{1}$$

Subject to

$$\begin{cases} h_i(\bar{x})=0 & \mathrm{i}=1,\ldots,\mathrm{q} \\ \mathrm{g}_i(\bar{x})\le 0 & \mathrm{i}=1,\ldots,p \end{cases} \tag{2}$$

where $f_i\left(\bar{x}\right)$ 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 $\bar{x}=\left(x_1,\ldots,x_n\right)\in\mathcal{F}\subseteq S$ is a solution or individual. The set $S\subseteq\mathbb{R}^n$ defines the search space and the set $\mathcal{F}\subseteq \mathrm{S}$ defines a feasible search space. The search space S is defined as an n-dimensional rectangle in $\mathbb{R}^n$ (domains of variables defined by their lower and upper bounds):

$$l\left(i\right)\le x_i\le u\left(i\right) \qquad 1\le i\le n$$

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

In this study design variables vector include the main parameters (length, beam, draft) and the hull offset which are limited by the lower and upper bounds. The ship hull displacement also is an inequality constraint.

Among the class of evolutionary algorithms, genetic algorithm (GA) is the most popular algorithm 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. Genetic algorithm can be applied to combinatorial problems as well. Genetic algorithm is 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 them 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 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 genetic algorithm is shown in Figure 1.

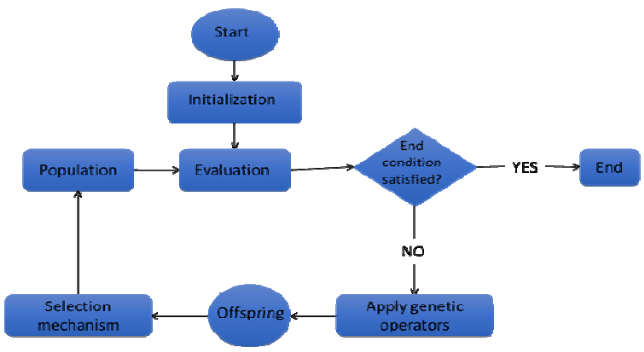


Figure 1. General flowchart of genetic algorithm

Genetic algorithm variables are divided into two categories: object and genetic variables. Variables in genetic algorithm commonly are as real-valued vectors because this algorithm is usually used for continuous parameters. A form of an individual in GA is as follows:

$$\langle x_1,\ldots,x_n\rangle$$

where x_i is the object variable. In object variables mutation, each gene (biologic name of a vector) changed whit mutation rate (genetic variable) in range of their lower and upper bounds. The mutation methodology for $i\in\{1, \ldots ,n\}$ is as follows:

$$\langle x_1,\ldots,x_n\rangle\rightarrow\langle x_1',\ldots,x_n'\rangle \quad \text{where} \quad x_i,x_i'\in\left[l(i),u(i)\right] \qquad (3)$$

Scatter recombination is one of main type of recombination (crossover) used in GA. This type of crossover creates a random binary vector. So, the genes are selected from the first parent where the vector is a 1, and from the second one where the vector is a 0. The $(\mu,\ \lambda)$ survivor selection scheme has advantages over its competitor, the $(\mu+\lambda)$ selection scheme but the $(\mu+\lambda)$ selection scheme is an elitist mechanism that can maintain the best solution to each generation (Eiben and Smith, 2003).

3 SEAKEEPING CALCULATION

The determination of hydrodynamic forces acting on a ship can be formulated as a linear boundary value problem in potential theory. Under the assumption that motion responses are linear, or at least can be linearized and are harmonic, the equations of motion for the advancing ship in waves may be written in the following general form:

$$\mathrm{L}_{kj}(\mathrm{H},\omega,\ \mathrm{U})\eta_j=\mathrm{F}_k\ ,\ k,j=1,2,\ldots,6 \qquad (4)$$

where H represents the hull geometry, ω is the wave frequency and U is the forward speed. Typically the operator $\boldsymbol{L_{kj}}$ is of the form

$$L_{kj}=-\left(\mathrm{M}_{kj}+\mathrm{A}_{kj}\right)\omega^2-i\mathrm{B}_{kj}\omega+\mathrm{C}_{kj} \qquad (5)$$

where M is the generalized mass matrix, A and B represent the added mass and fluid damping matrices associated with forces/ moments induced in the k th mode, as a consequence of motion in the j th mode and C is the hydrostatic restoration matrix. The degrees of freedom, j, correspond to surge, sway, heave, roll, pitch and yaw as j assumes the value 1-6, respectively. The dependence of the hydrodynamic coefficients and the hydrostatic restoration upon the hull form shape may be expressed as:

$$\begin{aligned}A_{kj}&=A_{kj}(H,\omega,\ U)\\ B_{kj}&=B_{kj}(H,\omega,\ U)\\ C_{kj}&=C_{kj}(H)\end{aligned} \qquad (6)$$

