Multi-Objective Optimization for Ship Hull Form Design

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at George Mason University

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Dedication

To my family
Acknowledgments

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Hydrodynamic optimization is an important aspect of ship design. The aim of this dissertation is to develop a computational fluid dynamics (CFD)-based computational tool for the hydrodynamic design of ship hull forms. The main components of this hull-form hydrodynamic optimization tool consist of a hull geometry modeling and modification module, an optimization module, and a CFD module. This CFD-based multi-objective optimization tool can automatically modify the shape of a ship hull by minimizing some user-defined objective functions associated with the hydrodynamic performance of the ship with the aid of CFD information.

This dissertation covers three main topics. The first topic is the development of a geometry modeling method to produce the initial hull form and to modify the hull surface during optimization cycles. Three hull-form modeling methods are developed, which are NURBS representation, parametric representation, and the combination of the NURBS and parametric representation to represent a complex geometry and to satisfy different design requirements. The second topic is the development of various optimization algorithms. Both single- and multi-objective optimization algorithms are implemented. Several optimization algorithms are employed and compared with one another in various hull form optimization applications. Finally, a CFD module is developed to compute the flow field and evaluate
the hydrodynamic performance of the new hull forms obtained during optimization cycles. A lower-fidelity CFD tool (computer code SSF) and a high-fidelity CFD tool (computer code FEFLO) are integrated into the CFD module to allow fast evaluation of the objective functions during design cycles and accurate analysis of the flow about the final optimal hull.

The CFD-based multi-objective optimization tool developed under this dissertation has been validated and applied in the design of various types of ships. A diverse set of optimal hull forms can be obtained using the present hydrodynamic optimization tool and significant improvement in hydrodynamic performance can be achieved.
Chapter 1: Introduction

Recently, demand for CFD-based optimization technique for ship hull forms has increased. There are several reasons for this high demand for ship designs. First of all, the limitations of the traditional hull design method, which is based on databases and ship designers experience, has already been reached. Since the requirements from the contractor are becoming detailed and diverse, the hull form designers need to take those details into account accordingly. Thus, it is necessary to modify the basic hull form obtained from database or experience. However, there are usually several additional modifications of hull form in order to confirm that new designed hull meets demanded performances in terms of speed and others requirements before initiating the manufacturing process. Several questions arise:

- How can the basic hull form be modified?
- Which main particulars need to be changed?
- Which parts of the hull need to be changed?
- How can it be confirmed for certain required performances before Model-Test?, and etc.

Basically, these problems correspond to fundamental considerations of the optimization process:

- What kind of modeling method will be appropriate for the given application?
- Which aspects need to be considered for optimization?
- Which method will be most appropriate to evaluate the cost functions?, and etc.

Therefore, the given problem can best be solved using optimization technique. Examples of the demand for optimization technique for hull form design caused by the change of hull main particulars are now considered.

Recently, it has been announced that the Panama canal will be extended to increase of ship dimensions in order to retain a significant market share. As a result, a new class
of ships, called *post-Panamax ships*, is developed to adjust to the increase of the Panama canal. In this case, optimization techniques are applied to provide an optimum hull form with the increased maximum breadth.

Another example of demand for optimizations is an increase displacement so that the ship carried more containers or crude-oil or natural gas. However, the ship length cannot be extended with considering the longitudinal bending moment. Possible choices of hull modification are limited to an increase of either the block coefficient ($C_b$) or the breadth.

In this example, the database or experience could provide the initial design of the required ship but it could not be the final design. Therefore, it is highly required to perform an optimization investigation for the new hull form design.

Secondly, early-stage ship design has to be performed in continually decreasing time spans in order to be competitive in the market. Accurate estimate of cost and performance are certainly required for a successful deal. However, many decisions need to be made since the specifications of ships are generally unique to each ship. If these decisions are not well-established in terms of performance or building cost or other considerations, building the ship will result in problems in terms of building costs and ship itself. Therefore, the optimization technique is beneficial for ship design, especially in the preliminary design stage, to be able to submit a successful bid.

As a last example, invention and development of new types of marine vehicles that involve different physical features such as *WIG*(Wing in Ground) vehicle, *SWATH*(Small Waterplane Area Twin Hull), planing vessel, hydrofoil vessel, *SES*(Surface Effect Ships), *ACV*(Air-Cushion Vehicle), and etc. involve a number of challenges.

In this application, the final hull designs need to be optimized in order to provide better performance for the specialized uses; otherwise there is no reason for using the vehicle rather than a conventional ship. Additionally, numerous modifications are expected during the design stage in order to achieve excellence of the invented or developed vehicles. This fact inevitably implies application of the CFD-based optimization technique.
1.1 CFD-based Optimization

CFD-based optimization was initially introduced by the aerospace-community for the design of 2-dimensional foil sections. Since then this optimization technique has been widely used in many other engineering design applications such as aerodynamic shape design, heat exchanger, chemical reactions, turbo-machinery design, etc. In the hydrodynamic community, CFD-based optimization technique is an important aspect of ship design. For the development of new ships, it has become increasingly important to both model hull forms accurately and evaluate hydrodynamic performance efficiently during the early stage of the design process. Today, computational methods in the fields of geometric modeling and fluid dynamics simulation are applied to determine a ship’s geometry and to predict its hydrodynamic performance. However, both Computer Aided Ship Hull Design (CASHD) and Computational Fluid Dynamics are still mostly utilized consecutively, i.e., one after the other and without direct feedback. Usually, the hull’s geometry is modeled in a highly iterative process that requires a considerable amount of time and labor resources to meet all design criteria. Then, the geometry is passed on to the numerical flow field analysis using CFD tool. On the basis of the numerical results, the geometry is changed, often intuitively, by interactive modification. This approach does not automatically generate an optimum hull form. In order to quantitatively compare the merit of different designs, an objective function is defined. This objective function depends on design variables, and the changes in flow variables associated with these design variables. The aim is then to minimize (or maximize) this objective function subject to PDE (Partial Differential Equations that govern the flow), geometry constraints, and physical constraints. Examples of objective functions are the drag or a prescribed pressure; for PDE constraints the Euler/Navier-Stokes equations or the Laplace equation; for geometric constraints the displacement or transverse moment of inertia of the waterplane; and for physical constraints a minimum pressure to prevent cavitation. Various optimization techniques can be used to minimize (or maximize) this objective function.

The CFD-based hull-form hydrodynamic optimization consists of a CFD solver that
can be used to compute the flow field and evaluate the objective function, and its gradient if required by the optimization technique, hull geometry modeling and modification that are linked to the design parameters, and an optimization technique that can be used to minimize the objective function under given constraints. While CFD-based hull-form optimization is not routinely used for ship design, applications of CFD tools to hydrodynamic optimization – mostly for reducing calm-water drag and wave patterns – have been reported in a significant number of studies. These studies attest to a rapidly growing interest in hydrodynamic optimization ([1–17]). The CFD solvers used in these studies consists of RANS solver or potential flow solver with various approximations to analyze ship hull boundary surface, free surface, and flow domain. An application to stern, sonar dome, and bow form of naval combatants was considered using RANS (Tahara et al.(2000),[12]). And Jason et al.(1997) investigated the zonal approach for hull optimization[1]. In this research, the flow domain is divided into three zones (potential flow zone, boundary layer zone, Navier-Stokes zone) and different computational methods are used in each zone. Tahara et al.(2006) used a Reynolds Average Navier-Stokes (RANS) solver for self-propulsion simulator to consider thrust deduction and maneuverability[16]. In addition, many interesting works were presented by Harries and colleagues. The use of an optimization scheme was investigated for fast ferries by employing potential flow panel code and 2D strip theory for wave resistance and sea-keeping, respectively [8–10,18,19]. Additionally, Compana et al.(2006) optimized the DTMB Model-5415 using NURBS surface modeling to minimize the total resistance ($R_T$) by using RANS code[20]. Although the initial hull was successfully optimized, the cost of one simulation was high.

Several optimization based on deterministic or probabilistic algorithms have been applied for ship hull form optimization. A GO (Global Optimization) algorithms for multi-objective problems has been developed by Peri et al.(2003) for both a commercial container ship and a destroyer ship. Several optimization algorithms were employed in Heimann et al.(2003) such as MOGA and SIMPLEX for a fast ferry ship. A SQP method was employed to optimize the DTMB Model-5415 in Tahara et al.(2004). A simple CFD tool is employed
to evaluate the wave drag coefficient of the ship in steady potential flow in Percival et al. (2001). The wave drag is estimated using the first-order of slender-ship approximation which has been applied to mono- and multi-hull optimization [6]. The authors showed that this approximation provides results that compare well with experimental measurements for series of hull forms. In addition, this approach allows dramatic reduction of computational cost for evaluating the objective function. In this dissertation, the single-objective problems are optimized by using both one local search and two global search algorithms. The gradient-based method is utilized for a local search approach, and two different global search techniques, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), are implemented to determine the global optimum solution. Finally, multi-objective optimization problem is considered by using the multi-objective genetic algorithm (MOGA) with Pareto Optimality by Ranking method.

1.2 Geometry Modeling

A number of alternative hull geometry modeling techniques have been developed. Harries et al. (2004) analyzed various modeling techniques and divide them into two categories: conventional modeling and parametric modeling. Conventional modeling techniques build on a low level-definition of the geometry [9]. For example, points are used to define curves, and curves are used to define surfaces. Conventional modeling techniques offer great flexibility with regard to geometry and topology. Parametric modeling techniques, on the other hand, build on high-level entities. These entities are called form parameters in geometric modeling. The most prominent advantage of parametric techniques is that small to intermediate modifications can be produced very efficiently. Moreover, the parametric modeling of the hull form requires a small number of design variables. Harries et al. (2004) and Abt et al. (2003) considered a parametric hull representation to improve efficiency rather than to reduce the number of design variables and to define realistic hull forms [9, 18]. Markov and Suzuki (2001) developed the shift and deformation method for ship sections to reduce
the wave resistance of the Series-60 hull. In this work, B-spline patch was employed to model the modified hull surfaces [21]. In addition, Pérez et al. (2008) introduced fully parameterized hull representation technique [22] based on NURBS surface modeling. However, a defect of this approach based on the three parametric curves is that it leads to difficulties for representing complex hull geometries such as bulbous bow or midship sections of full hull forms as usually found in tankers. Finally, Kim (2008) has developed the approach based on parametric hull representation by introducing a modification function as well as bell-shape modification function [23].

In the present dissertation, both the conventional and the parametric modeling of the hull form are adopted. At first the hull surface is represented by NURBS, which allows for large variation of hull form during optimization cycles. Secondly, the parametric hull form representation is utilized in order to interact with the optimization algorithms. Finally, a combination of two modeling techniques is adopted to take advantage of two different modification approaches at the same time.

1.3 Flow solver

Hydrodynamic design of ships involves several stages, from preliminary and early-stage design to late-stage and final design. Preliminary and early hydrodynamic design requires computational tools that account for essential (but not necessarily all) relevant physics, and are highly efficient (with respect to CPU and user input time) and robust. Thus, linear potential flow assumptions may be suitable for this stage of the design. As the design progresses, the level of physical realism needs to be upgraded, leading to Euler, RANS, and perhaps VLES runs at the final stages of the design. As the objective of this study is to develop a practical hydrodynamic optimization tool for the design of a monohull ship at early design stage, a practical design-oriented CFD tool based on a new theory, called Neumann-Michell (NM) theory, is used to compute the steady flow about a ship. Yang et al. (2007) showed that the wave drag predicted by the NM theory is in fairly good agreement with
experimental measurements[24]. In addition, the computer code based on the NM theory is very robust and highly efficient. Specifically, only surface mesh on the hull is required. The CPU time for evaluating the flow about a ship hull that is approximated by 10,000 panels is approximately 10 seconds per Froude number using an Intel Pentium 4 Processor PC. An advanced flow solver, incompressible flow solver based on finite element approximation is also utilized in order to provide high resolution of the flow field for the optimal hull form design that is obtained via the simple CFD code and optimize the initial hull form so that the optimal hull forms obtained by two different flow solvers are compared. The advanced CFD computer code based on Euler/RANS equations and nonlinear free surface condition is used. This advanced code has been validated for various hull forms in a number of literature [25, 26].

1.4 Optimization Process

A brief optimization process is as follows:

**STEP1**
Define the objective function and constrains.
Define the initial design of the ship.
Define the Optimization-Module.
Define the Surface Modification-Module.
Define the CFD-Module.
Evaluate the objective function of the initial Design by defined CFD-Module.
Set $k = 0$.

**STEP2**
Modification according to Optimization-Module.
Modeling the modified ship hull form according to Surface Modification-Module.
Evaluate the objective function of the modified Design by defined CFD-Module.
Set $k = k + 1$.

**STEP3**
Check the convergence criterion. 

If the convergence criterion is satisfied, then STOP. 

If the $k_{Max} = k$, then STOP. 

Otherwise, go to STEP2.

At the beginning of the optimization procedure, it is necessary to define the objective function and constraints for the given application. Since there are multiple choices of optimization algorithms, surface modeling methods, and flow solvers, these 3-Modules also need to be specified before starting the iterative process of optimization. Using the chosen CFD-Tool, the objective function is then evaluated. Now, the iteration is basically initiated. Therefore, hull designs are modified in each iteration according to the Optimization-Module through the Surface Modification-Module. Finally, the optimal hull form is obtained in the course of iterations.

