APPLICATION OF CFD-BASED EFFICIENT GLOBAL OPTIMIZATION METHOD TO SHIP HULL DESIGN

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With the growth in computing power of computers and the advances in computational techniques, computational fluid dynamics (CFD) has become an invaluable tool for ship hull form optimization design. However, in the process of ship optimization design, the number of objective function (certain hydrodynamic performances to be improved) evaluations using high-fidelity numerical analysis solvers, is enormous but severely limited by computational time and cost, even with the aid of supercomputers. One alternative is to construct surrogate models based on finite sample points instead of direct numerical evaluations one by one [1]. In this paper, The Efficient Global Optimization method (EGO) is used in ship optimization design based on our in-house solver OPTShip-SJTU. It is a sequential design of experiments aiming at gaining as much information as possible from as few sample points as possible by a skillful choice of adding new sample points in a sequential way

Approach
In classical ship optimization design [2-4], the surrogate model may need a bigger design of experiments like a space filling design or the like, directly evaluated by experiments of numerical simulations. The results would be evaluated by means of a regression model (such as Kriging model), estimating the unknown points in the design space. Finally, the optimal solution would be determined regarding the surrogate model. Unfortunately, this procedure has at least two significant drawbacks: the time for carrying-out of many experiments and the need to repeat the whole procedure in case of a poor fit to sample data.
The EGO method mentioned herein is a Kriging-based global optimization method considering the uncertainty of the surrogate prediction [5, 6] The key to the EGO method lies in balancing the need to fully exploit the surrogate model (by sampling where it is minimized) with the need to improve the accuracy of surrogate model (by sampling where prediction error may be high). The concept is expressed in the infill criterion of Expected Improvement (EI). The EI of optimization problem can be calculated as:

$$E[I(x)] = (f_{\min} - \hat{y})\Phi[(f_{\min} - \hat{y})/s] + s\phi[(f_{\min} - \hat{y})/s] \tag{1}$$

Where $f_{\min}$ is the minimum value among n sampled values, Φ and ϕ being the standard distribution and normal density, respectively, $\hat{y}$ the prediction of surrogate model, and s the root mean squared error of the surrogate prediction
A simple flow chart of the EGO method applied for a simple mathematical function is shown in Fig. 1. The EGO method is added to our in-house solver OPTShip-SJTU for ship optimization design based on CFD.

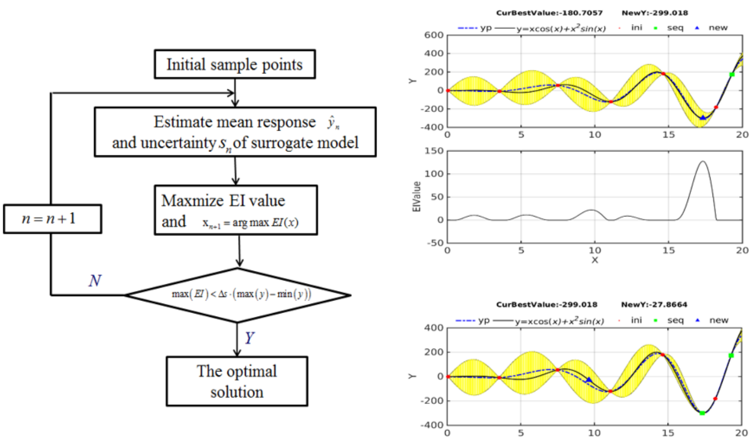

Figure 1: The flow chart of efficient global optimization: on the left, the steps are briefly described; on the right, an example is given (predetermined design points as red dots, the added new points as green squares and the next new point as a blue triangle).

