Dunja Matulja, Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia
Roko Dejhalla, Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia

HYDRODYNAMIC OPTIMIZATION OF THE FORE PART OF THE SHIP

Summary

The paper discusses the application of a genetic algorithm, coupled with a three-dimensional potential flow solver, in order to deal with the hydrodynamic optimization of a ship hull form with a bulbous bow. The bulb is defined by several geometrical parameters and a set of splines in tension has been used to describe the ship forebody and to allow its modifications. The optimization procedure is fully automated, and once the basis hull form, objective function and constrains are defined, it requires no user interaction. According to the predefined constraints, an optimized hull form has been obtained, and hence analyzed and compared to the basis hull form in order to demonstrate the effectiveness and validity of the developed procedure.

Key words: *ship hull, spline in tension, hydrodynamic optimization, genetic algorithm*

HIDRODINAMIČKA OPTIMIZACIJA PRAMČANOG DIJELA BRODA

Sažetak

U radu je prikazana primjena genetskog algoritma, koji je povezan sa programom za trodimenzijsko rješenje potencijalnog strujanja, u svrhu hidrodinamičke optimizacije brodske forme s pramčanim bulbom. Pramčani bulb je definiran s više geometrijskih parametara, a skupina napetih splajnova korištena je za opisivanje pramčanog dijela broda te za omogućavanje izmjena. Optimizacijski postupak je potpuno automatiziran, te nakon definiranja početne forme broda, ograničenja i funkcije cilja, daljnja interakcija korisnika nije potrebna. U skladu s prethodno odabranim ograničenjima, dobivena je optimizirana brodska forma koja je zatim analizirana i uspoređena s početnom kako bi se pokazala učinkovitost i valjanost korištenog postupka.

Ključne riječi: *forma broda, napeti splajn, hidrodinamička optimizacija, genetski algoritam*

1. Introduction

The prediction of ship resistance is normally based on results from model tests at towing tanks. Even with accurate CFD simulations which are increasingly performed in ship design, these model tests are still a very important method in determining and verifying the ship resistance and power requirements. However, different powerful computational tools can be used for preliminary selection of hull forms before testing, as well as to study flow details to gain insight into how a ship hull form can be improved.

The ship hull form design is a complex process where compromises must be made among various and often conflicting requirements. The problem can be formulated as determination of a set of design variables subjected to certain relations between variables and restrictions of these variables. In general, many factors must be considered and not all of them are hydrodynamic in nature. But, from the hydrodynamic point of view, the most interesting optimization contribution is to minimize the ship resistance, or the ship resistance components. Many interesting works on hull form optimization have been presented through the years [1], [2], [3], [4].

Numerical optimization is a well established mathematical field and there are numerous references on the theory and application of numerical optimization tools. Such optimization is usually much faster and cheaper than experiments and it offers more insight into flow details.

2. The optimization problem formulation

Optimization is a procedure which allows finding the best solution within a limited or unlimited number of choices. Many optimization problems may be generally formulated as problems of minimizing an objective function $f(\boldsymbol{\xi})$, of a number of variables ξ_1, ξ_2, ξ_3,..., ξ_n subject to a group of constraints that can be formulated as equalities or inequalities.

The solution of the optimization problem calls for the formulation of a suitable optimization procedure. Therefore, the potential flow solver [5]and the genetic algorithm [6] have been coupled to build a procedure for the bulbous bow optimization. The wave resistance has been selected as the objective function for the presented study, since it is one of the most important resistance components, and it can be accurately computed by a potential flow solver. Experience has shown that this resistance component is sensitive to modifications in the hull form design, and reductions of the wave resistance can often be obtained without any important sacrifice in displacement volume.