The wave excitation F_k is also a function of wave heading

$$F_k=F_k(H,\omega,\ U,\beta) \qquad (7)$$

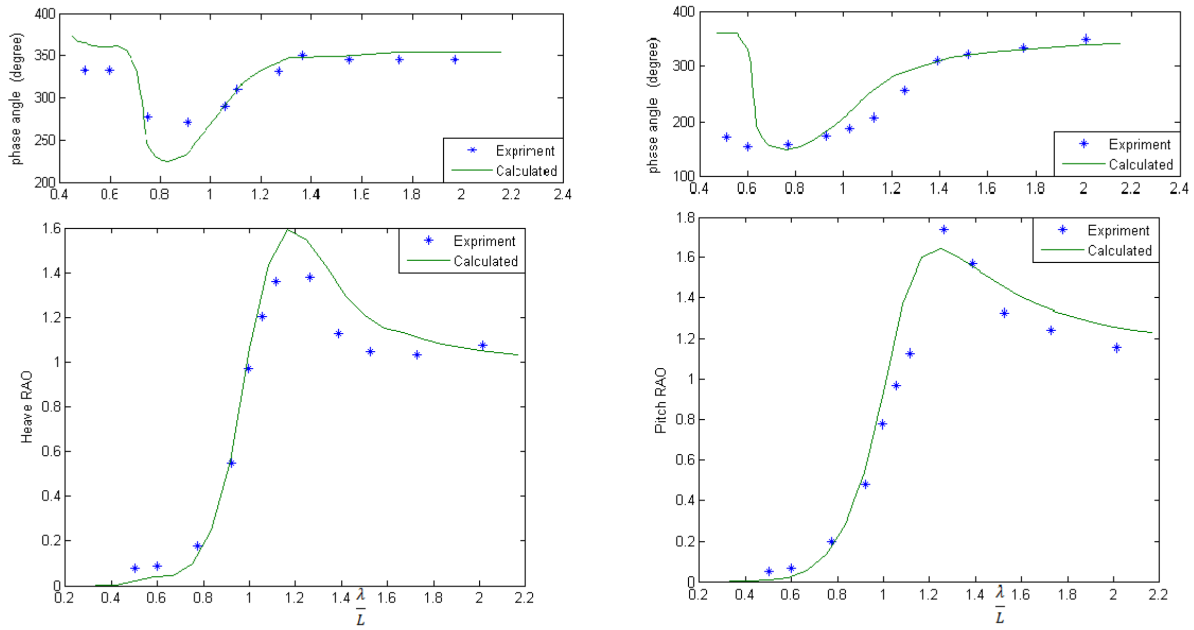


Figure 2. Comparison of heave and pitch RAO coefficient for models of the Wigley hull

The added mass, damping, restoring force and wave exciting force terms can be calculated by using well established numerical procedures. In order to reduce the computing time a linear strip theory approach is adopted as described by Salvesen et al. (1970). The sectional added mass and damping coefficients are calculated by using the well-known Frank Close-Fit method (1967). The seakeeping responses in head sea are generally the most important responses for mono-hulls. Thus, all calculations were carried out for vertical motions and related kinematics certainly. The computed ship responses include vertical motion and acceleration at bow region (at a point 0.15LBP behind the forward perpendicular). All the results are given for regular head waves.

The comparison of Delft University of Technology (DUT) Report experiment(1992) with a 3 m Wigley hulls with length to beam ratio L/B = 10 and length to draft ratio *L/T = 16* in head regular wave whit 4 cm wave height, heave and pitch RAO respectively are shown in Figure 2. Using the numerical method described above for computing Ship vertical motion leads to good agreement and errors between predictions and the experiments (white respect to linear theory was employed) lie within about %10 for the design Froude number (Fn=0.3). It should be noted that according to the figure 2, the heave and pitch RAO at λ/L-1.2 that the peak value occurs, have a 180 degree phase difference. The vertical bow motion (objective function) is a function of the main dimension (length, beam and draft) and the hull offsets of the ship in the optimization process which must be minimized.