In this paper, two optimization cases of Wigley and KCS ship model sailing in calm water are studied. One is ship hull form optimization of Wigley with the minimum wave-making resistance, while the other one is ship hull form optimization of KCS with the minimum total resistance. The EGO method also starts with an initial ship design which is evaluated directly by the CFD simulation[7]. The classical Kriging surrogate model is then established. The resistance of any new ship on the optimization process is analyzed by means of Kriging model, instead of a CFD-based simulation. A new design sample point is found through optimizing an infill criterion based on the surrogate model. This new design point is the next new ship directly evaluated by CFD method. The surrogate model will be rebuilt by the total sample points. This step of model reconstruction and generation of additional new design point is not iterated until a stop criterion is fulfilled.

Results

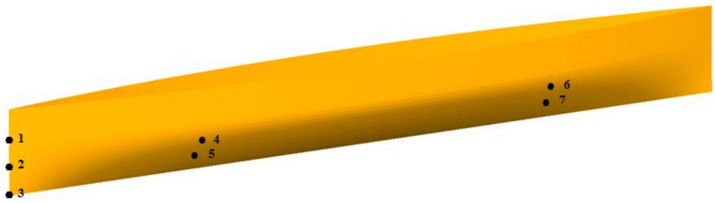

Figure 2: The control points distributed on Wigley hull by RBF method

At the early stage of optimization design, 35 sample points are spread over the design space and selected by Optimal Latin Hypercube Sampling (OLHS) to obtain a Kriging model. The wave-making resistance coefficients of 35 sample hull form and additional sample points are all evaluated using a potential flow theory, Neumann-Michell method [8]. After EGO search, the total number of sample points reached 45 after adding 10 more sample points. The objective function converges to the minimum value, 1.046E-03, a larger reduction of 18.46% than the initial value. Details are shown in Fig. 3-6.

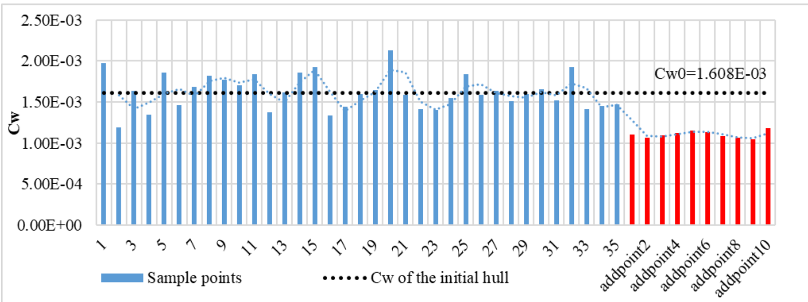

Figure 3: The initial sample hulls and the additional new hulls used in the EGO method

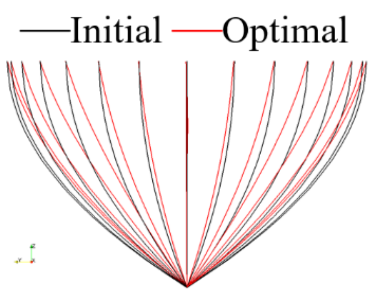

Figure 4: Comparisons of the body lines between the initial and optimal ships

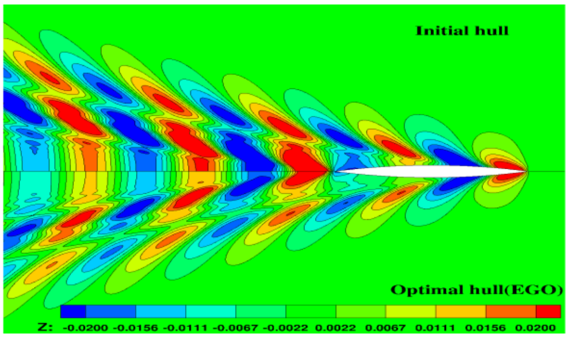

Figure 5: Comparison of free surface elevation between the initial and optimal ships