For the applications, the present dissertation considers a simple hydrodynamic-optimization problem: minimization of the total drag or the wave drag of a monohull ship while keeping the displacement unchanged. Several hull forms are taken as initial hulls and the present hydrodynamic optimization tool is used to determine the optimal hull forms for either single design speed or for a given speed range with displacement constraint.
Chapter 2: Optimization

In general, the optimization problem is defined as,

\[ \text{minimize } f(x) \] (2.1a)

subject to \( x \in \Omega \) (2.1b)

The function from the set \( \mathbb{R}^n \) into the set \( \mathbb{R} \) is a real-valued function called the objective function or cost function. The vector \( x \) is an \( n \)-vector of independent variables. Therefore, \( x \) is expressed as \( x = [x_1, x_2, \cdots, x_n]^T \). The variables \( x_1, x_2, \cdots, x_n \) are design variables. Finally, the given function is minimized within the constraint set or feasible domain, \( \Omega \) which is a subset of \( \mathbb{R}^n \).

In this dissertation, two kinds of problems are considered. At first, it is necessary to take the single-objective optimization problem into account by making use of one local search technique and two global optimization algorithms. However, the single objective formulation is extended to reflect the real-world of multi-objective problems where there is not only one objective function to optimize, indeed, but many objective functions. Therefore, there is not only one solution, but a set of solutions are existing. With this reason, the genetic algorithm using the Pareto front technique is applied to solve the multi-objective optimization problem, secondly.

2.1 Gradient Method

There are several optimization algorithms have been introduced to evaluate a descent direction for optimization. The gradient method or the steepest descent method is the simplest, most popular method for searching a local optimal solution. The idea of this method is to
find the direction \( (d) \) at the given position in which the objective function \( f(x) \) decrease. Then the current point is moved along the direction of \( d \). Finally, these main 2 steps are used in the iterative process. Since only the gradient of the objective function is utilized to evaluate the search direction, the gradient method is categorized into a first-order method.

The gradient of a objective function \( f(x) \) or \( f(x_1, x_2, x_3, \cdots, x_n) \) is defined as

\[
\mathbf{c} = \nabla f = \left[ \frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \frac{\partial f}{\partial x_3}, \cdots, \frac{\partial f}{\partial x_n} \right]^T \tag{2.2}
\]

It should be noted that the gradient at a point \( x \) indicates the direction of maximum increase in the objective function. Therefore, the direction of maximum decrease in opposite to the gradient \( \mathbf{c} \) as

\[
d = -\mathbf{c}, \quad \text{or} \quad d_i = -c_i = \frac{\partial f}{\partial x_i}; \quad i = 1, 2, \cdots, n \tag{2.3}
\]

Using Eq. (2.3), the current design point is changed in the domain with making use of Eq. (2.4).

\[
x^{k+1} = x^k + \alpha^k d^k \tag{2.4}
\]

where \( k \) means k-th iteration and \( \alpha \) represents step size.

As mentioned earlier, the main idea of gradient method is simple. At the beginning, the direction of the steepest descent is evaluated on the initial point as a given value. Using that direction, the current location of the point is moved in order to reduce a value of the objective function. Then, an evaluation of the steepest direction at the new point is carried out again and the entire process are repeated until either convergence criterion is obtained or maximum iteration number as an input value is reached. A detail for the iteration process is explained as follows:

**STEP1**
Define the initial point \((x^0)\), maximum iteration \((k_{\text{max}})\) and convergence criterion \(\epsilon\).

Set iteration \(k = 0\).

Scaling design variables.

**STEP2**

Set step size \(\alpha^k\).

**STEP3**

Evaluate derivative for each component \((x_i)\).

Calculate the steepest descent direction \((d^k)\) by Eqs. (2.2) and (2.3).

**STEP4**

Evaluate \(f\) at \(x^* = x^k + \alpha^k d^k\).

If \(f(x^*) > f(x^k)\), then change \(\alpha^k\) and goto **STEP3**. Otherwise, continue.

Search best step size to minimize objective function at \(x^* = x^k + \alpha^*_k d^k\), set \(\alpha^k = \alpha^*_k\).

**STEP5**

Update design point using Eq. (2.4) for \(x^{k+1}\).

If \(|f(x^{k+1}) - f(x^k)| < \epsilon\), then STOP.

Otherwise goto **STEP2**.

In the given gradient method, there are two main operations. The first is to evaluate the gradient at the given point. The other is to determine step size in order to obtain the position which yields in the minimum value of the objective function along the search direction. Particularly, this operation is always one-dimensional minimization problem (i.e. line search optimization). Therefore, any line search algorithms may improve the gradient method in terms of computation cost as well as the final optimal solution. In this dissertation, a very simple algorithm was applied. The step size will be increased by certain rate until reaches local minimum.

A simple problem has been applied to illustrate the presented gradient method. The
The objective function is given as

\[ \text{minimize } f(x_1, x_2) = -\exp[(x_1 - 0.9)^2 + (x_2 - 0.1)^2]/100 \]  

subject to

\[ -1.0 \leq x_1, x_2 \leq 1.0 \]  

Figure 2.1: Distribution of the objective function in Eq. (2.5) and the result of gradient method

The distribution of the objective function value is shown in Fig. 2.1. The given objective function has only one optimal solution at \((0.9, 0.1)\) with \(f(0.9, 0.1) = 0.0\), and does not exist any other local minimum in the convex set of feasible domain. Particularly, gradient method is probably the fastest algorithm because the steepest descent always points around optimum solution at any point in the given feasible domain. For numerical experiment for the given function, convergence parameter set as \(\epsilon = 1.0 \times 10^9\), the number of maximum
iteration is $k_{\text{max}} = 100$, and $2^{\text{nd}} - \text{order}$ central finite different scheme is employed to evaluate derivatives for each component of the design variables. Fig. 2.1 displays trace of the result according to the each iteration step. The initial point is placed at the one of the corner in the domain. The given gradient algorithm straightforwardly guide to search the optimal solution. As a result, the total number of objective function evaluations is 203 with 25 iterations. The final optimal solution is $x_1 = 0.89999, x_2 = 0.09999$ with satisfactory objective function value ($f(x_1, x_2) = 0.00000$). In the given simple numerical example, the presented gradient method has been applied successfully.

The next numerical example is the well-known Griewank function, first introduced by Griewank, which has been employed as an objective function for global optimization technique in many papers. A special property of the Griewank function is that there is one global optimum solution while a large number of local minimum are distributed in the feasible domain. The definition is as follows

$$\text{minimize } f_n(x) = \sum_{i=1}^{n} \frac{x_i^2}{M} - \prod_{i=1}^{n} \cos \left( \frac{x_i}{\sqrt{i}} \right) + 1 \quad (2.6a)$$

subject to

$$-600 \leq x_i \leq 600, \quad i = 1, 2, \cdots, n \quad (2.6b)$$

As shown in Fig. 2.2 which displays the distribution of the Griewank function, the global minimum value is 0 and the global minimum is located at the origin. However, the function also has many local minima, which exponentially increasing with the dimension $n$. In this numerical example, the feasible domain is modified as $-17.5 \leq x_i \leq 2.5$ in order to place the global optimum around the corner of the feasible domain. At first, the initial point ($\text{Ind} - 1$) is $(12, 12)$. It takes 212 evaluations of total objective function which result in 20 iterations for the gradient algorithm. Since this given initial condition is near to the local minimum, the steepest descent direction is detected toward that local minimum. This is the well-known defect of the gradient method which using the steepest descent direction.
In addition, 4 more different initial points ($Ind_2$ – $Ind_5$) are tried in order to obtain global optimum solution. Except the case of $Ind_5$, each case results in the local optimum. Especially, the case of $Ind_4$, even though the initial point is very close to the global solution, final solution of that point is obtained with local minimum which is the next to the global optimum. Since the direction is obeyed by the steepest descent direction at the point, this initial point also failed to find the global optimum solution. Finally, the case $Ind_5$ lies on the steepest direction to the global optimum solution, successfully detects the desired solution. Overall, all the cases take approximately 200s evaluations of total objective function which is corresponding 20 iterations of gradient vector calculations. This fact shows that the gradient method is very efficient algorithm when a initial point lies on the direction to the global solution. Otherwise, it is very easy to result in the local optimum as mentioned above.
2.2 Genetic Algorithm (GA)

As illustrated in the previous section with the numerical example of the Griewank function, it is necessary either to employ algorithms for searching a global optimum solution. On this purpose, the genetic algorithm is adopted as one of the global optimizations. Genetic algorithms are based on how the populations evolve in the course of generations through a natural selection. Since most of computational operations are based on random number generation, genetic algorithms are categorized as stochastic search optimization methods. The algorithms use only the objective function values in the search operation to provide a optimum solution. The algorithms are very general so that they can easily cover all kinds of applications, such as discrete, continuous, and nondifferentiable. The basic idea of genetic algorithms is to begin with set of design points (called the first generation or the initial generation), which are randomly generated within the allowable range for the each design variable. Next, each design of the set is assigned a fitness value which is related with objective function. From the current designs, random operation are utilized in order to generate a new set of designs. The process is continued until a convergence criterion is reached. Details of algorithms will be explained later in this section. First, it is necessary to introduce terminology of the genetic algorithms.

**Population**  The set of design points in each iteration.

**Generation**  An iteration of the genetic algorithm. Each generation has a size of population.

**Individual**  Design point. Thus, the number of individuals in one iteration is a size of population.

**Chromosome**  Design variable. Thus, chromosome is used to specify a design point or an individual.

**Fitness function**  Generally, the fitness function defines the importance of an individual. In order to adjust to the given problem, any specific fitness definition could be used. In this dissertation, the fitness function is identical with the objective function. As mentioned earlier, the key process of genetic algorithm is an evolution of the next generation from the
previous generation based on the value of the fitness function. This process is achieved by 
3 main operations: selection, crossover, and mutation.

**Selection**

Selection is an operation to select a set of individuals from the current generation and pass 
them on the next generation. In nature, the stronger individuals are dominating over the 
weaker because of the competition for insufficient resources. It is necessary to simulate or 
implement of this natural system into genetic algorithm. Therefore, value of the fitness 
function is employed to evaluate the relative importance. There are two simple methods for 
the selection operation. First, a roulette wheel method is widely used for selection opera-
tion. In this method, the probability of individual represents the proportion on the wheel 
and sized with this ratio. The wheel is then rotated with a certain amount of rotation based 
on the random number. After spinning the wheel, the individual which is located at the 
prescribed angle on the wheel is selected to carry into the next generation. And the other 
simple method for selection process is cut-off method. In this method, the first step is to 
sort according to the value of the fitness function of individuals in the current generation. 
The next step is that a set of individuals are selected to inclusion for the next generation 
by the prescribed cut-off value. For example, if cut-off value is set as 30% with a size of 
population 10, then the best top 3 individual out of 10 is selected for the next generation. 
From the different point of view, the selection operation is the process to prevent the ex-
tinction of the fittest individuals over the evolutions. Additionally, the other 7 individuals 
are still on the consideration for the next generation with a further selection. Therefore, 10 
candidates for the next generation are ready for additional operation.

**Crossover**

Crossover operation plays a major role to provide variation into the population. Crossover 
is achieved by the operation of blending two different chromosomes (design variables) in 
the population. The common three methods, one-cut point, two-cut point and random mix 
method are illustrated in Fig. 2.3. In the one-cut point method, a position on the string is 
randomly selected then exchanges a part with each other in order to produce new children
(A) One-cut point

(B) Two-cut point

(C) Random mix

Figure 2.3: Three types of crossover operations

(design points). The next method is using two-cut point to divide the string of chromosomes for both parent, then replace the one part from the other parent. Then the two new children are successfully generated. At last, randomly selected chromosomes are exchanged with the ones from each other parent in the random mix method. In this dissertation, the last method is employed to perform crossover operation. Additionally, the mating pool which is the database of population is obtained from selection operation and the parent are selected the closest couple from the mating pool.

**Mutation**

Mutation is the last operation to introduce new individuals of the next generation. The
main idea is to introduce another variation in the course of evolution. Selecting several members from individuals of the generation, then change a few chromosomes by random manner. This procedure is depicted in Fig. 2.4 using a simple example. In this example, the individual consist with 10 chromosomes which is obtained from both selection and crossover operation. By performing mutation operation, several chromosomes which are randomly selected are switched from 0 to 1 or 1 to 0.

In addition, at each generation, the best individual which provides the minimum objective function value among all the design points is defined as the leader of the population. If the leader from the previous generation is still provide the lowest cost function value, then this individual still treated as the leader. However, if new member from the current population yields in the minimum value, then the new one takes over a position of the leader. A benefit of using a leader is that this individual can survive in the course of generation as long as its value is still relatively low than the others. In order to perform this idea in the algorithm, it is necessary to sort the individuals in each generation. In other words, it is required to order the design points in terms of cost function values. Since the basic ideas and the main operations are presented, the details of the genetic algorithm used in this dissertation is stated as follow:

**STEP1**

Define problem: \( N_{ind}, N_{chro}, N_{gene} \).

Define the coefficient for the 3 main operation: \( C_{keep}, C_{cutoff}, C_{mutate} \).

Generate the initial generation with \( N_{ind} \).

Set \( igene = 0 \).
**STEP2**

*Evaluate the fitness values for all the individuals.*

*Set* $i_{gene} = i_{gene} + 1$.

**STEP3**

*Check the convergence criterion.*

*If the convergence criterion is satisfied, then STOP.*

*Otherwise, continue.*

**STEP4**

*Sort the individuals according to the fitness values.*

*Store* $Ind_{best}^{i_{gene}}$.

*Selection operation.*

**STEP5**

*Crossover operation.*

**STEP6**

*Mutation operation.*

*Store the all new individuals at* $Ind_{new}$.