4 PROCEDURE OF THE HULL FORM OPTIMIZATION

The procedure of optimizing a ship hull form in order to find a hull shape with minimum bow vertical motion 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 vertical motion at bow reign in each generation.

The Wigley and S60 hull forms are considered as initial hull forms. 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 genetic algorithm is a successful technique for the hull form optimization problems from a seakeeping 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 ±10 percent variation in the principal dimensions and the offsets points are limited to ±3 percent of the initial hull offsets. Table 1 represents variation percent of variables used in test cases.

Table 1. Variation percent of variables used in test cases

Variables	Hull offsets	L	B	T
Variation percent	±3	±10	±10	±10

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:

$$f(x,y)=\frac{B}{2}\left[1-\left(\frac{2x}{L}\right)^2\right]\left[1-\left(\frac{z}{T}\right)^2\right] \quad (8)$$

where B is the ship beam, L is the ship length, T is the ship draft, $-L/2 \le x \le L/2$ and $-T \le z \le 0$. Vertical motions of hull section are predicted by coupled strip theory and Frank method. The hull form optimization is carried out at a single Froude number ($Fn = U/\sqrt{gL}$) that constant for each model and that is 0.3 for Wigley model and 0.2 for S60 model where U and L, speed and waterline length of the model respectively. Table 2 shows the main dimensions of the Wigley and S60 hull models.

Table 2. Main dimensions of the Wigley and S60 hull models

Model type	Length [m]	Beam [m]	Draft [m]	Design Fn
Wigley hull form	3	0.3	0.1875	0.3
S60 hull form	122	17	7	0.2

The process of optimization is performed by the genetic algorithm. The offset points and principal dimensions can be represented by real-valued vectors in the limits as already mentioned. The scatter recombination has been used in the object variables. The mutation operator has been applied to the individuals as mentioned. 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 and well-known S60 as parent models. 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 RESULTS AND DISCUSSION

5.1 *Case of the Wigley hull*

In order to perform the optimization of hull for minimizing the vertical motion peak value at bow region of the ship, which is a important 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 offset of the hull form and the main dimensions. The first example is for the hydrodynamic optimization of the Wigley hull form with respect to the minimum peak value for absolute vertical motion at a point 0.15LBP behind the forward perpendicular. The Wigley model with length to beam ratio *L/B = 10* and length to draft ratio *L/T = 16* is optimized for a speed, corresponding to Froude number of 0.3. The offsets values and main dimensions of the hull are limited in the range of 97 to 103 and 90 to 110 percent of initial ones respectively and displacement is fixed. The number 130 hull forms in each generation are created and among them, the best 10 hull forms are selected to seed the next generation based on the fitness i.e. the vertical bow motion the better hull form. Figure 3 depicts body plan of the optimal hull form (dashed lines) generated by use of the genetic algorithm optimization technique and body plan of the initial Wigley hull(solid lines). The optimization procedure improved the initial hull and produced a reasonable hull form. The new hull is smoothed because of using B-Spline.

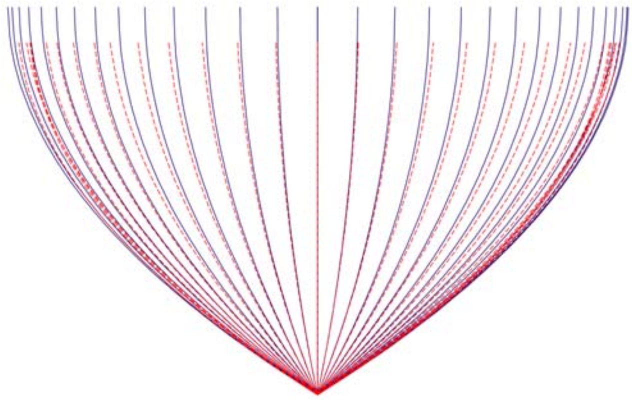


Figure 3. Bodyplan of original Wigley hull and optimal hull (solid line is initial and dashed line is optimal hull)

As can be seen in Figure 3, the beam of the optimized hull is wider than the beam of the initial Wigley hull in fore and aft sections and thinner in the amidships. The draft of the optimized hull has decreased dramatically. The 3D view of the initial and optimized Wigley hull form are presented in Figure 4. During the run of the optimization algorithm in addition to the hull offsets the length, beam and draft of the hull are changed. The variation of the main dimensions of the hull versus iteration number are shown in Figure 5. These two figures (5-b and 5-c) confirm that the hull has a tendency toward a less draft and approximately fixed beam during the optimization algorithm. The length of the hull is rapidly increased in the initial iterations and after that is remained fixed. The changes in the variable parameters of the hull are to reach minimum vertical motion peak value and match the constraint for the displacement.