The optimization procedure starts from a specified basis hull form, by calculating the flow past the hull form and evaluating the wave resistance. The genetic algorithm creates an initial population of specified number of individuals (hull shapes), randomly generated within upper and lower bounds for the design variables. The bow geometry modification algorithm is an integral component of the optimization procedure. It allows to obtain the changes of the bulb shape and to automatically remesh the fore part of the hull form for each design case. In every generation, each individual is evaluated using a fitness function and assigned a fitness value. The fitness of an individual is determined calling the potential flow solver. Based on their relative fitness values, individuals in the current population are selected for reproduction. Based upon genetic and evolutionary principles, the genetic algorithm repeatedly modifies the population of artificial individuals. Generating a new generation, individuals in its current population are improved by performing genetic algorithm operators. The process continues until the specified number of generations is attained and acceptable or the best possible solution evolves. The developed procedure is fully automatic and no user interference is needed during the optimization.

There are several important aspects which need to be set when using a genetic algorithm. The objective function needs to be defined, and the genetic representation must be defined and implemented, as well as the genetic operators. For the presented optimization problem the real coding has been chosen.

To transform a minimization problem to a maximization problem needed for the genetic algorithm procedure, it is necessary to map the objective function to a fitness function form (so called "raw fitness") through one or more mappings. The following transformation has been used:

$$\text{Fitness} = \begin{cases} C_{\max} - \mathrm{f}(\xi) & \text{when} \quad \mathrm{f}(\xi) < C_{\max} \\ 0 & \text{otherwise} \end{cases}.$$

The value of parameter $C_{\max}$ is taken as input coefficient to avoid negative fitness values and its value should be greater than the expected largest value of objective function in the simulation.

The results presented in the study have been carried out by means of a genetic algorithm employing the raw fitness linear scaling, the stochastic uniform sampling as selection operator, the two-point crossover as crossover operator and the multi-bit mutation as mutation operator. In addition, the following genetic algorithm parameters have been adopted:

- String length = 7
- Crossover probability $p_c = 0.5$
- Mutation probability $p_m = 0.3$
- Population size = 10
- Number of generations = 20

As geometrical constraints, the design waterline was kept the same as in the basis form, while the stem profile and the shape of the fore part were allowed to change. To do so, a set of design variables in terms of x, y and z coordinates, was taken as the required set of variables ξ_1, ξ_2, ξ_3,..., ξ_n introduced previously. The number of design variables n treated in the optimization procedure must remain within some reasonable range. On the other hand, the grid used in computation must capture the ship geometry appropriately in order to resolve changes in the flow with sufficient resolution.

In order to obtain a wide range of changes with the lowest possible number of parameters, a set of splines in tension has been applied to describe the geometry of the bulbous bow.

3. The spline in tension

In order to allow the modifications of the bulbous bow defined by several parameters [7] the spline in tension has been applied to describe the geometry of the bulb. The splines in tension were first introduced by Schweikert [8]. These curves behave smoothly through the data points with a minimum number of oscillations or inflection points. By varying the tension factor σ, the constructed curve can take different shapes:

a) If $\sigma \to 0$, the curve converges to a cubic spline
b) If $\sigma \to \infty$, the curve converges to a piecewise linear curve, with still sharp but rounded corners.

The main advantages of the use of tension splines for the representation of the bulbous bow are the fairness and the robustness of the curves. Also, the shape of the curve can be altered by simply varying the tangent angles in the first or last point of the curve, Fig.1.