**STEP7**

*Check the variation of* $Ind_{new}$.

*If the variation is too small, then go to **STEP5***

*Otherwise, set* $Ind_{best}^{i_{gene}} = Ind_{new}$. *Go to **STEP2***

---

$N_{ind}$ : the number of individuals, population

$N_{chro}$ : the number of design variables or chromosomes

$N_{gene}$ : the number of desired maximum generation

$C_{keep}$ : the percentage for keeping top ranked individuals

$C_{cutoff}$ : the percentage for cutting off lower ranked individuals

$C_{mutate}$ : the coefficient for mutation
In Figs. 2.5 – 2.6, the initial individuals and the population are displayed in the feasible domain, respectively. The randomly generated initial individuals are distributed on the domain. Since only 10 initials are generated, the individuals are not uniformly distributed as shown in Fig. 2.5. However, this fact does not affect on the search for a global optimum solution, because the higher ranked individuals in terms of the objective function value play main role to evolve the new generations. Therefore, many of populations are placed close to the optimal solution as shown in Fig. 2.6. The history of the leaders which provide the lowest fitness values in each iteration or generation are depicted in Fig. 2.8. Since the presented genetic algorithm is capable of global search, the global optimal solution is successfully detected. The final optimal solution is \((0.1353 \times 10^{-3}, 0.3399 \times 10^{-3})\), the corresponding objective function value is \(0.3873 \times 10^{-7}\) during the maximum iteration \((N_{gene}) 100\) with the total number of objective function evaluations 994. The genetic algorithm detected reasonable optimum solution \((f_{obj} \leq 1.0 \times 10^{5})\) at the iteration number 90. In addition,
some of the initial individuals which yield in high objective function values show that does 
not affect on the generation for the new individuals. In other words, the points which have 
high fitness values among the initials result in the scarcity of neighbors as shown in Fig. 2.6

2.3 Particle Swarm Optimization (PSO)

Another algorithm is considered and implemented in order to search the global optimum 
solution by making use of the recently introduced evolutionary method, Particle Swarm 
Optimization (PSO). James Kennedy and Russell Eberhart [27] proposed the particle 
swarming approach inspired by the social behavior of a bird flock. The main idea of this 
approach is to simulate the movement of a group of birds or bees which aim to find food 

sources.

The key operation is to make use of a velocity vector in order to move current particles.
The position of each particle is updated based on the social behavior. The information sharing which possibly is the place of food or any other sources among the individuals in nature. In the computational implementation, this information is store as history or database of all the particles. Consequently, the database is utilized to update the velocity vector in order to move the particles for the current positions to the new positions as shown in Eq. (2.7).

\[
x_{k+1}^i = x_k^i + v_{k+1}^i \Delta t
\]  

(2.7)

where \(x_{k+1}^i\) is the position of particle \(i\) at \(k+1\)th iteration, \(v_{k+1}^i\) is corresponding velocity vector to update the location of particle \(i\) and \(\Delta t\) is time step.

Although many schemes for updating the velocity of each particle are introduced, the most commonly used scheme is employed to reposition the particle in Eq. (2.8).

\[
x_{k+1}^i = w v_k^i + c_1 r_1 \frac{(p^i - x_k^i)}{\Delta t} + c_2 r_2 \frac{(p^g - x_k^i)}{\Delta t}
\]  

(2.8)

where \(r_1\) and \(r_2\) are independent random number between 0 and 1, \(p^i\) is the best position which is found in the history of \(i\)–th particles and \(p^g\) is the best position in the history of swarm. There are three parameters to define the proposed PSO algorithm, the inertia weight parameter \(w\) and two trust parameters \(c_1\) and \(c_2\). The inertia parameter controls the search characteristic of the algorithm. A global search is accomplished by employing larger value while a local search is assigned by smaller. Therefore, the first term which involves \(w\) is called inertia term. The other two trust parameters, \(c_1\) and \(c_2\), are called self-trust parameter and swarm-trust parameter, respectively. The self-trust parameter \(c_1\) represents how much confidence the current particle has in itself, and the swarm-trust parameter \(c_2\) indicates how much confidence the particle has in the swarm. Therefore, each term called self-trust and swarm-trust term.
2.3.1 Enhanced Particle Swarm Optimization (PSO)

In order to implement PSO, several techniques are necessary to enhance the given basic PSO algorithm.

Initialization of the swarm

Instead of using a random generator in order to distribute the initial particle in the feasible domain, utilized in the numerical experiment for the genetic algorithm as shown in Fig. 2.5, a deterministic approach is employed. In detail, the initial swarm is placed on the center of each face on the feasible domain. Thus, the total number of particle is $2n$ in $n$-dimensional problem. Additionally, the initial vector is set 0 in order to preserve the deterministic property.

Boundary Search Phase

According to the Eq. (2.7) and Eq. (2.8), each particle is attracted by the others. This fact implies that, unless the inertia weight parameter is relatively large, the movement of particles are confined within a certain design space which is specified by the link among the particles. In other words, the corners of the feasible domain cannot be searched by any particle since the initial swarm is located on the center of each face. Therefore, the additional technique is introduced in order to force the search along the boundaries as defined in Eq. (2.9).

$$|v^o_k| = \frac{|x^o_{max} - x^o_{min}|}{c_{b,s,p}}$$  \hspace{1cm} (2.9)

where $o$ indicates the orthogonal to the face where the particle has been initially placed. Therefore, the orthogonal component of the velocity is limited by the threshold value $|v^o_k|$.

Violated Particles

Since the optimization problem in this dissertation has constraint condition $\Omega$ as defined in Eq. (2.6a), a special attention is required for the particles with violated constraints. The proposed method[28] is quite simple but is very effective in most cases to point back to the feasible domain. The main idea is to set the inertia weight parameter as 0. The only
influence for updating the velocity vector is the best particles either itself or swarm. Thus, the velocity vector is updated by using only trust terms in Eq. (2.8).

**Craziness Operator**

In order to provide an additional global search phase, the craziness operator [28] is introduced which acts similar to the mutate operation in genetic algorithm. At first, a small number of particles which provide lower objective function values at each iteration are selected for evaluation of the coefficient of variation (COV). If the COV is less than a pre-defined threshold value, the all particles are relocated more than two standard deviations from the center of the swarm.

**Variable Inertia Weight Parameter**

The inertia weight parameter $w$ is employed to consider the impact of the previous history of velocities on the current ones. It controls the search phase between the global and local exploration. As mentioned earlier, a large value intends global search, and a small value results in the local search phase. Experimental results indicates that it is better to set the initial value for the inertia weight parameter with a large value in order to promote global search of the design space and gradually decrease to perform a local exploration if the COV of the all swarm is less than prescribed threshold. Therefore, the inertia parameter is variated by making use of Eq. (2.10).

$$w_k = w_{k-1} - gw$$  

(2.10)

where $w_k$ is the newly adjusted value for the inertia weight parameter, $w_{k-1}$ is the previous value and $gw$ is a prescribed constant value. In this dissertation, $gw$ is set as 0.975 and the $w$ begins with 1.4 while the minimum is set as 0.25.

**Convergence Criterion**

A convergence is detected by a combination of two conditions. The first one is, at each iteration, all the particles of the swarm are evaluated in terms of the objective function
values. If a trend is detected for a given consecutive steps as shown in Eq. (2.11),

$$
\begin{align}
\left\{ [f_k(x^i) - f_{k-1}(x^i)] \cdot [f_{k-1}(x^i) - f_{k-2}(x^i)] & \geq 0 \\
  f_k(x^i) - f_{k-1}(x^i) & \leq 0 
\right. 
\end{align}
$$

(2.11)

If the first condition is satisfied to stop the given PSO process, then the second one starts to evaluate the average distance from the center of the high ranked particles yield in lower function values. If the average radius is less than the predefined threshold for a given number of consecutive iterations, then this condition force to stop the PSO algorithm.

Finally, the presented PSO algorithm using the enhancement methods, including the initialization technique, enforcement for the boundary search, treatment for the particles which violate the feasible domain, modification of the inertia weight parameter, and the appropriate convergence criteria for the PSO, is as follows:

**STEP1**

Define PSO : $w_0, c_1, c_2$.

Define the details : $g_w$, other thresholds.

Generate the initial particles.

Set $k = 0$ and $v_k = 0$.

**STEP2**

Evaluate the objective function for all the particles.

Set $k = k + 1$.

**STEP3**

Check the convergence criterion.

If the convergence criterion is satisfied, then STOP.

Otherwise, continue.

**STEP4**

Sort the individuals according to the objective function values.
Find the best position in itself.
If the best position yields in the lowest function value.
Then Update the best position, otherwise continue.
Find the best particle in the current swarm.
If the best particle yields in the lowest function value.
Then Update the best position in the swarm, otherwise continue.

**STEP 5**
Evaluate velocity for the inertia component.
Evaluate velocity for the self-trust component.
Evaluate velocity for the swarm-trust component.

**STEP 6**
Check the variation of the inertia weight parameter.
Update new position of all the particles.

**STEP 7**
Check the craziness operator.
If the variation is too small, then modify the position.
Otherwise, go to **STEP 2**.

A numerical experiment is performed by applying to the Griewank function in Eqs. (2.6a) and (2.6b). Since the dimension $n = 2$ is employed, the four initial particles are located at the center of each face which is the edge of the square as shown in Fig. 2.7. The maximum iteration number is set as 400 and the corresponding total number of the objective function evaluations is 1600. In this figure, the trace can be easily detected because the velocity term is mostly dominated by the inertia term. As a result of comparison study for the existence of the additional random operator, the craziness operator is not considered in this example. Moreover, no random generator is used in order to maintain the proposed algorithms as deterministic search method. Each particle shows that the boundary search phase is successfully utilized in Fig. 2.7. In a different point of view, the various search phase
Figure 2.7: Application of particle swarm optimization to the Griewank function \((n = 2)\) and the trace of the particles

also applied in a perfect way. In other words, each particle moves toward the global optimal solution with large portion of the inertia term at the beginning of iteration, and then each particles gathers in a small region in order to detect the global minimum solution with the relatively small inertia component and interacts with the others. In fact, most population are shown in the narrow range which includes the solution except the particles lies on the course to the solution. In fact, the best particle in the swarm detected reasonable optimum solution \((f_{obj} \leq 1.0 \times 10^5)\) at the iteration number 50 as shown in Fig. 2.8. After this iteration, the \(PSO\) algorithm are turning into fine-tune search to detect global solution. The comparison between the genetic algorithm and the particle swarm optimization are shown in the Fig. 2.8 in terms of the leaders of the \(GA\) and the best particles in the swarm of the \(PSO\). Overall, two global optimization algorithms are successfully detect the desired solution which is less than \(1.0 \times 10^7\).
2.4 Multi-Objective Genetic Algorithm (MOGA)

Up to now, a single-objective function is needed to be optimized. However, there are many practical applications where the designers may want to optimize two or more objective functions. This problems are called multi-objective optimization problems. The general multi-objective model is defined as follows:

\[
\begin{align*}
\text{minimize } & \quad f(x) = (f_1(x), f_2(x), \cdots, f_m(x)) \\
\text{subject to } & \quad \Omega = x|h_i = 0; i = 1, \cdots, p \text{ and } g_j \leq 0; j = 1, \cdots, q
\end{align*}
\]  

(2.12a) (2.12b)

where \( p \) is the number of equality constraints, \( q \) is the number of inequality constraints, the vector \( x \) is an \( n \)-vector of independent variables, and \( m \) is the number of objective functions. In other words, \( f(x) \) is a \( m \)-dimensional vector of objective functions. Finally, \( \Omega \)
is the feasible design space (feasible domain).

\[ x_1, x_2 \]

\[ f_1, f_2 \]

Figure 2.9: Multi-objective optimization problems: (a) Feasible design space and (b) Objective function space (Criterion space)

An optimization for a single-objective problem simply involves detecting a local minimum or maximum, and obtaining the global optimum solution as shown in Figs. 2.1 – 2.2, and 2.6. In contrast, the process of determining a solution or a set of solutions for a multi-objective optimization problem is more complex than that of a single-objective problem. As depicted Fig. 2.10, the point \( A \) provides the minimum value for the objective function \( f_1 \), the corresponding \( x = (0.9, 0.1) \), and the point \( B \) yields the lowest value for the objective function \( f_2 \), the corresponding \( x = (0.1, 0.9) \). However, the problem is to find the solutions which minimize both objective functions \( f_1 \) and \( f_2 \) concurrently. Therefore, it is necessary to introduce a solution to solve the multi-objective optimization problems.

### 2.4.1 Pareto Optimality

The most commonly used method to define solutions for multi-objective optimization problem is based on Pareto front approach. The definition of Pareto Optimal[29] is as follow:

A solution \( x \in \Omega \) is said to be Pareto Optimal if and only if there is no \( x^* \in \Omega \) for which \( v = f_{x^*} \) dominates \( u = f_x \).

In other words, \( x \) is called Pareto optimal if there is no other point \( x^* \) in the feasible
domain $\Omega$ that reduces at least one objective function without increasing another function. As shown in 2.10, a set of Pareto optimal is displayed in a line, which implies any point on this line is considered as the Pareto optimal. Within Pareto front or Pareto Optimal, there is one concept, dominance, needed to be explained.

**Dominated or Nondominated**

A vector of objective functions $\mathbf{f}^* = f(\mathbf{x})$ in the objective function domain $Z$ is nondominated if and only if there does not exist another vector $\mathbf{f}$ in the set $Z$ such that $\mathbf{f} \leq \mathbf{f}^*$, with at least one $f_i \leq f^*_i$.