The changes of Fitness value versus iteration number of the vertical motion are shown in Figure 5-d. The reduction of vertical bow motion peak value leads to reduction of vertical motion and acceleration in the range of wave length as shown in Figure 6.

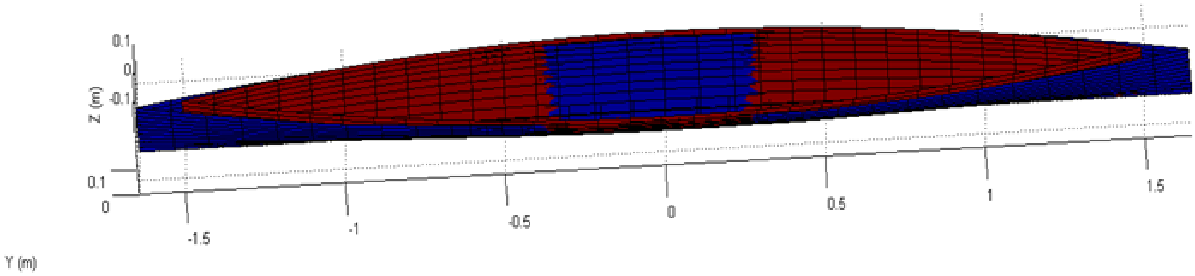
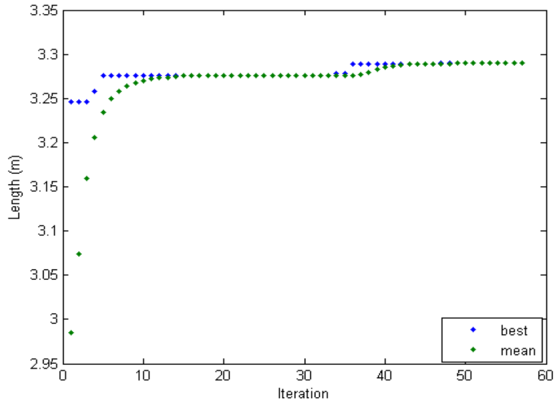
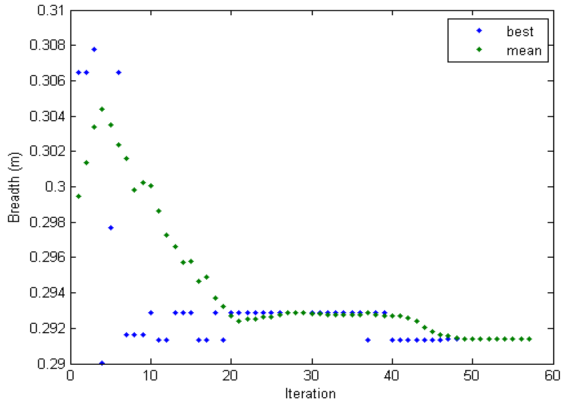


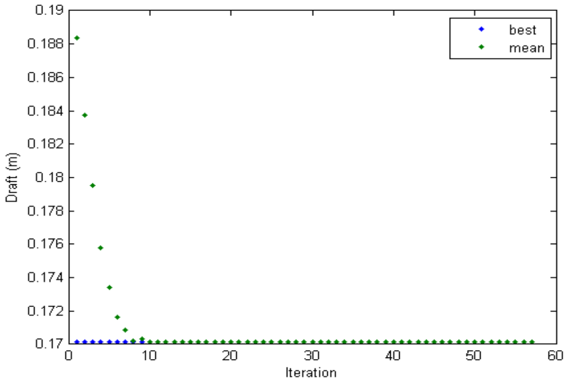
Figure 4 3D hull form, (Red is optimized hull and blue is initial hull)