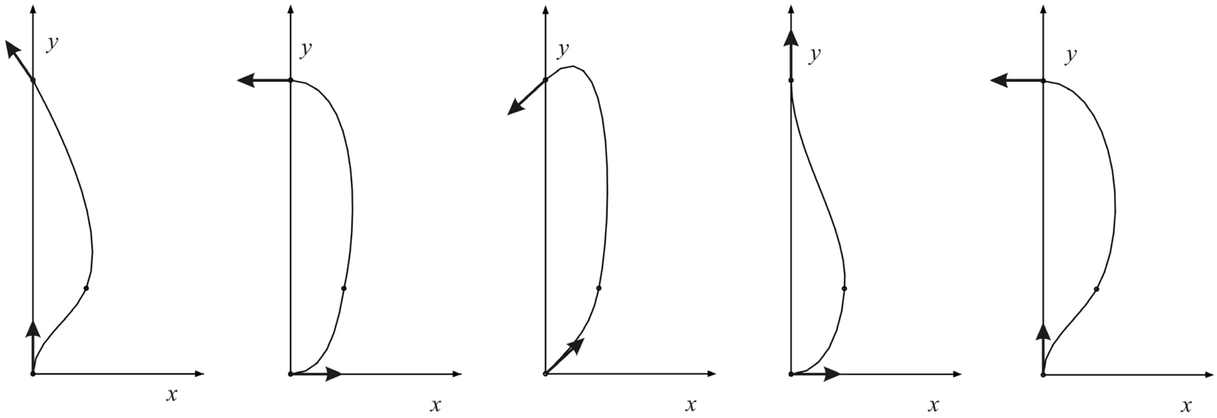

Fig. 1 The influence of the tangent angle on the shape of the spline in tension

Slika 1. Utjecaj kuta tangente na oblik napetog splajna

To create a spline in tension, a set of points $x_1, x_2, \dots, x_n$ must be given, with the corresponding values of $y_1, y_2, \dots, y_n$. This formulation requires the values on the abscissa to be strictly increasing ($x_i < x_{i+1}$), otherwise a parametric formulation must be used. A real-valued function f needs to be found, with a continuous first and second derivative, and such that:

$$f(x_i) = y_i, \text{ for each } i = 1, \dots n. \tag{1}$$

It is also required the quantity $\left(f'' - \sigma^2 f\right)$ to vary linearly on each of the intervals $[x_i, x_{i+1}]$, $i = 1, \dots, n$-1. For each x, such as $x_i \le x \le x_{i+1}$, the following equation can be set:

$$\begin{aligned} f''(x) - \sigma^2 f(x) = \left[f''(x_i) - \sigma^2 y_i\right] \cdot (x_{i+1} - x)/h_i + \\ + \left[f''(x_{i+1}) - \sigma^2 y_{i+1}\right] \cdot (x - x_i)/h_i \end{aligned} . \tag{2}$$

where $h_i = x_{i+1} - x_i$, for $i = 1, \dots, n$-1.

Solving (2), and invoking conditions (1), result in:

$$\begin{aligned} f(x) = \left[f''(x_i)/\sigma^2\right] \cdot \sinh[\sigma(x_{i+1} - x)]/\sinh(\sigma h_i) + \\ + \left[y_i - f''(x_i)/\sigma^2\right] \cdot (x_{i+1} - x)/h_i + \\ + \left[f''(x_{i+1})/\sigma^2\right] \cdot \sinh[\sigma(x - x_i)]/\sinh(\sigma h_i) + \\ + \left[y_{i+1} - f''(x_{i+1})/\sigma^2\right] \cdot (x - x_i)/h_i \end{aligned} \tag{3}$$

The above formulation of the spline in tension is not applicable for any set of points [9], for example closed curves or curves with the tangent parallel to the y-axis at some point. Such problem can be overcome by introducing the parametric form of the spline in tension [10], which requests to adopt the curvilinear abscissa as independent variable. The additional variable s is defined as:

$$\begin{aligned} s_i &= 0, \; i = 1 \\ s_i &= s_{i-1} + \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}, \; i = 2, n \end{aligned} , \tag{4}$$

where s is the arc length of the polygonal passing through the given points.

If the parametric form of the spline in tension is applied, the linear system of equations is similar to the previously introduced, except for the variable which in this case is s instead of x or y.

To describe the fore part of the hull form, two splines in tension have been used: one for the stem profile (spline A in Fig.2) and one for the maximum beam line (spline B in Fig. 2). The maximum beam line refers to a line connecting the points in which a beam modification will be allowed. The design variables, ξ_1, ξ_2, ξ_3,..., ξ_{12} , allow modifications in the x and z direction on the stem profile, and modifications in the y and z direction on the maximum beam line.