For example, the point C is dominated point by both the point A in terms of $f_1$ and the point B in terms of $f_2$. In other words, the points A and B are nondominated points. The definitions of Pareto optimal and nondominated points are similar. The only difference is that Pareto optimal refers to points in the design space $\Omega$ while nondominated points refer to the points in the objective function space (criterion space) $Z$. However, Pareto optimal generally refers both the feasible space $\Omega$ and the criterion space $Z$.

In this dissertation, multi-objective problem is optimized by employing genetic algorithm called MOGA. A discrete set of potential solution points in each iteration or generation is updated and stored in genetic algorithm. Each new addition to this set of points is compared with all the objective function values of potential solutions to determine if the new design or individual is dominated. If it is nondominated, then it is kept in the set of Pareto optimal. In order to produce Pareto front, the Ranking approach is applied. In this method, for a given set of designs, the objective functions are evaluated at each individual. All nondominated points are marked as a rank of 1. Determining whether dominated or nondominated involves with comparing the vector of objective function values at the point with the vector at all other points. Then, the points ranked 1 are temporarily removed from the consideration to establish the set of points with a rank of 2. This process is repeated until all individuals are ranked. Therefore, the points with the lowest rank are treated as Pareto optimal at the current generation as shown in Fig. 2.10

In order to illustrate the multi-objective optimization problems, a simple numerical
example is applied as follow:

\[
\begin{align*}
\text{minimize} & \quad \begin{cases} 
  f_1(x_1, x_2) = -1 + e^{[(x_1 - 0.9)^2 + (x_2 - 0.1)^2]/100} \\
  f_2(x_1, x_2) = -1 + e^{[(x_1 - 0.1)^2 + (x_2 - 0.9)^2]/100}
\end{cases} \\
\text{subject to} & \quad -1 \leq x \leq 1
\end{align*}
\]  

(2.13a)

(2.13b)

In this problem, two objective functions \((f_1, f_2)\) are needed to minimized within the feasible design space of two design variables \((x_1, x_2)\). In Figs. 2.9 – 2.10, the feasible design space and the corresponding objective function space (cost space) are depicted for the given numerical example in Eq. (2.13), respectively. The minimum solution for the objective function \(f_1\) is located on \(x = (0.9, 0.1)\) and \(x = (0.1, 0.9)\) for the objective function \(f_2\). The maximum generation number is set 1000, and the corresponding total number of objective function evaluation is 9867. The multi-objective genetic algorithm is begin with 10 initial population. In Fig. 2.11, all the individuals are plotted on the feasible design space as well as the distributions of the objective functions. Most of the individuals are located between the points of the minimum values for each objective function. In particularly,
these individuals represent Pareto optimal on the criterion space as shown in Fig. 2.12. Moreover, Pareto front is successfully obtained by multi-objective genetic algorithm. Since a set of solutions is provided, it truly depends on the problems or applications either how to select or which design to be selected.

![Figure 2.11: Result of the multi-objective problem as in Eq. (2.13) and distribution of the population in the feasible design space](image)

2.5 Summary

In this chapter, the single-objective problems are optimized by using both the local search and the global search algorithms. Gradient-based method is successfully applied for the quadratic optimization problem as in Eq. (2.5). However, this approach cannot be applied to find the global solution in the design space which includes a number of local maximums and minimums such as the Griewank function in Eq. (2.6) and Fig. 2.2. Therefore,
two different global search techniques are implemented in order to detect the global optimum solution. At first, well-known Genetic Algorithm (GA) is successfully utilized to provide the global solution in Fig. 2.6. Secondly, the recently introduced Particle Swarm Optimization (PSO) is implemented to search the global optimal solution as shown in Fig. 2.7. Additionally, both global search algorithms are compared as depicted in Fig. 2.8 which indicates that both approaches are very efficient for the global optimization problems. Finally, multi-objective optimization problem is considered with making use of multi-objective genetic algorithm (MOGA) with Pareto Optimality by Ranking method. With this approach, a set of Pareto optimal is successfully provided as displayed in Figs. 2.11 – 2.12.
Chapter 3: Surface Representation & Modification

Surface representation module is one of major component in the CFD-based optimization technique. In other words, it certainly plays a key role in the shape optimization that how to represent the modified surface and how to control the surface modification during optimization. Thus, both developed surface representation and surface modification techniques are described in this chapter. At first, Non Uniform Rational B-Spline (NURBS) is employed to represent a given initial or modified hull for optimization procedure. Additionally, a useful modification tool using exponential spline is presented in order to provide an efficient surface modification module. Finally, two parametric surface representation and modification techniques are utilized and developed. One technique is making use of three parametric curves - sectional area curve (SAC), waterline and sectional profile. And the other is the surface modification technique based on the only SAC. As a result, the both parametric methods have resulted in a very fair surface as well as reduction of the number of design variables in an effective way.

3.1 NURBS Surface Representation

Surfaces and their description play an important role in shape optimization as well as design and manufacturing. Apparently, the optimization of ship hulls, marine propellers, aircraft wings and bodies are examples. However, most of these real-life shape or geometry unfortunately does not have analytical descriptions. Therefore, these surfaces are represented in a piecewise manner. Additionally, a parametric approach is necessary to describe these surfaces because of axis independent and avoiding infinite slope to an arbitrary axis. With these reasons, NURBS\textsuperscript{[30–32]} not only satisfies for surface representation but also provides
an effective surface modification technique. Nowadays, NURBS techniques are the standard for describing and modeling curves and surfaces in computer aided design (CAD) and computer graphics. A NURBS surface is a special case of a general rational B-spline surface that uses a particular form of knot vector. The knot vector has multiplicity of identical knot values equal to the order of the basis function at the end.

**NURBS curves**

A rational B-spline curve is the projection of a nonrational B-spline curve defined in four-dimension \((x, y, z, w)\) homogeneous coordinate space back into three-dimension \((x, y, z)\) physical space. \(k\)th-degree NURBS curve is defined by

\[
P(u) = \sum_{i=1}^{n+1} B_i^w N_{i,k}(u) \tag{3.1}
\]

where the \(B_i^h\) are the four-dimension control points, the \(N_{i,k}(u)\) is the nonrational B-spline basis function

\[
N_{i,k}(u) = \begin{cases} 
-1 & \text{if } x_i < 0 < x_{i+1} \\ 
0 & \text{otherwise} 
\end{cases} \tag{3.2a}
\]

and

\[
N_{i,k}(u) = \frac{(u - x_i)N_{i,k-1}(u)}{x_{i+k-1} - x_i} + \frac{(x_{i+k} - t)N_{i+1,k-1}(u)}{x_{i+k} - x_{i+1}} \tag{3.2b}
\]

where \(x_i\) are elements of a knot vector.

Projecting backing into three-dimensional physical space by dividing into the rational B-spline curve and weight

\[
P(u) = \frac{\sum_{i=1}^{n+1} B_i w_i N_{i,k}(u)}{\sum_{i=1}^{n+1} w_i N_{i,k}(u)} = \sum_{i=1}^{n+1} B_i R_{i,k}(u) \tag{3.3}
\]
where the \( B_i \) are the three-dimension control vertices for the rational B-spline curve and the

\[
R_{i,k}(u) = \frac{\sum_{i=1}^{n+1} h_i N_{i,k}(u)}{\sum_{i=1}^{n+1} h_i N_{i,k}(u)}
\]  

(3.4)

are the rational B-spline basis function. \( w_i \) called homogeneous weighting factors or weights. These weights are capable of the additional blending. The definition of affine space is when \( w = 1 \) which corresponds to physical space. The effect of the \( w \) on the rational B-spline basis functions is shown in Fig. 3.1. An open uniform knot vector \([0 \ 0 \ 0 \ 0 \ 1 \ 2 \ 3 \ 3 \ 3 \ ]\) \((n + 1 = 5, k = 3)\) is used with a homogeneous coordinate vector \( w_i = 1, i \neq 3 \). Values of \( w_3 \) range from 0 to 5. The rational B-spline basis function shown in Fig. 3.3(c) with \( w = 1 \) are identical to the corresponding nonrational basis functions. Fig. 3.2 shows the rational B-spline curve for \( w_3 = 1 \), which is also identical to the corresponding nonrational B-spline curve. In case for \( w_3 = 0 \) shows \( R_{3,3} = 0 \) at everywhere. Thus, the corresponding polygon vertex, \( B_3 \), has no influence on the shape of the corresponding B-spline curve. This effect is shown in Fig. 3.2, where the defining polygon vertices \( B_2 \) and \( B_4 \) are connected by a straight line. Fig. 3.1 also shows that as \( w_3 \) increases, \( R_{2,3} \) and \( R_{4,3} \) decrease. The effects on the corresponding rational B-spline curves are shown Fig. 3.2. It should be noticed that as \( w_3 \) increases the curve is pulled closer to \( B_3 \). This shows that weights provide blending capability. Similar characteristics are described for the fourth-order \((k = 4)\) rational B-spline basis function and the corresponding curves in Figs. 3.3 – 3.4. Since fourth-order does use all the five control points, the curve for \( w_3 = 0 \) does not degenerate to a straight line between \( B_2 \) and \( b_4 \).
A Cartesian product rational B-spline surface in four-dimensional homogeneous coordinate space is given by

$$S(u, v) = \sum_{i=1}^{n+1} \sum_{j=1}^{m+1} B_{i,j}^w N_{i,k}(u) M_{j,l}(v)$$  \hspace{1cm} (3.5)
where the $B^{w}_{i,j}$ are the four-dimensional homogeneous polygonal control vertices, and $N_{i,k}(u)$ and $M_{j,l}(v)$ are the nonrational B-spline basis functions previously given in Eq. (3.2).

Projecting backing into three-dimensional physical space by dividing into the rational B-spline curve and weight

$$S(u, v) = \frac{\sum_{i=1}^{n+1} \sum_{j=1}^{m+1} w_{i,j} B_{i,j} N_{i,k}(u) M_{j,l}(v)}{\sum_{i=1}^{n+1} \sum_{j=1}^{m+1} w_{i,j} N_{i,k}(u) M_{j,l}(v)} = \sum_{i=1}^{n+1} \sum_{j=1}^{m+1} B_{i,j} Q_{i,j}(u, v) \quad (3.6)$$

where the $B_{i,j}$ are the three-dimensional control net, and the $Q_{i,j}(u, v)$ are the bivariate rational B-spline surface basis functions

$$Q_{i,j}(u, v) = \frac{w_{i,j} N_{i,k}(u) M_{j,l}(v)}{\sum_{p=1}^{n+1} \sum_{q=1}^{m+1} w_{p,q} N_{p,k}(u) M_{q,l}(v)} = \frac{w_{i,j} N_{i,k}(u) M_{j,l}(v)}{\sum (u, v)} \quad (3.7)$$

where

$$\sum (u, v) = \sum_{p=1}^{n+1} \sum_{q=1}^{m+1} w_{p,q} N_{p,k}(u) M_{q,l}(v)$$

An example is shown in Fig. 3.5. An open ($k = l = 3$) B-spline surface is defined by $5 \times 5$ $(m = n = 4)$ control net. The control net is flat except for the center point as shown.
Figure 3.3: Rational B-spline basis function for \( n + 1 = 5, k = 4 \) with open knot vector \( [X] = [0 \ 0 \ 0 \ 1 \ 2 \ 2 \ 2 \ 2] \), \( [W] = [1 \ 1 \ w_3 \ 1 \ 1] \). (a) \( w_3 = 0 \); (b) \( w_3 = 0.25 \); (c) \( w_3 = 2 \); (d) \( w_3 = 5 \).

in Fig. 3.5(a). The open knot vector in both parametric direction is

\[
[0 \ 0 \ 0 \ 1 \ 2 \ 3 \ 3 \ 3]
\]

Thus, there are four parametric spans in each direction. Each parametric quadrilateral forms a B-spline surface subpatch. Three weights, in particular, are used in this example to exhibit the effect of different weight. The results with 1., 5. and negative weight factors \(-1\) are shown in Figs. 3.5(b) – (d). Similar to NURBS curve, as \( w_{3,3} \) increases the surface in
Figure 3.4: Rational B-spline curve for \( n + 1 = 5, k = 3 \) with open knot vector \([X] = [0 \ 0 \ 0 \ 0 \ 1 \ 2 \ 2 \ 2 \ 2], [W] = [1 \ 1 \ w_3 \ 1 \ 1] \).

pulled closer to \( B_{3,3} \). Meanwhile, a B-spline surface with a negative homogeneous weighting factor is not contained within the convex hull of the control net. Additionally, another example with flat surface except for the two points is shown in Fig. 3.6(a). Finally, the composite surface control net and the B-spline surface is shown in Fig. 3.7 Here is a simple algorithm for evaluation of NURBS surface.

Read the number of control points in the \( u, v \) directions

Read the order in each of the \( u, v \) directions

Read the number of isoparametric lines in each of the \( u, v \) directions

Read the control net and store in an array

Calculate the knot vector in the \( u \) direction and store in an array

Calculate the knot vector in the \( v \) direction and store in an array

Loop over specified \( u \)

Evaluate the basis functions, \( N_{i,k}(u) \) and store in an array

Loop over specified \( v \)

Evaluate the basis functions, \( M_{j,l}(v) \) and store in an array

Evaluate the Sum function
Loop over control vertex in the \textit{u} direction

Loop over control vertex in the \textit{v} direction

Calculate the surface point, \( S_{u,v} \) and store in an array

End loop

End loop

End loop

End loop

3.2 Surface Modification

3.2.1 NURBS Control Net Method

NURBS technique is employed to represent surfaces. For example, Fig. 5.1 shows NURBS control points and net in the left and NURBS surface in the right for both an initial Wigley hull surface and an intermediate surface during optimization cycle. It is also shown that the variation of the control points generates deformation of Wigley hull surface from the intermediate. The initial Wigley hull is represented by 15 \( \times \) 6 points. Part of these 90 control points are used as design variables. Fig. 5.1 shows that the distribution of the initial control points used to define the Wigley hull (top row of Fig. 5.1) and the distribution of intermediate control points used in one of the intermediate design cycle to define a new hull surface (bottom row of Fig. 5.1).