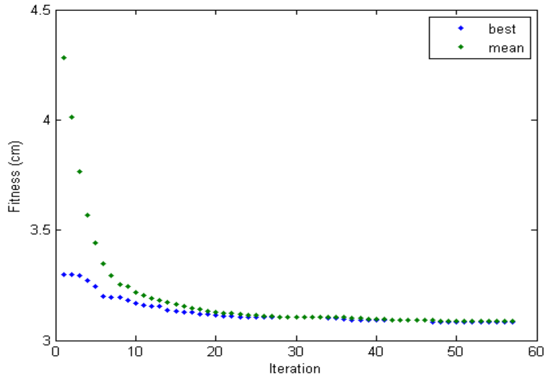
a) Length



b) Beam

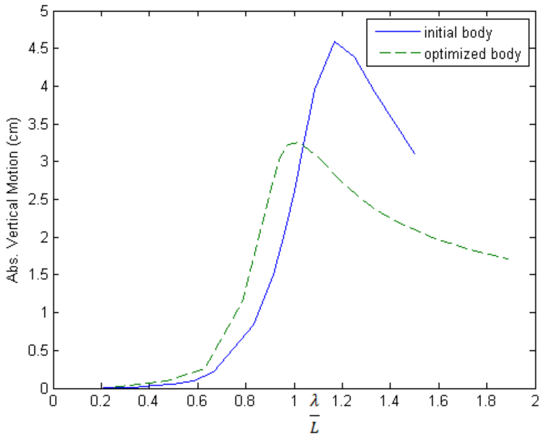


c) Draft

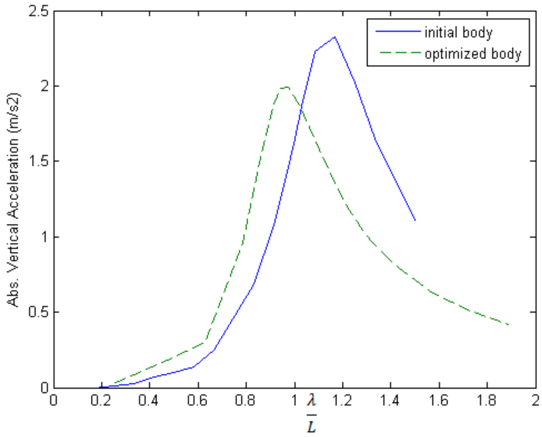


d) Fitness

Figure 5. Variation of dimensions parameters and the history of the Fitness value of the Wigley hull by iteration number



a) Absolute Vertical Motion



b) Absolute Vertical Acceleration

Figure 6. Absolute vertical motion and acceleration for the initial and optimum Wigley hull form

5.2 *Case of the S60 hull*

In this example, a 122 m in length of the S60 hull form (C_B = *0.7*) with length to beam ratio L/B = 7 and beam to draft ratio B/T = 3 is chosen in order to derive a hull with minimum bow vertical motion at Fn = 0.2. As was said before the optimization of the hull form is based on minimizing the hydrodynamic factors of the ship i.e. bow vertical motion with given design constraints. The variation range in the offsets values is between 97 and 103 percent of the initial S60 hull offsets and the main dimensions are changed in the limits between 90 and 110 percent of the main dimensions of initial hull and displacement is fixed. The bodyplan of the initial hull form (solid lines) and the optimized hull form (dashed lines) are shown in Figure 7. In each generation 200 hulls are created and then among them, the best 15 hull forms are considered to go to the next generation based on lower vertical motion peak value in bow of ship. Use of the genetic algorithm in combination with the B-spline produced optimized fair hull. To acquire a hull form with minimum bow vertical motion and match the constraint for the displacement. The beam and draft of the optimized hull are approximately fixed and deeper than the initial S60 hull.

The 3D view of the initial and optimized S60 hull form is shown in Figure 8. During the implementation of the optimization algorithm in addition to hull offsets the length, beam and draft of the hull are varied and the changes of them by evaluation number are as in the previous case, but the difference is the hull has a tendency towards approximately smaller length (see figures 9-a, 9-b and 9-c). As can be seen in this Figure the significant changes of four characteristics of the hull are at the early evaluation of objective function and after that remain fixed.

Figure 9-d demonstrates the changes of the fitness value of hull by iteration number. As can be seen in this figure during the optimization process the vertical motion peak value decreased. This is due to variation of the length and draft and the hull form in the optimization process.

Evaluating the hydrodynamic performance of the initial hull and the optimized hull in terms of the vertical motion and acceleration is shown in Figure 10.