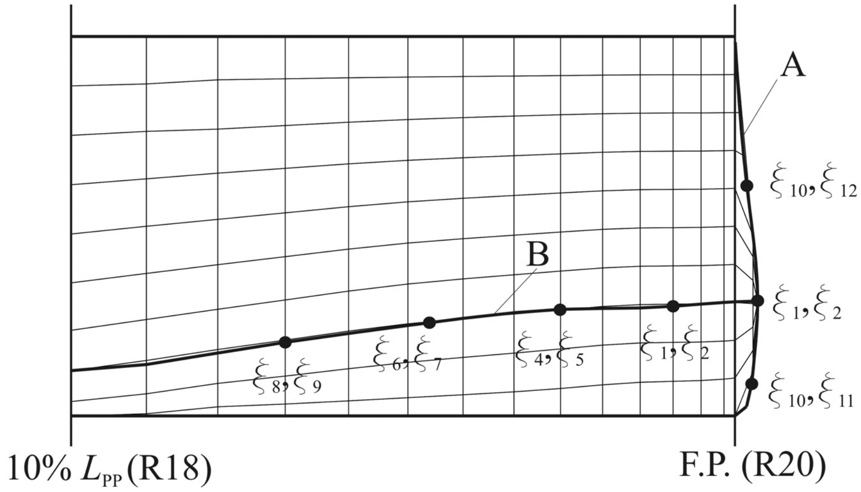

Fig. 2. The design variables and the meshed fore part of the starting hull form

Slika 2. Korištene varijable i paneli na pramčanom dijelu početne forme

4. Results

The optimization procedure has been applied to the Series 60 C_B=0.7 hull form taken as the basis hull form. The principal ship particulars are given in Table 1.

Table 1 Principal particulars of the basis hull form (Series 60, C_B=0.70)

Tablica 1. Glavne karakteristike osnovne forme (Serija 60, C_B=0.70)

Length between perpendiculars, L_{PP}	121.92 m
Breadth, B	17.416 m
Draught, T	6.968 m
Block coefficient, C_B	0.70
Midship coefficient, C_M	0.986

The fore part of the hull form has been optimized for a single speed corresponding to the Froude number 0.289, based on L_{PP}. The wave resistance R_W is calculated as:

$$R_W = 0.5 \rho C_W U^2 S \tag{5}$$

The wave resistance coefficient C_W is obtained by integrating the x components of the pressure forces acting on the submerged portion of the hull form. In (5) ρ represents the water density in kg/m^3, U is the ship speed in m/s and S is the wetted surface in m^2.

It must be pointed out that the original Series 60 stem profile has been slightly altered to obtain an initial bulb shape, to make sure that the GA would route in the right way. This is treated as the starting hull form, Fig. 3.

The optimal solution i.e. the hull form with the lowest value of the wave resistance has been identified as the 1st individual in the 20th generation.

The optimized bulb shape is compared to the initial bow shape in Figs 3. and 4. The resulting bow shape is entirely dictated by the hydrodynamic behavior associated with the changes in the bow sections shape. The results of the optimization procedure are evident.