Fig. 5.2 depicts initial control points for the Wigley hull in the profile view as well as design variables. The control points, except the points plotted in solid square in Fig. 5.2, are used as design variables that can have 1 to 3 degrees of freedom (DOF) movement. As shown in Fig. 5.2, 31 out of 90 control points can have various degrees of freedom movement.

The type of the movement for the points on the waterline is also shown in Fig. 5.3. In this case, 15 control points are placed on the waterline, and 11 of them are fixed. The remaining 4 points have either 1-DOF or 2-DOF movement. In the present example, the high-resolution NURBS surface, generated from each perturbation of the design variables, is divide into
Figure 3.5: NURBS surface with NURBS control net; (a) control net (b) $w = 1.0$, (c) $w = 5.0$, (d) $w = -1.0$
Figure 3.6: NURBS surface with NURBS control net; (a) control net (b) $w = 1.0$, (c) $w = 5.0$, (d) $w = -0.5$
Figure 3.7: NURBS surface (b) with the corresponding NURBS control net (a)
approximately 50,000 roughly uniform triangular panels. These triangular panels are then used to define the hull surface in a discrete manner into an in-house preprocess software, and a new computational grids (approximately 8,000 triangular panels) required by the CFD tool are then generated automatically.

3.2.2 Grouping Method

In the previous sections, NURBS surface representation and modification technique has been introduced. With taking advantage of NURBS, it could be easily achieved that not only fair surface descriptions but also variations of the given surface in order to search the optimal shape for objective functions. However, the main drawback of the presented NURBS technique is possibly engaged with a large number of the design variables. For instance from the Wigley hull which is represented by 90 control points for NURBS, almost 60 design variables had been employed only for the bow region optimization. This indicates that 120 of objective function evaluations in order to obtain the gradient at each iteration for the secant method, 120 of population in one generation for the genetic algorithm and 120 of particles in one iteration for the particle swarm optimization. If the number of maximum iteration is 100, then the total number of objective function evaluations is going to be at least 12000. Even if a fast simple potential flow solver (SSF) which takes approximately 7.8 seconds per one speed is adopted, it is no more efficient optimization module in terms of the computation. Therefore, it is necessary to introduce additional technique to reduce the number of design variables in order to take advantage of the fast flow solver as well as efficiently to search computational domain. With this reason, in this dissertation, two grouping methods are introduced. One is named "E-Grouping", and the other is "Flat-Grouping".

At first, E-Grouping is based on the theory of the exponential spline \([33, 34]\) to take advantage of its predominant property of shape preserving. Fig. 3.8 depicts the superiority of shape preserving comparing to the conventional cubic spline interpolation. While no wiggle is detected from the exponential spline, the interpolated curve by cubic spline
shows oscillation when the line coming down from the maximum peak. Since this unstable interpolation curve causes more complex and unpractical shape or unfair curve or geometry, the exponential spline interpolation approach is utilized rather than the conventional cubic spline method.

Fig. 3.9 depicts that the effect of one control point on the NURBS curve as an example. Only one point out of the given nine original control points is relocated to deform the original NURBS curve. As a result, new curve is obtained by NURBS using eight of original control points and one disturbed vertex in Fig. 3.9. It is obviously detected that relocation of one control point locally affects within two neighbor vertices. However, this kind of modification is required in certain parts of ship hull, i.e. bulsbow, stem line and sonar dome, etc. Generally, larger affected area is actually preferable, particularly in forward or after shoulder part and mid body of the ship. There are several possible ways to achieve a wide deformation. The first is that to increase order of NURBS surface which could result in the loss of local deformation for the region of bow and others. The second method is to change the weighting factors in the NURBS surface. In such case, the weighting factors are going to be additional design variables. The next possible way is to use neighbor control points as additional design variables, which also is increase of the number of design variables. Finally, the last approach is similar to the third method but use neighbors as dependent design variables, so called "Grouping Method". In the proposed method, the dependent
design variables, neighbor points of the independent design variable, are relocated according to the variation of the independent control points using the exponential spline method. Figs. 3.9 – 3.11 show that difference in terms of the number of dependent design variables. At first, Fig. 3.9 represents no dependent design ($V_{D}$) variables selected. Thus, the effect of control points ($V_{Ind}$) relocation is distributed in a very narrow range. The two nearest neighbor points ($V_{1D}^{1}, V_{2D}^{2}$) out of eight control vertices are relocated according to the modification of the independent variables using the exponential spline in Fig. 3.10. The modification on the independent design variables affects on the two neighbor points so that modification on the NURBS curve becomes wider than the one without any dependent variables. Finally, four nearest points ($V_{1D}^{1} \sim V_{4D}^{4}$) from the dependent design variable are selected in order to reposition in Fig. 3.11. The NURBS curve is modified globally by the combination of the one independent design variable and four dependent variables.

In addition, the Flat-Grouping method is also shown in Fig. 3.12 with selecting two neighbor control points ($V_{D}^{1}, V_{D}^{2}$) as dependent design variables. In this method, the selected neighbors are modified by the same value with the dependent design variable as shown in Fig. 3.12. Therefore, the modification on the new NURBS curve is wider than the E-grouping method with two neighbors. It should be noticed that wider maximum region exists around the independent design point than the result of the E-grouping method. However, the new curve of Flat-grouping method rapidly decreases comparing to E-grouping curve as shown in Fig. 3.13.

Several grouping methods are demonstrated in order to both reduce the number of design variables and provide fair curve and surface according to the location of the point. It is highly recommended to make use of any combination of the presented grouping method for the shape optimization, in particular, using NURBS control points as design variables.
Figure 3.9: E-grouping method: Modification of 1 independent design variable ($V_{Ind}$)

Figure 3.10: E-grouping method: Modification of 1 independent design variable ($V_{Ind}$) and 2 dependent variables ($V^1_D$, $V^2_D$)

Figure 3.11: E-grouping method: Modification of 1 independent design variable ($V_{Ind}$) and 4 dependent variables ($V^1_D \sim V^4_D$)
3.3 Parametric Surface Modification

Previously, a surface representation technique based on the NURBS surface was developed in order to modify the given hull surface during the optimization process. However, a large number of design variables is inevitable even if the proposed grouping method is adopted. A large size of design variables causes an expensive computational cost. In this reason, high level of surface representation and modification technique is necessary in order to decrease the number of design variables. Therefore, two high level parametric surface representation techniques are utilized and developed in this dissertation. The first method is utilized three
parametric curves, sectional area curve (SAC), waterline and sectional profile. The next approach is based on the SAC only.

### 3.3.1 Parametric Generation Method

This method was introduced by Pérez et al. [35]. The main idea of this method is three curves are utilized to generate hull forms. The first curve is the sectional area curve (SAC) which represents the distribution of nondimensional sectional area into the longitudinal direction. The others are the waterplane and sectional profile.

- **Sectional area curve**

Pérez et al. proposed the polynomial sectional area curve is generated by the following parameters which is generally used by naval architect [36].

- Displacement ($\nabla$)
- Longitudinal center of buoyancy ($LCB$)
- Maximum midship area ($Ax$)
- Longitudinal position of maximum midship area ($LCX$)
- Waterline length ($LWL$)
- Entrance angle ($\alpha_e$)
- Trailing angle ($\alpha_t$)
- Transom wetted area ($A_0$)

As shown in Fig. 3.14, the sectional area curve is divided into two curves ($S_a$ & $S_f$) which are expressed in mathematical forms, fourth degree of polynomials as shown in Eq. (3.8).

$$S_a(x) = A_4x^4 + A_3x^3 + A_2x^2 + A_1x + A_0 \quad (3.8a)$$

$$S_f(x) = B_4(x - x_m)^4 + B_3(x - x_m)^3 + B_2(x - x_m)^2 + B_1(x - x_m) + B_0 \quad (3.8b)$$

From the two equations above, 10 coefficients of the polynomials are undecided. In order to obtain these values, 10 conditions are required to solve linear system of equations. Therefore,
it is necessary to obtain the 10 conditions from the parameters as well as from the curves by geometrically as follows:

\[ S_a(0) = A_0 \] (3.9a)

\[ S_a'(0) = \tan(\alpha_t) \] (3.9b)

\[ S_a(x_m) = 1.0 \] (3.9c)

\[ S_a'(x_m) = 0.0 \] (3.9d)

\[ S_f(1) = 0.0 \] (3.9e)

\[ S_f'(1) = \tan(\alpha_e) \] (3.9f)

\[ S_f(x_m) = 1.0 \] (3.9g)

\[ S_f'(x_m) = 0.0 \] (3.9h)

\[ \int_0^{x_m} S_a(x)dx + \int_{x_m}^1 S_f(x)dx = \nabla \] (3.9i)

\[ \int_0^{x_m} xS_a(x)dx + \int_{x_m}^1 xS_f(x)dx = LCB \] (3.9j)

- **Waterline curve**

In a similar fashion, the polynomial waterplane curve is generated by the following generally used parameters by naval architect.

Waterplane area \((A_{wp})\)

Longitudinal flotation center \((LCF)\)

Maximum half-breadth \((B_x)\)

Longitudinal position of maximum half-breadth \((LCXF)\)

Waterline length \((LWL)\)

Entrance angle of waterline \((\beta_e)\)
Figure 3.14: Definition of sectional area curve

Trailing angle of waterline ($\beta_t$)

Transom wetted half-breadth ($B_0$)

As shown in Fig. 3.15, the sectional area curve is divided into two curves ($W_a$ & $W_f$) which are expressed in mathematical forms, fourth degree of polynomials as shown in Eqs. (3.10).

\[
W_a(x) = C_4x^4 + C_3x^3 + C_2x^2 + C_1x + C_0 \quad (3.10a)
\]

\[
W_f(x) = D_4(x - x_{mw})^4 + D_3(x - x_{mw})^3 + D_2(x - x_{mw})^2 + D_1(x - x_{mw}) + D_0 \quad (3.10b)
\]

Same with the sectional area curve, 10 coefficients of the polynomials are unknown of the two polynomials above. In order to obtain values of the coefficients, 10 conditions are essential in order to solve $10 \times 10$ linear system. Therefore, it is necessary to find the required 10 conditions from the parameters and the curves by geometrically as follows:

\[
W_a(0) = B_0 \quad (3.11a)
\]
\[ W'_a(0) = \tan(\beta_t) \] (3.11b)

\[ W_a(x_{mw}) = 1.0 \] (3.11c)

\[ W'_a(x_{mw}) = 0.0 \] (3.11d)

\[ W_f(1) = 0.0 \] (3.11e)

\[ W'_f(1) = \tan(\beta_e) \] (3.11f)

\[ W_f(x_{mw}) = 1.0 \] (3.11g)

\[ W'_f(x_{mW}) = 0.0 \] (3.11h)

\[ \int_{x_{mw}}^{x_{mW}} W_a(x)dx + \int_{x_{mw}}^{1} W_f(x)dx = Awp \] (3.11i)

\[ \int_{x_{mw}}^{x_{mW}} xW_a(x)dx + \int_{x_{mw}}^{1} xW_f(x)dx = LCF \] (3.11j)

Sectional profile curve

Finally, sectional profile is described in mathematical form by the expression of Jorde[37]. In Eq. (3.12), \( k_n \cdot y \) defines the straight line and \( p_n \cdot y^{q_n} \) intends the curved zone of the sectional profile. However, this simple expression is inappropriate to define the sections of a bulbous bow or midship sections with square shape which generally can be found commercial ship, such as crude carriers. Therefore, this mathematical expression is proper to provide simple section shape.

\[ z = (T - T_n) + K_n \cdot y + P_n \cdot y^{q_n} \] (3.12)

\[ q_n = \left( T_n - k_n \frac{B_n}{2} \right) \frac{B_n}{2} \left[ T_n \frac{B_n}{2} - S_n - \frac{k_n}{2} \left( \frac{B_n}{2} \right) \right] - 1 \] (3.13)
where $y$ is the breadth at certain height, $K_n$ is the tangent in midship, so called deadrise angle, $T$ is the draft and $T_n$ is the draft at $n$ station. The breadth of the $n$-station can be found from the waterplane curve as shown in Fig. 3.15 and the area of the $n$-station is obtained from the sectional area curve in Fig. 3.15. Therefore, the deadrise angle ($k_n$) and the draft ($T_n$) can be the parameters to specialize the section shape at $n$-station.