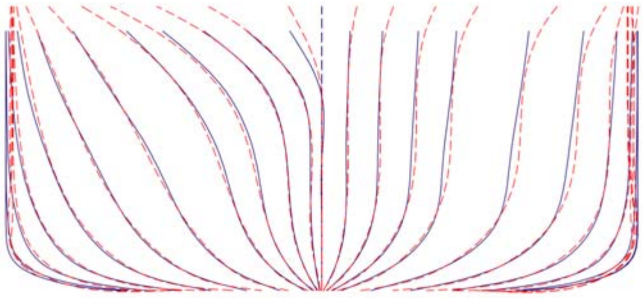


Figure 7. Bodyplan of original S60 (C_B = *0.7*) hull and optimal hull
(solid line is initial and dashed line is optimal hull)

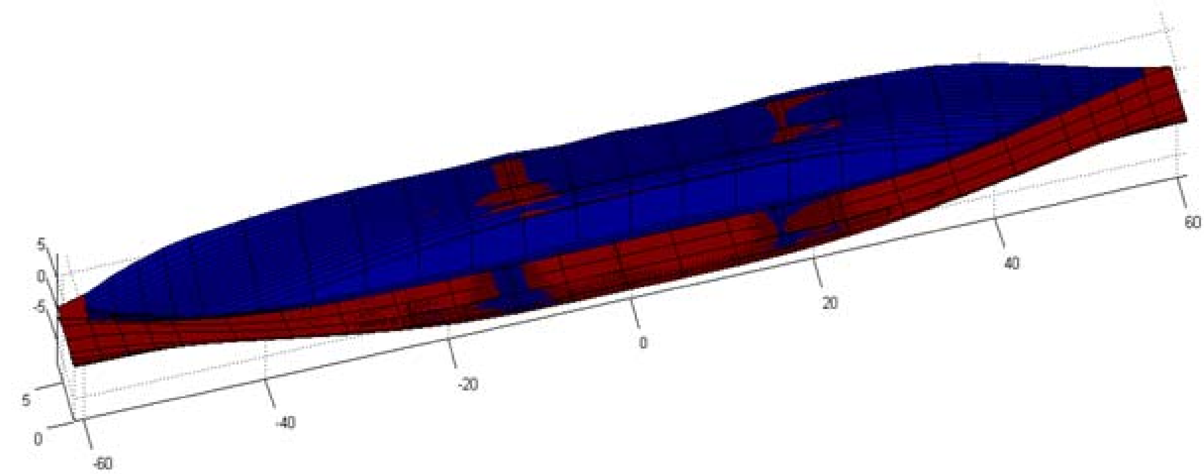
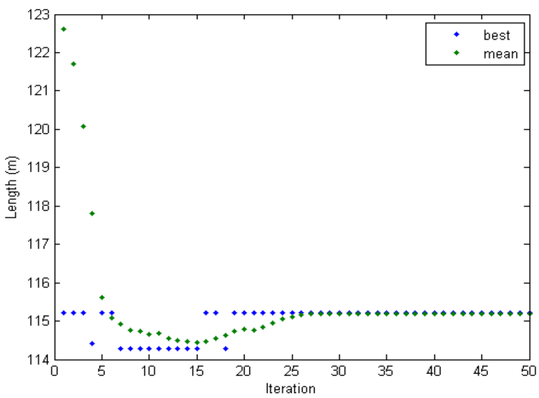
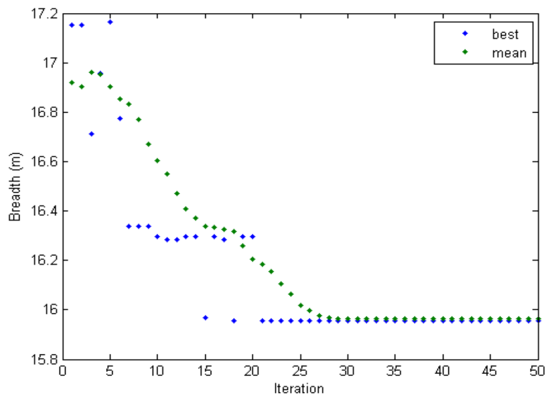