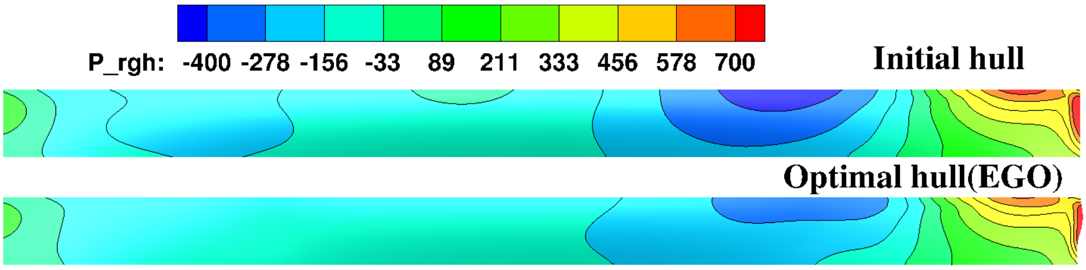

Figure 6: Comparison of pressure distribution between the initial and optimal hulls

The second design problem is to minimize the total resistance of KCS at the design speed. The Free-form Deformation (FFD) method (Thomas W. S. et al.,1986) is applied to modify ship hull form locally. In this study, a total of 5 design variables are used to define the modification of ship hull form. Originally, the total resistance of 30 sample ships are evaluated using a RANS-based CFD method. The objective function R_t is transformed to the corresponding EI to find the global optimum point robustly. By the EGO iterative approach with 10 added new sample ships, not only is the accuracy of the Kriging model improved but also the optimal solution is obtained. In this case, the total resistance reduces by about 4%. The differences of the initial and optimal ships are shown in Fig.7-9 from different point of view.

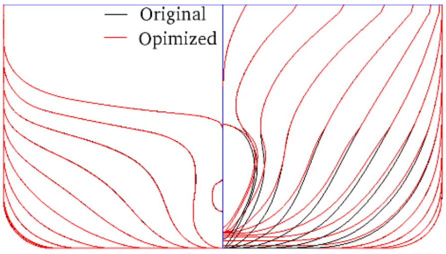

Figure 7: Comparison of the body lines of the initial and optimal hull forms

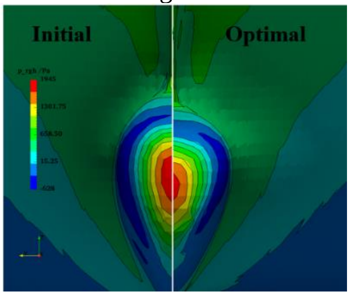

Figure 8: Contour plot of the pressure distribution of the initial and the optimal hull forms (Fr=0.26)

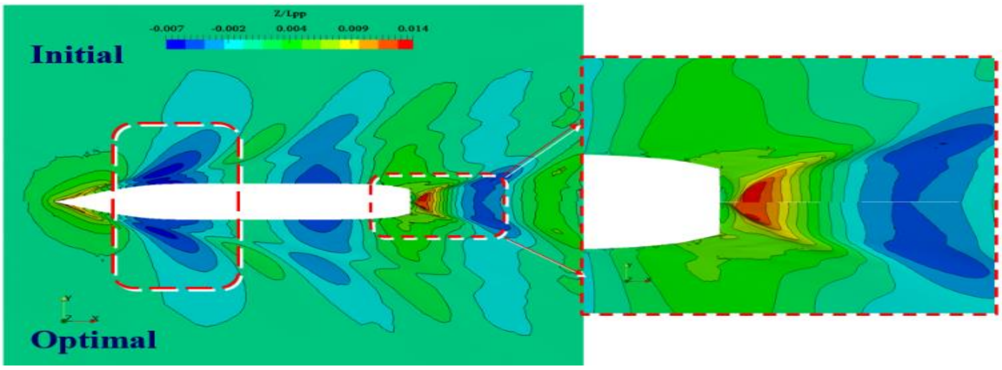

Figure 9: Contour plot of the wave patterns of the initial and the optimal hull forms (Fr=0.26)

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