3.3.2 Shifting Method

Finally, the last surface modification in this dissertation is called "Shifting Method". Because this approach is quite simple than any others, in reality, the ship designers on the fields are still dealing with this shifting technique based on the Lackenby method [38]. The given sectional area curve modified in certain way, then find out the movement of any station along the longitudinal direction. Thus, the waterlines and profile body plan for the
hull must shift according to the amount from the sectional area curve. Figs. 3.17 – 3.18 depict that the given sectional area curve as well as the modified curve. The amount of shift at any section is evaluated, then the existing original hull surface is transformed by the rearrangement into a new modified hull form. As shown in Fig. 3.17, the sectional area curve is divided into three parts: Run, Middle parallel and Entrance part. Since the curve for the middle parallel part is straight line, the other two parts are needed to be described with mathematical form. Eq. (3.15) shows a general cubic spline technique are adopted to express each of curve to make use of both naval architecture parameters and new introduced parameters as follows: 

- **Sectional area curve**
  
1. Trailing angle in stern ($\alpha_t$)
2. Entrance angle in bow ($\alpha_e$)
3. Nondimensional area of the fixed station for Aft-body ($S_a(x_a)$)
4. Nondimensional area of the fixed station for Fore-body ($S_f(x_f)$)
5. Longitudinal position of parallel part for Aft-body ($S(x_p^a)$)
6. Longitudinal position of parallel part for Fore-body ($S(x_p^f)$)

7. Displacement ($\nabla$)

- Profile plan

8. Bulb-Height ($H_b$)

 Particularly, displacement ($\nabla$) is selected in this dissertation in order to apply inverse optimization [39] technique - minimize the drag as well as maximize the displacement concurrently - as a future work.

\[
S_a(x) = \begin{cases} 
S_1^a(x) = A_3x^3 + A_2x^2 + A_1x + A_0 , & x \in (x_{a0}, x_a) \\
S_2^a(x) = B_3x^3 + B_2x^2 + B_1x + B_0 , & x \in (x_a, x_p^a)
\end{cases} \quad (3.15a)
\]

\[
S_f(x) = \begin{cases} 
S_1^f(x) = C_3x^3 + C_2x^2 + C_1x + C_0 , & x \in (x_p^f, x_f) \\
S_2^f(x) = D_3x^3 + D_2x^2 + D_1x + D_0 , & x \in (x_f, x_{f0})
\end{cases} \quad (3.15b)
\]
In order to obtain the value of the 16 coefficients, it must be applied using the boundary conditions as explained in Eqs. (3.16) – (3.18) to solve the linear system of equations. The given conditions are categorized into three groups (Given points, spline and displacement conditions).

1. Given points conditions:

\[ S_1^a(x_{a0}) = \text{transom area} ; \quad S_2^f(x_{f0}) = \text{bow area} \]
\[ S_2^a(x_{a0}) = 1 ; \quad S_1^f(x_{f0}) = 1 \quad (3.16) \]
\[ S_1^a(x_{a}) = S_2^a(x_{a}) = S_1^f(x_{f}) = S_2^f(x_{f}) = S_2^a(x_{a}) = S_2^f(x_{a}) \]

2. Cubic spline conditions:

\[ S_1^\prime_a(x_{a0}) = \alpha_s ; \quad S_2^\prime_f(x_{f0}) = \alpha_e \]
\[ S_1^\prime_a(x_{a}) = S_2^\prime_f(x_{a}) ; \quad S_1^\prime_a(x_{a}) = S_1^\prime_a(x_{a}) \]
\[ S_1^\prime\prime_a(x_{a}) = S_2^\prime\prime_a(x_{a}) ; \quad S_1^\prime\prime_a(x_{a}) = S_1^\prime\prime_a(x_{a}) \]
\[ S_2^\prime_a(x_{a}) = 0 ; \quad S_2^\prime_f(x_{f}) = 0 \quad (3.17) \]

3. Displacement conditions:

\[ \int_{x_{a0}}^{x_{a}} S_1^a(x)dx + \int_{x_{a}}^{x_{f}} S_2^a(x)dx = \nabla - \nabla_p - \nabla_f \]
\[ \int_{x_{f}}^{x_{f}} S_1^f(x)dx + \int_{x_{f}}^{x_{a0}} S_2^f(x)dx = \nabla - \nabla_p - \nabla_a \quad (3.18) \]

The three parts of sectional area curves are now easily generated by Eq. (3.15) with making use of conditions as described in Eqs. (3.16) – (3.18). As a result of variation for the given parameters except displacement, the original sectional area curve and the modified curve are depicted in Fig. 3.18. Since the modified sectional area curve has the mathematical expression piece-wisely, the movement at any frame can be easily obtained by a certain numerical algorithms. Finally, new hull surface is formed by shifting the
Figure 3.18: Variation of the sectional area curve for shifting method

given original hull surface. In addition, it is available that either using an existing grid or
relocating control net for NURBS surface technique according to the amount of shift value
in the longitudinal direction. In particular, the presented shifting technique has shown a
fair surface from the applications to the container ships, tankers and surface combatant
ships. Details will be presented in Chapter 5.
Chapter 4: Flow Solver

In optimization for ship hull form design, the flow solver is one of the main three components as mentioned earlier. This flow solver provides the information of hull performance in terms of the drag ($R_W$, $R_T$) and others. In fact, the values of the hull performance are utilized for the objective function either directly or indirectly. Therefore, optimization operation is able to guide to search a better hull form by interacting with CFD computer code during the optimization cycles. Although there are many various flow solvers have been introduced in the literatures, two different flow solvers are utilized in this thesis. At first, a potential flow solver based on the slender-ship approximation[40] and Neumann-Michell theory[41] is employed as a simple flow solver. Yang & Nobless[42–45] introduced a practical design-oriented CFD tool (SSF) for the design of a monohull ship at early design stage. Even its less computational efforts, this flow code yields in a good agreement with the experimental data for the Wigley and the Series-60 ($C_b = 0.6$) hulls. In particular, the CPU time for evaluation of the flow about a ship hull which is represented by 10,000 triangular panels is less than 10 seconds per Froude number using a desktop PC. Therefore, this fast flow code allows the designers to obtain the basic idea of the optimal hull form with considering the specifications of a ship in a short duration especially for a primary design. In addition, it should be also noticed that the optimization algorithms which require a large number of objective function evaluations such as GO (Global Optimization) may take advantage of this simple flow solver.

Secondly, incompressible flow solver (FEFLO) based on finite element approximation is also utilized in order to i) provide high resolution of the flow field for the optimal hull form design which is obtained via the simple CFD code (SSF) ii) optimize the initial hull form so that the optimal hull forms obtained by two different flow solvers are able to be compared.
The advanced CFD computer code $FEFLO$ based on Euler/RANS equations and nonlinear free surface condition is used on the purpose of pursuing more realistic predictions of wave resistance as well as the flow on the given domain. This advanced code $FEFLO$ has been validated for various hull forms in a number of literature. Löhner et al. (1999)[25] presented the numerical experiments for a submerged $NACA0012$ foil section, the Wigley hull, the Series-60 hull, and a submerged DAROA submarine model, and the results showed quantitatively good agreement with experimental measurements. In addition, Yang and Löhner have been extend to consider the sinkage and trim effects in the calculation of steady ship wave[26]. In this paper, the result of the sinkage, the trim, wave profiles, and the wave drag for a wide range of Froude numbers are in an excellent agreement with experimental data for both the Wigley hull and the Series-60 hull forms.

4.1 Potential Flow Solver (SSF)

In this dissertation, free surface flows due to advancing ships in a condition of a steady flow at constant speed in calm water are considered. An integral equation for the velocity potential, $\nabla \phi$ is formulated using a Green function. This equation represents the velocity potential at a point within the flow domain in boundary-integral form.

A field point, $\tilde{x} = (\tilde{x}, \tilde{y}, \tilde{z})$ and a boundary point, $x = (x, y, z)$, in the nondimensional Cartesian coordinates are defined in terms of a length of the ship ($L$), i.e. $\tilde{x} = \tilde{X}/L$ and $x = X/L$. The velocity, $u$ is defined in terms of a reference velocity $U(= \sqrt{gL})$. The nondimensional velocity potential, $\tilde{\phi}$ or $\phi$, is then expressed in terms of $\tilde{\phi} = \tilde{\Phi}/(UL)$ or $UL$ as $\phi = \Phi/(UL)$. $\tilde{\phi}$ is the velocity potential at a flow-field point $\tilde{x}$, $\phi$ is the velocity potential at a boundary point $x$. The Green function used to formulate the boundary-integral representation is associated with a field-point/source-point pair and is designated $G(\tilde{x}, x)$. In the integral expressions that follow, the quantity $dA$ stands for a differential area element at a boundary point $x$ of the boundary surface $\Sigma$. A unit vector, normal $n$ to $\Sigma$, is pointing into the flow domain at $x$. The typical gradient operator $\nabla$ is understood to
have the usual meaning, i.e. $\nabla = (\partial x, \partial y, \partial z)$. Likewise, the operator $\tilde{\nabla}$ is taken to mean $\tilde{\nabla} = (\partial \tilde{x}, \partial \tilde{y}, \partial \tilde{z})$.

According to the potential theory, a potential $\phi$ that is a solution of the Laplace equation given by

$$\nabla^2 \phi = \phi_{xx} + \phi_{yy} + \phi_{zz} = 0 \quad (4.1a)$$

is considered within a finite three-dimensional flow region $\mathcal{D}$ which is bounded by a closed surface $\Sigma$. Given a function $G \equiv G(x; \tilde{x})$ that satisfies

$$\nabla^2 G = G_{xx} + G_{yy} + G_{zz} = \delta(x - \tilde{x})\delta(y - \tilde{y})\delta(z - \tilde{z}) \quad (4.1b)$$

in $\mathcal{D}$ or in a larger region containing $\mathcal{D}$, the divergence theorem can be applied to the function $\phi \nabla G - G \nabla \phi$ to yield the classical Green identity,

$$\int_{\mathcal{D}} dV \phi \nabla^2 G - G \nabla^2 \phi = \int_{\Sigma} dA (G\mathbf{n} \cdot \nabla \phi - \phi \mathbf{n} \cdot \nabla G) \quad (4.2)$$

The symbol $dV$ stands for a differential element of volume in the flow region $\mathcal{D}$ while the symbol $dA$ stands for a differential element of area on the boundary surface $\Gamma$, and $\mathbf{n}$ is a unit vector normal to $\Sigma$ pointing into the flow domain $\mathcal{D}$. The expression Eq.(4.2) defines the potential $\phi$ in terms of boundary distributions of sources with strength $\mathbf{n} \cdot \nabla \phi$ and the normal dipoles with strength $\phi$. Additionally, combining Eq.(4.2) with Eq.(4.1) yields in the Green’s classical boundary-integral representation given by,

$$\tilde{C}\phi = \int_{\Sigma} dA(G\mathbf{n} \cdot \nabla \phi - \phi \mathbf{n} \cdot \nabla G) \quad (4.3a)$$
An alternative representation to Green’s classical potential representation Eq.(4.2), introduced in Noblesse and Yang,(2004)[43], is

\[ \tilde{\phi} = \int_{\Sigma} dA \left[ G n \cdot \nabla \phi + G \cdot (n \times \nabla \phi) \right] \] (4.4)

where \( G \) stands for a vector Green function that is defined in terms of the usual Green function \( G(\tilde{x}; x) \) as follow,

\[ \nabla \times G = \nabla G \] (4.5)

This relation implies that \( G \) and \( G \) are comparable in the behaviors of both the nearfield and farfield. In particular, a vector Green function \( G \) is no more singular than \( G \) in the nearfield. Thus, the alternative potential representation Eq.(4.4) is weakly singular in comparison to the classical representation Eq.(4.3).

### 4.1.1 Simple free-surface Green function

A simple Green function given in Noblesse and Yang.(2004)[42] is defined as,

\[ 4\pi G(\tilde{x}; x) = R + W \] (4.6)

where \( R \) stands for a local-flow component defined in terms of three elementary free-surface Rankine sources, and \( W \) is a wave component given by a one- dimension Fourier superposition of elementary waves. The Rankine component \( R(\tilde{x}; x) \) in the Rankine-Fourier...
decomposition Eq.(4.6) is given by

\[ R = -\frac{1}{r} + \frac{1}{r_*} - \frac{2}{r_F} \]  \hspace{1cm} (4.7)

where \( r, r_*, r_F \) are defined as

\[
\begin{align*}
    r &= \sqrt{H^2 + Z^2} \\
    r_* &= \sqrt{H^2 + Z_*^2} \\
    r_F &= \sqrt{H^2 + Z_F^2}
\end{align*}
\]

\[
\begin{align*}
    H &= \sqrt{X^2 + Y^2} & X &= \tilde{x} - x \\
    Y &= \tilde{y} - y \\
    Z &= \tilde{z} - z+ & Z_* &= \tilde{z} + z+ \\
    Z_F &= Z_* - \sigma F^2 \text{ with } 1/2 < \sigma F \approx 1
\end{align*}
\]  \hspace{1cm} (4.8)

In Eqs.(4.7) – (4.8), the Rankine component \( R \) consists of three elementary free-surface Rankine sources. A unit source at the singular point \( \mathbf{x} = (x, y, z) \), a unit sink at the mirror image \( (x, y, -z) \) of \( \mathbf{x} \) with respect to the mean free-surface plane \( z = 0 \), and a double source with strength 2 at the point \( (x, y, -z - F^2) \).

The wave component \( W(\tilde{x}; \mathbf{x}) \) in Eq.(4.6) for the Green function \( G \) is given by

\[ W = \int_{-\beta_{\infty}}^{\beta_{\infty}} \frac{A\alpha}{k - k_*} e^{kZ_*} \Re e^{i(1 - \Theta)e^{-i(\alpha X + \beta Y)}} \]  \hspace{1cm} (4.9)

In Eq.(4.9), the finite limits of integration \( \pm \beta_{\infty} \) and the filter-function \( A \) eliminate unrealistic short waves affected by surface tension and viscosity, \( \Re \) means imaginary part, and

\[
\begin{align*}
    k_* &= 1/(2F^2) & \alpha &= \sqrt{k}/F & k &= k_* + \sqrt{k_*^2 + \beta} \\
    X &= \tilde{x} - x & Y &= \tilde{y} - y & Z_* &= \tilde{z} + z
\end{align*}
\]  \hspace{1cm} (4.10)

the function \( \Theta \) is given by

\[
\Theta = \pm \tanh \frac{\Phi + iV}{3\sigma \Theta} = \pm \frac{\sinh(\Phi/\sigma \Theta) + i \pm \sin(V/\sigma \Theta)}{\cosh(\Phi/\sigma \Theta) + \pm \cos(V/\sigma \Theta)} = \Theta_r + i\Theta_i \]  \hspace{1cm} (4.11a)

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with $\Phi$ and $V$ defined as

$$\Phi = \alpha X + \beta Y \quad - \sigma^{\Theta} C^V = k Z,$$

(4.11b)

where $C^V < \pi$.