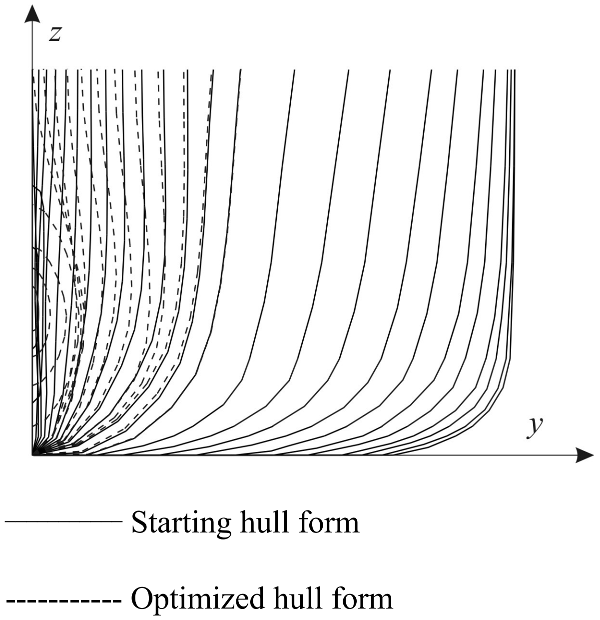

Fig. 3. Comparison of the starting and optimized form

Slika 3. Usporedba početne i optimizirane forme

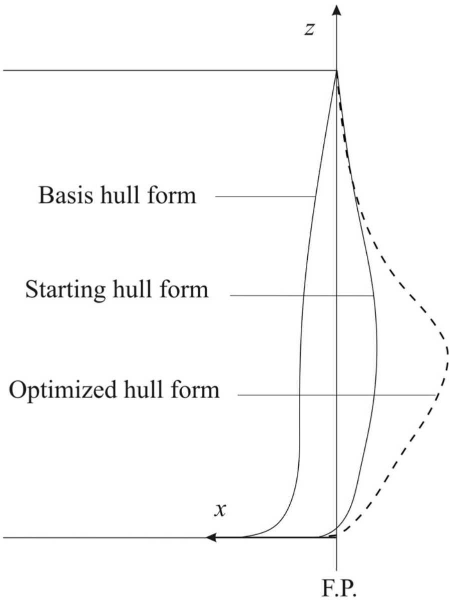

Fig. 4. Comparison of the basis, starting and obtained stem profile

Slika 4. Usporedba osnovnog, početnog i dobivenog profila pramčane statve

Fig. 5. presents the comparison of the wave profile for the basis hull form and optimized hull form advancing at $Fr = 0.289$. Both the hull length and the wave elevations are normalized by $L_{PP}/2$. Wave elevations η are plotted for the collocation points of the panels next to the centerline ($y/L_{PP}=0.0$), when $2x/L_{PP} < -1.0$ or $2x/L_{PP} > 1.0$, and for the panels next to the hull when $-1 < 2x/L_{PP} < 1.0$. As the result of the optimization, a certain wave elevation reduction can be noticed near the fore perpendicular.

Finally, although the problem is treated as a single point design problem, additional numerical tests have been performed with obtained hull form for Froude numbers ranging from 0.20 to 0.40. The predicted wave resistance coefficients are summarized in Table 2. and Fig. 6.

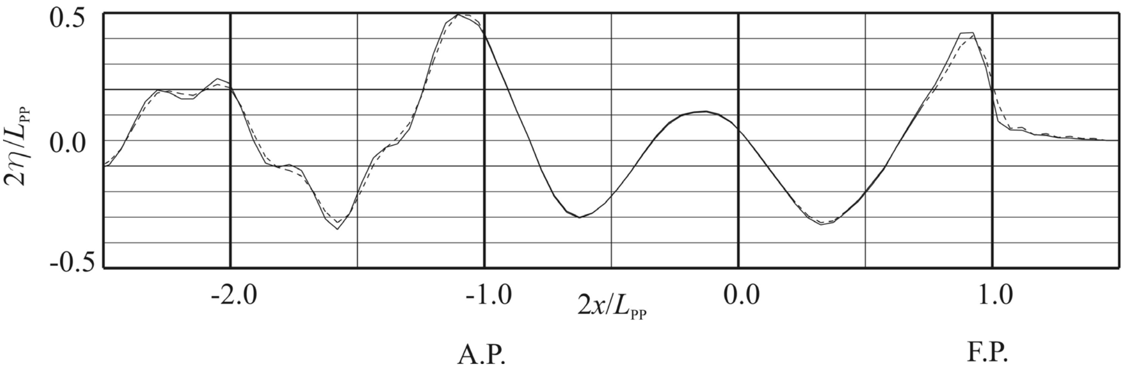

Fig. 5. Wave profile at $Fr = 0.289$ ——— Basis hull form ---------- Optimized hull form

Slika 5. Profil vala za $Fr = 0.289$ ——— Osnovna forma ---------- Optimizirana forma