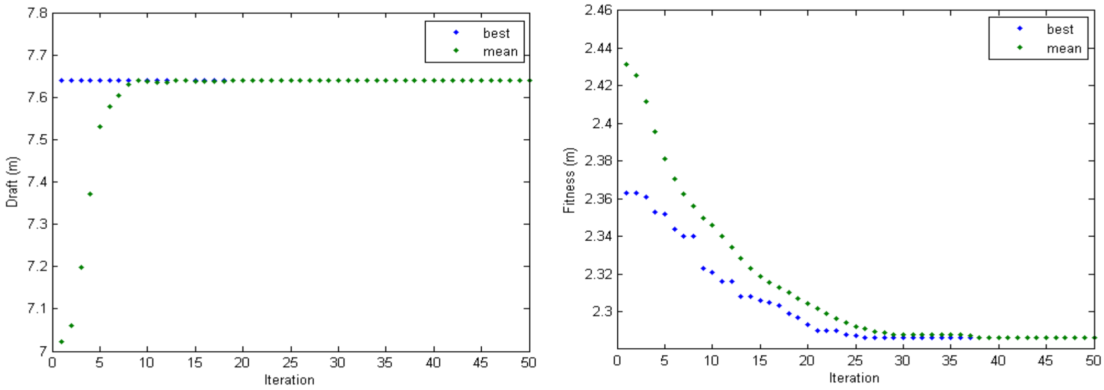
Figure 8. 3D hull form, (Red is initial hull and blue is optimized hull)



a) Length



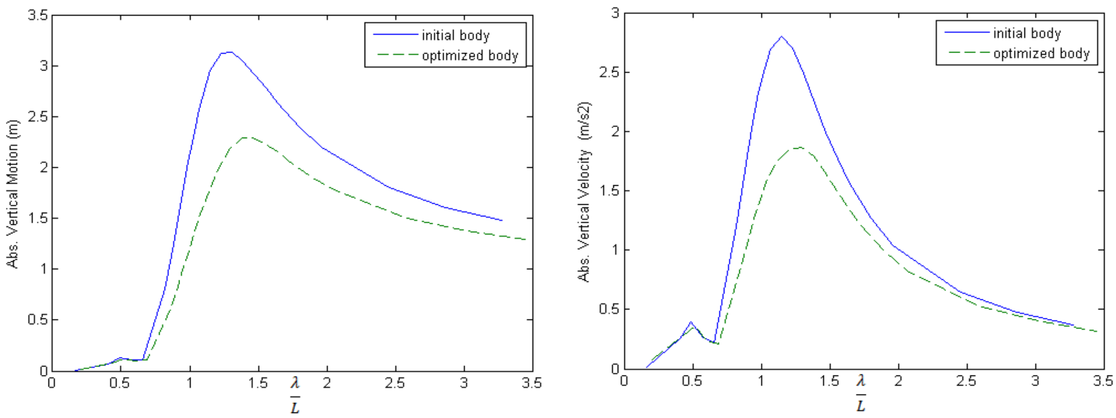
b) Beam



c) Draft

d) Fitness

Figure 9 Variation of dimensions parameters and the history of the Fitness value of the S60 hull by iteration number



a) Absolute Vertical Motion

b) Absolute Vertical Acceleration

Figure 10. Absolute vertical motion and acceleration for the initial and optimum S60 hull form

It is interesting to note that in each test case, trend of variation main dimensions such as, length and draft is different. In the Wigley test case length and draft are increased and decreased respectively but in S60 test case length and daft are decreased and increased. However, Lloyd (1992) expressed that in the optimization of floating body, type of hull form as parameter changes depends on type of hull form. In each test case; change of the main dimensions lead to the lower vertical motion and acceleration.

6 CONCLUSIONS

A numerical method has been proposed for hydrodynamic hull form optimization in regular wave with respect to vertical motion of bow of the ship as the only objective function. The genetic algorithm is combined with a numerical method for minimizing peak value of vertical motion characteristic (the ship motion in wave based on strip theory and the sectional added mass and damping coefficients calculation by the well-known Frank Close-Fit method). The design variables are included the hull offsets and the main dimensions (Length, breadth and draft) and the displacement is used as the design constraint during the optimization with Wigley and S60 hull forms as standard models at constant speed Fn (is 0.3 for Wigley model and 0.2 for S60 model) to develop optimized ship hull forms. Compared with the initial hull the peak value of vertical motion of the improved hull is reduced by 33% in the first example and 27% in the second one. The hull fairing procedure has been applied by using B-spline. As can be showed in figures the reduction percent achieved in vertical acceleration is considerable comparing with other papers. The gains in terms of fitness value reductions were considerable at both cases and this resulted in improvements in the entire ship range. Therefore, we can get conclusion that genetic algorithm using in this study are effective and robust techniques for hull form optimization.

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