The simple Green function defined by Eqs.(4.6) – (4.11) satisfies the Laplace equation and the radiation condition. The free-surface boundary condition is also satisfied. Since the Green function only involves elementary functions of real arguments as shown in Eqs.(4.6) – (4.11), the defined Green function is appreciably simpler than the alternative free-surface Green functions given in the literature. Yang et al.(2004)[45] show that the classical and simple Green functions are identical in the farfield and that a relatively small difference in the nearfield.

### 4.1.2 Neumann-Michell linear flow model

As mentioned earlier, nondimensional coordinates $x \equiv (x, y, z) \equiv X/L$ are defined in terms of a reference length $L$, typically taken as the ship length. The $z$ axis is vertical and points upward, and the mean free surface is taken as the plane $z = 0$. The $x$ axis is chosen along the path of the ship and points toward the ship bow. The Froude number $F_N$ is defined as

$$F_N \equiv U / \sqrt{g L}$$

(4.12)

with $U \equiv$ ship speed and $g \equiv$ gravitational acceleration.

The flow about the ship is observed from a frame of reference attached to the advancing ship. The flow observed in this moving system of coordinates is steady (independent of time) and given by the sum of a uniform current that opposes the ship speed $U$ and the flow $(V^x, V^y, V^z) \equiv U (v^x, v^y, v^z)$ due to the ship. Thus, the total flow velocity (uniform stream + disturbance flow due to the ship) is given by $U (v^x - 1, v^y, v^z)$. 

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The water pressure is given by the Bernoulli relation

\[
\frac{P}{\rho} + gZ + \frac{(V_X - U)^2 + (V_Y)^2 + (V_Z)^2}{2} = \frac{P_a}{\rho} + \frac{U^2}{2}
\]

Here, \( \rho \) is the water density, \( P_a \) is the atmospheric pressure at the free surface, and the left side becomes equal to the right side far ahead of the ship. The water pressure is then given by

\[
(P - P_a)/\rho = U^2p^* - gLz
\] (4.13)

with

\[
p^* \equiv v^x - \left[ (v^x)^2 + (v^y)^2 + (v^z)^2 \right]/2.
\] (4.14)

The components \( U^2p^* \) and \( -gLz \) in (4.13) correspond to hydrodynamic and hydrostatic pressures. The water pressure at the wetted ship hull \( H_{wet} \) is given by \(-P\mathbf{n}_\mathbf{n}\), where \( P \) is given by (4.13) and \( \mathbf{n} = (n_x, n_y, n_z) \) stands for a unit vector that is normal to the ship hull and points into the water.

The Neumann-Michell linear flow model expresses the nondimensional flow velocity \( \tilde{v} \) at a flow-field point \( \tilde{x} \) as

\[
\tilde{v} = \hat{\nabla} \int_{H} da \left[ n^x G + (\mathbf{n} \times \mathbf{v}) \cdot \mathbf{G} \right]
\] (4.15)

where \( \hat{\nabla} \equiv (\partial/\partial x, \partial/\partial y, \partial/\partial z) \), \( da \equiv da(\mathbf{x}) \), \( \mathbf{n} \equiv \mathbf{n}(\mathbf{x}) \), \( \mathbf{v} \equiv \mathbf{v}(\mathbf{x}) \), \( G \equiv G(\tilde{x}; \mathbf{x}) \), and \( \mathbf{x} \) is a point of the mean wetted ship hull \( H \). Furthermore, \( \mathbf{G} \equiv \mathbf{G}(\tilde{x}; \mathbf{x}) \) is a vector Green function that is defined in terms of the usual (scalar) Green function \( G(\tilde{x}; \mathbf{x}) \) via the relation

\[
\mathbf{G} = (0, G_x^x, -G_y^x)
\]

where a subscript means differentiation as usual and a superscript means integration. The Green function \( G \) in (4.15) is assumed to satisfy the linearized Michell free-surface boundary
condition, although the simplified free-surface Green function given in Yang et al. (2004) [45] is used here. The NM flow representation (4.15) only involves distributions of singularities over the mean wetted ship hull surface \( H \). Thus, this linear flow model does not involve a line integral around the mean ship waterline, unlike the Neumann-Kelvin linear flow model.

An iterative solution procedure based on the straightforward recurrence relation

\[
\tilde{v}_{j+1} = \tilde{\nabla} \int_{H} da \left[ n^x G + (n \times v_j) \cdot G \right] \quad (4.16a)
\]

with \( 0 \leq j \) and \( v_0 \equiv 0 \) is used. The first approximation

\[
\tilde{v}_1 = \int_{H} da \, n^x \tilde{\nabla} G \quad (4.16b)
\]

in this iterative scheme is the solution corresponding to the slender-ship approximation. Thus, the solution procedure (4.16) defines a sequence of approximations that may be regarded as a series of slender-ship approximations.

The wave drag coefficient \( C^W \) can be evaluated via integration of the dynamic pressure \( p^* \) over the ship hull. An alternative to this nearfield pressure-integration method is the farfield method, in which \( C^W \) is determined from the energy radiated by the farfield waves via the classical relation

\[
C^W = \frac{k_s}{2\pi} \int_{-\beta_{\infty}}^{\beta_{\infty}} d\beta \frac{A k}{k - k_s} \left[ (S^W_r)^2 + (S^W_i)^2 \right]. \quad (4.17a)
\]

Here, the finite limits of integration \( \pm \beta_{\infty} \) and the filter-function \( A(\beta) \) eliminate unrealistic short waves affected by surface tension and viscosity, and \( k \) and \( k_s \) are defined as

\[
k = k_s + \sqrt{k_s^2 + \beta^2} \quad k_s = 1/(2F^2) \quad (4.17b)
\]
with $F$ given by (4.12). The real and imaginary parts $S_W^r$ and $S_W^i$ of the farfield wave-
spectrum function $S_W^W(\beta)$ are given by

$$\begin{align*}
\begin{cases}
S_W^r = \\
S_W^i = 
\end{cases}
\int_H da 
\left( e^{kz} \left( (n^x + A^r) C - A^i S \right) \right)
\left( (n^x + A^r) S + A^i C \right).
\end{align*}$$

(4.17c)

Here, $H$ stands for the mean wetted ship hull, $da$ is the differential element of area of the
surface $H$, and $n = (n^x, n^y, n^z)$ is a unit vector that is normal to $H$ and points outside the
ship, as already noted. The real and imaginary parts $A^r$ and $A^i$ of the amplitude function $A$
in (4.17c) are defined as

$$\begin{align*}
\begin{cases}
A^r = & (n^y v^x - n^x v^y) \beta/\alpha \\
A^i = & (n^x v^z - n^z v^x) k/\alpha
\end{cases}
\quad \text{with} \quad \alpha = \frac{\sqrt{k}}{F}.
\end{align*}$$

(4.17d)

Here, $(v^x, v^y, v^z)$ are the components of the nondimensional flow velocity $\mathbf{v} = \mathbf{V}/U$ due to
the ship. Finally, the functions $C$ and $S$ in (4.17c) are defined as

$$\begin{align*}
\begin{cases}
C = & \cos(\alpha x + \beta y) \\
S = & \sin(\alpha x + \beta y)
\end{cases}
\quad \text{with} \quad \alpha = \frac{\sqrt{k}}{F}.
\end{align*}$$

(4.17e)

and $k$ given by (4.17b). The wavenumber $k$ in (4.17a) and (4.17c)–(4.17e) are defined, via
(4.17b), in terms of the Fourier integration variable $\beta$ in the Havelock wave-drag formula
(4.17a).

A related series of slender-ship approximations to the wave drag can readily be defined
by taking the velocity $\mathbf{v}$ in the amplitude function (4.17d) as $\mathbf{v}_j$. In particular, the zeroth-
order slender-ship approximation to the farfield wave-spectrum function $S_W^W(\beta)$ corresponds
to \( \mathbf{v}_0 \equiv 0 \), and thus is given by

\[
\begin{pmatrix}
S_r^W \\
S_i^W
\end{pmatrix} = \int_H da e^{kz} n^x \begin{pmatrix} C \\ S \end{pmatrix}.
\]

Expressions (4.17a), (4.17b), (4.17e) and (4.18) provide a particularly simple approximation to the wave drag of a ship.

It is noted that the wave drag coefficient \( C^W \) in Eq.(4.17a) is defined as

\[
C^W = \frac{R_W}{\rho U^2 L^2}
\]

where \( R_W \) is wave drag, \( \rho \) is the density of water, and \( L \) is the reference length.

The total drag coefficient is defined as:

\[
C_T = \frac{R_T}{\frac{1}{2} \rho U^2 S} = C^W + C_F
\]

where \( S \) is wetted surface area, \( R_T \) the total drag, \( C^W \) the wave drag coefficient non-dimensionalized using a conventional way as:

\[
C^W = \frac{R_W}{\frac{1}{2} \rho U^2 S}
\]

and \( C_F \) frictional drag coefficient evaluated using ITTC 1957 Model-Ship Correlation Line as follows:

\[
C_F = \frac{R_F}{\frac{1}{2} \rho U^2 S} = 0.0075 \frac{0.0075}{[\log_{10}(R_e) - 2]^2}
\]

where \( R_F \) is friction drag, and \( R_e \) is Reynolds number. For the purpose of validation, the
computer code based on the NM theory and ITTC 1957 Model-Ship Correlation Line is used to evaluate the wave drag and total drag for the Wigley hull and the series 60 $C_b = 0.6$ ship model, respectively, for the hulls held fixed (no sinkage or trim allowed). Fig. 4.1.2 shows the comparisons of experimental measurements and theoretical predictions of the wave drag coefficient and total drag coefficient, where the wave drag coefficient is obtained using both the farfield (Havelock) approach and the nearfield (pressure-integration) approach. The experimental data were obtained at University of Tokyo (UT1, UT2, UT3, UT4) and Akishima Laboratories (AL1, AL2, AL3).
4.2 Incompressible Flow Solver (FEFLO)

The advanced CFD code **FEFLO** has been developed a parallel free-surface flow solver based on unstructured grid for steady ship wave resistance problem. The problem is formulated in terms of the Euler or Reynolds-average Navier Stokes (RANS) equation and then extended to incorporate the dynamic sinkage and trim to the steady wave calculation. The overall scheme combines a finite element, projection type three-dimensional incompressible flow solver with a finite element, two-dimensional advection equation solver for the free-surface equation. An unstructured grid is used in order to provide an enhancement for the flexibility of geometry. An grid generator based on the advancing front method is used to generate both triangular surface grids and tetrahedral volume grids. In particular, an automatic remeshing for simulating fully nonlinear waves are linked to the flow solver.

4.2.1 Incompressible Euler Equations

A nondimensional coordinates \( \mathbf{x} \equiv (x, y, z) \equiv \mathbf{X}/L \) are defined in terms of a ship length \( L \). The \( z \) axis is vertical and points upward, and initially free-surface is embedded at plane \( z = 0 \). A positive \( x \) axis points toward the down stream in the flow domain as well as the running-part in the ship hull. The incompressible Euler equations are employed as the governing equations for a flow domain as follows,

\[
\nabla \cdot \mathbf{v} = 0 \quad (4.23a)
\]

\[
\mathbf{v}_t + \mathbf{v} \cdot \nabla \mathbf{v} + \nabla \Psi = 0 \quad (4.23b)
\]

where \( \mathbf{v} = (u, v, w) \) as the velocity vector and \( \Psi \), which implies the pressure on the free-surface will be same with the atmospheric pressure, defined as

\[
\Psi = p + \frac{z}{F_N^2}, \quad F_N = \frac{|\mathbf{v}_\infty|}{\sqrt{g \cdot L}}. \quad (4.24)
\]
In particular on the free-surface, a kinematic boundary condition, which implies that a particle initially on the boundary will remain on the boundary, is applied using the following advection equation in terms of the free surface height $\beta$,

$$\beta_t + u\beta_x + v\beta_y - w = 0 \quad \text{for} \quad z = \beta(x, y; t). \quad (4.25)$$

Several boundary conditions are applied on the flow domain. At first, the uniform stream ($\mathbf{u} = (1, 0, 0)$) is given at inflow plane with the prescribed pressure ($\Psi = 0$) and the free surface elevation ($\beta = 0$). However, the natural Neumann conditions for the pressure is applied and the velocities and elevations are extrapolated at outflow plane instead of the prescribed quantities. For free-surface, the pressure $p$ is prescribed to be $p = 0$ in order to consider the dynamic boundary conditions. Two different ways to take into account of the bottom boundary condition are considered. One is wall boundary condition by vanishing normal velocity. And the other is infinite boundary condition by making use of the prescribed pressure while no special consideration is required for the velocities. At last, general wall boundary conditions are imposed on the ship hull as well as side plane.