Table 2 Comparison of the results

Tablica 2. Usporedba rezultata

	Basis hull form		Optimized hull form
Fr	C_W – Experiment [11]	C_W - Calculation	C_W - Calculation
0.200	$0.050 \cdot 10^{-3}$	$0.305 \cdot 10^{-3}$	$0.204 \cdot 10^{-3}$
0.250	$0.550 \cdot 10^{-3}$	$1.182 \cdot 10^{-3}$	$0.895 \cdot 10^{-3}$
0.289	$2.850 \cdot 10^{-3}$	$4.005 \cdot 10^{-3}$	$3.625 \cdot 10^{-3}$
0.300	$5.750 \cdot 10^{-3}$	$5.850 \cdot 10^{-3}$	$5.326 \cdot 10^{-3}$
0.325	$6.740 \cdot 10^{-3}$	$6.948 \cdot 10^{-3}$	$6.450 \cdot 10^{-3}$
0.350	$5.300 \cdot 10^{-3}$	$6.181 \cdot 10^{-3}$	$5.739 \cdot 10^{-3}$
0.375	$5.400 \cdot 10^{-3}$	$5.725 \cdot 10^{-3}$	$5.356 \cdot 10^{-3}$

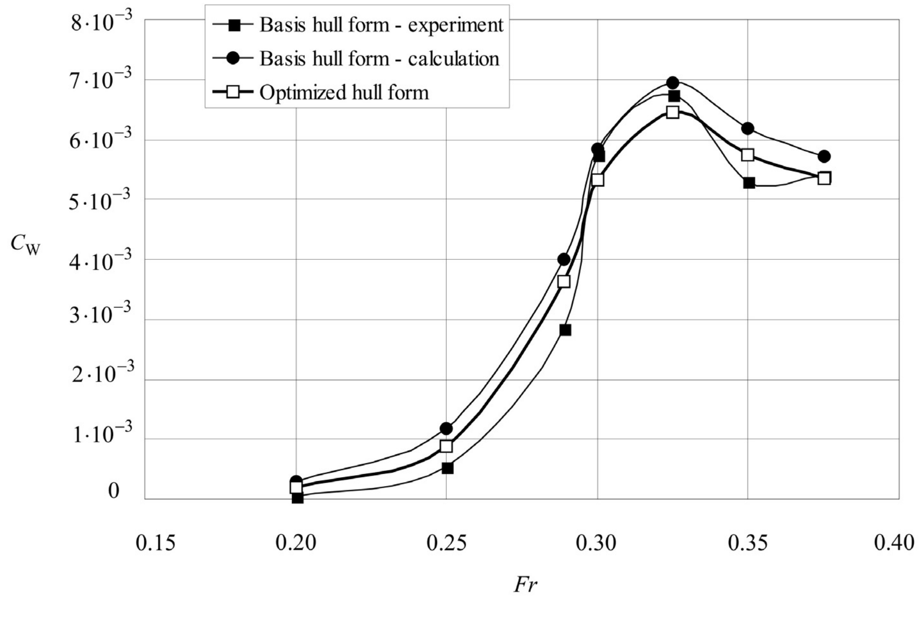

Fig. 6. Comparison of wave resistance coefficients versus Froude number

Slika 6. Usporedba koeficijenata otpora valova u funkcji Froudeovog broja

The wave resistance coefficients are calculated for the panelized version of the hull forms. The values of C_W obtained by the potential flow solver are slightly higher than the experimental ones for lower and higher Froude number, while for the design speed the results agree well. Comparing the optimized hull form to the basis one, it is evident that the reduction of the wave resistance coefficient has been achieved over a wide range of Froude numbers. For the design speed, corresponding to $Fr = 0.289$, a wave resistance coefficient reduction of 10% can be noticed.

5. Conclusion

At present time, the most common application of potential flow solvers is the analysis of fore part of the ship hull form. The potential flow solvers are additionally attractive due to their low computational costs.

A numerical procedure for the optimization of a ship hull form with the bulbous bow from a hydrodynamic point of view is established. The procedure is based on the genetic algorithm and a linearized potential flow solver. The method uses wave resistance as a single objective function to find the optimal hull. The study has shown that the developed optimization procedure can be successfully applied to the optimization of the fore part of the ship hull and used as a valuable method to favorably modify a ship hull.

An additional work is intended to be done for the application of the developed optimization procedure. In such further work, instead of wave resistance, other objective functions, as well as design variables and geometrical constraints, which inevitably arise from resistance or other requirements, will be included. Also, a nonlinear potential flow solver will be used as computational tool, to achieve a more accurate objective function evaluation.

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