4.2.2 Numerical Implementation

The governing equations (i.e., the incompressible Euler equations) in Eq.(4.23) are a system of equations which are solved in iteration-manner. The unknowns in the equations are velocity and pressure. However, there is no direct link for the pressure between two equations. In other words, the Eq.(4.23a) dose not involve the pressure. Therefore, it is necessary to introduce the linkage between the continuity and momentum equations by the Poisson equation for the pressure as shown in Eq.(4.27c). Three operations are performed in each timestep. At first, the Dilatation term ($\nabla \cdot \mathbf{u}$) will not be set to zero by introducing the Adveotive prediction operation as shown in Eq.(4.26), then the pressure will be corrected by making use of the pressure Poisson equation in Eq.(4.27c) in Pressure correction step. Finally, the velocity is updated by the corrected pressure in the last operation. The details
of the operations are as follows,

(a) *Advection prediction*: $\nu^n \rightarrow \nu^*$

\[
\frac{\nu^* - \nu^n}{\Delta t} + \nu^n \cdot \nabla \nu^n + \nabla \Psi^n = 0 \quad (4.26)
\]

(b) *Pressure correction*: $\Psi^n \rightarrow \Psi^{n+1}$

\[
\nabla \cdot \nu^{n+1} = 0 \quad (4.27a)
\]

\[
\frac{\nu^{n+1} - \nu^*}{\Delta t} + \nabla (\Psi^{n+1} - \Psi^{n+1}) = 0 \quad (4.27b)
\]

which results in

\[
\nabla^2 (\Psi^{n+1} - \Psi^{n+1}) = \frac{\nabla \cdot \nu^*}{\Delta t} \quad (4.27c)
\]

(c) *Velocity correction*: $\nu^* \rightarrow \nu^{n+1}$

\[
\nu^{n+1} = \nu^* - \Delta t + \nabla (\Psi^{n+1} - \Psi^{n+1}) \quad (4.28)
\]

Overall, one complete timestep consists of the following steps,

- *Given the boundary conditions for the pressure* $\Psi$, update the unknowns in the 3-D fluid domain.
- *Extract the velocity* $\nu$ at free-surface and plug it into 2-D free-surface module.
- *Given the velocity*, update the free-surface elevation $\beta$.
- *Update the new free-surface height* to the 3-D domain, and impose new boundary conditions for the pressure $\Psi$.

In addition, the local time step is used with the consideration of faster convergence to the final solution.

Yang and Löhner has been validated for various hull forms in the reference [25, 26] as shown in Fig. 4.2. A comparison of the computed wave drag coefficient with experimental
Figure 4.2: Comparison of Wave Drag Coefficient at Fixed-condition (top) and Free-
condition (bottom) for (a) the Wigley Hull and (b) the Series-60($C_b = 0.6$) Ship Model
(Yang and Lohner(2002))

measurements for the Wigley hull and the Series-60 hull forms, respectively. The results
are in fair agreement with the experimental data in the condition of both fixed (top) and
free (bottom), respectively. Therefore, FEFLO may be utilized as an advanced flow solver
for the optimization application to the ship hull form and as an high-fidelity flow solver
compared to the simple flow computer code SSF.
In this chapter, several practical applications are demonstrated using various hull forms.

At first, the classic Wigley hull is adapted as the initial hull form in this dissertation. Since the geometry is simple wedged shape which can be expressed in mathematical formula, both NURBS surface and the parametric hull representation approaches are easily applied to the Wigley hull. Secondly, the present optimization technique is applied to the Korean Research Institute for Ships and Ocean Engineering (KRISO) container ship (KCS) as a case of modern container ships. The KCS hull form was selected in the Gothenburg 2000 workshop for a modern slender ship case as a replacement for the Series 60 \( (C_b = 0.6) \) model in the earlier workshop for the first time. Fig. 5.42 and Table 5.13 presents an overview of the KCS hull form and main particulars, respectively. The ship length between perpendiculars \( (L_{pp}) \) is 230m and 7.2786m for full and model scales, respectively. The model draft \( (T) \) is 0.3418m and the model wetted surface area \( (S_{wet}) \) is 9.4379m\(^2\) and the block coefficient \( (C_b) \) is 0.65. It may helpful to consider some important features of a geometry of the KCS. At first, a long bulbous bow toward upstream is enough to keep drawing interests from the shape optimization community of marine vehicles. The other notable feature of the KCS is that existence of an extended stern overhang, which is conditionally wet transom. This type of stern is commonly seen in recent container ship designs, and it produces complex flow in the stern and wake wave fields. Even though the static waterline shape is normal, at design speed, it results in a conditionally wet transom. Several works for the KCS hull have been presented in the literature in terms of not only the optimization but also the CFD flow solvers[15, 16, 23, 46]. The most controversial topic in the KCS shape optimization at present is the stern optimization for wake field in the extension of self-propulsion. Another application of the present technique is the surface combatant ship, David Taylor Model Basin Model-5415, which was selected in the Gothenburg 2000 workshop for a representative of
modern navy ship. The length between perpendiculars \((Lpp)\) is 142\(m\) and 5.719\(m\) for full and model scales, respectively. The model draft \((T)\) is 0.2488\(m\) and the model wetted surface area \((S_{wet})\) is 4.861\(m^2\) and the block coefficient \((C_b)\) is 0.506. Since an existence of a sonar dome in the bow area and transom, DTMB Model-5415 has been treated as a typical instance of a highly complicated hull form to optimize. Also, the experimental data are available. Thus, the comparison between experimental measurements and numerical approximations, both a simple flow code\((SSF)\) and an advanced CFD flow solver\((FEFLO)\) are utilized to provide the performance of the hull form during optimization process is shown in this chapter. The last numerical example in this dissertation is the application of the presented optimization module to the well-known classical hull, the Series-60 Hull \((C_b = 0.6)\). This hull has a relatively simple geometry: no bulbous bow but stern exists with plain geometry. The full scale is used. Markov and Suzuki. [21] presented the minimize the wave drag coefficient \((C_W)\) by making use of the Davidson-Fletcher-Powell (CFP) optimization procedure by shift and deformation of ship sections.

5.1 The Wigley hull

For the first application, the present study considers a simple hydrodynamic-optimization problem: minimization of the total drag of a monohull ship while applying the displacement constraints. The classical Wigley hull is taken as an initial hull and the present hydrodynamic optimization tool is used to obtain the optimal hull forms for three single design speeds and for a given speed range with volume constraint.

The classical Wigley hull is taken as an initial hull. Only half of the hull surface is considered hereafter due to the symmetric property. The non-dimensionalized Wigley hull surface is given by the following expression:

\[
y = 0.5B \left[ 1 - 4x^2 \right] \left[ 1 - \left( \frac{z}{D} \right)^2 \right]
\]  
(5.1)
where $B$ and $D$ are the beam and the draft of the ship, respectively, and are taken as $B = 0.1$ and $D = 0.0625$ in this study.

In this application, NURBS is employed to represent and modify the initial surface. Fig. 5.1 shows NURBS control points and net in the left and NURBS surface in the right for both the initial Wigley hull surface and an intermediate surface during optimization cycle. It is also shown that the variation of the control points generates deformation of Wigley surface.

The expression Eq. (5.1) can be used to generate a set of initial points that are used as the control points of the NURBS. Part of these control points are used as design variables. In order to account for the large curvature at the bow and the stern and also allow the large deformation in these regions during the optimization process, points are distributed using cosine spacing along the longitudinal direction and even spacing along the depth. The initial Wigley hull is represented by 15 section lines and each section line by 6 points, which results in 90 control points in total. Part of these 90 control points are used as design variables. Fig. 5.1 shows that the distribution of the initial control points used to define the Wigley hull (top row of Fig. 5.1) and the distribution of intermediate control points used in one of the intermediate design cycle to define a new hull surface (bottom row of Fig. 5.1).

It can be observed from Fig. 5.1 that the control points in both the bow and the stern area are much closer to its neighbors compared with those in the mid sections as what it is expected.

Fig. 5.2 depicts initial control points for the Wigley hull in the profile view as well as design variables. The control points, except ones plotted in solid square in Fig. 5.2, are used as design variables that can have 1 to 3 degrees of freedom (DOF) movement. As shown in Fig. 5.2, 31 out of 90 control points can have various degrees of freedom movement. Specifically, 12 points can have 1-DOF movement, 16 points can have 2-DOF movement, and 3 points can have 3-DOF movement, which implies that a total of 53 design variables are considered in the optimization.
The type of the movement for the points on the waterline is also shown in Fig. 5.3. There are 15 control points on the waterline, and 11 of them are fixed. The remaining 4 points have either 1-DOF or 2-DOF movement.

Although points are allowed to move along particular direction(s), an allowable movement is bounded by a maximum or a minimum value to avoid the generation of the unreasonable hull surface (e.g., twisted NURBS surface, etc).

It should be noted that there are two possible ways to generate panels on the surface required by the CFD tool. One is to generate triangular panels for each new hull form obtained during the optimization process. The other is to deform the existing panels to obtain a new hull surface. Since a large number of iterations are needed before the minimum objective function is found. The objective function needs to be evaluated several-thousand times during optimization process, which means the panels need to be generated for several-thousand new hull forms. Therefore, it is necessary that additional computational cost to generate a new hull form. In stead of regenerate panels every time, one can also generate new hull form by deforming the existing panels. However, the panels might be too deformed,
which provides less accurate of the flow solution as a result. In the present dissertation, the high-resolution NURBS surface, generated from each perturbation of the design variables, is divide into approximately 50,000 roughly uniform triangular panels. These triangular panels are then used to define the hull surface in a discrete manner in an in-house preprocess software, and a new computational grids (approximately 8,000 triangular panels) required by the CFD tool are then generated automatically.
5.1.1 Optimization for the minimum total drag coefficient ($C_T$) at model-scale

There are several choices to obtain the optimal hull form in terms of objective function. This implies that the optimum solution truly depends on a selection of the objective function. For example, if the objective function consists only with the wave drag coefficient ($C_W$), the optimal hull form has the minimum wave drag coefficient. However, this optimum solution possibly yields in an increase in terms of wave drag ($R_W$) or total drag ($R_T$) when the wetted surface area is increased even though the decrease of the wave drag coefficient ($C_W$) as it is expected. Therefore, it is highly recommended that the consideration for the wetted surface area constraint need to be made up as well as volume constraints. However, the total drag coefficient at model-scale is considered as the objective function in the first application of the present application. It is the reason to choose $C_T$ that to check whether the proposed NURBS-surface is suitable such a large deformation or not.

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A brief summary of the present application is given in Table 5.1. As mentioned, the proposed optimization technique is applied to obtain the optimal hull form which has a minimum total drag coefficient ($C_T$) in this section. Therefore, the optimal hull form is
determined by minimizing the objective function \( f \) defined as follow.

\[
f(\vec{\beta}) = W_1 \cdot \left( \frac{\nabla_i - \nabla_0}{\nabla_0} \right)^2 + \sum_{j=1}^{n} \cdot \left( W_2 \frac{C_j^T_i}{C_j^T_0} \right)
\]

(5.2)

here \( \vec{\beta} \) denotes design variables, \( \nabla_0 \) and \( C_{T_0} \) initial displacement and total drag coefficient, respectively, \( \nabla_i \) and \( C_{T_i} \) new displacement and total drag coefficient, respectively, and \( W_1 \) and \( W_2 \) weights for each term. It is clear from Eq. (5.2) that any change of displacement \( (\nabla_i) \) results in an increase of the objective function. Therefore, volume constraint condition can be considered by including the second term into objective function. In addition, it would be better if wetted surface area considered as a constraint condition so that the actual drag force(\( R_T \) or \( R_W \)) also can be considered. Because the growth of wetted area yields to increase of drag force according to the definition of the coefficient ( \( C = \frac{R}{0.6 \rho SV^2} \)).

The gradient-based optimization technique is adapted in this application to minimize the objective function defined by Eq. (5.2). The required gradients \( f_{\vec{\beta}} \) are evaluated via a central finite difference scheme. By selecting weights \( W_1 \) and \( W_2 \) properly, the minimization of the objective function \( f(\vec{\beta}) \) can yield an optimal hull form that has a minimum total drag and with very little change of the displacement.

The following 4 cases (named as Case – I, Case – II, Case – III, and Case – IV) are now considered using the hydrodynamic optimization tool described above. The hull is optimized for a single design speed in the first three cases that correspond to \( F_N = 0.25, 0.316, 0.408 \), respectively. In the Case – IV, the hull is optimized for a given speed range that corresponds to the minimization of the sum of the total drag coefficients evaluated at \( F_N = 0.25, 0.316, 0.408 \), respectively.

The convergence history for the displacement, wave drag coefficient, and total drag coefficient are plotted in Fig. 5.4 for Case – I, Case – II, Case – III and Case – IV, respectively. As it is also shown in Fig. 5.4 that the number of iterations to reach the convergence are 10, 14, 15 and 15 for Case – I, Case – II, Case – III and Case – IV,
Figure 5.4: Convergence history of the displacement, wetted surface area, wave drag coefficient\((C_W)\) and total drag coefficient\((C_T)\) for Case – I to Case – IV.
respectively, and the changes of the displacement in all cases are less than 1%. It should be noted that the changes of the wetted surface area are less than 1% for the first three cases, and about 4% for the Case – IV. The reduction of the wave drag coefficient ($C_W$) and the total drag coefficient ($C_T$) are listed in the Table 5.2.

Table 5.2: Reduction of drag coefficient (Initial Hull=100%)

<table>
<thead>
<tr>
<th>$F_N$</th>
<th>Case – I</th>
<th>Case – II</th>
<th>Case – III</th>
<th>Case – IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.250</td>
<td>42.16</td>
<td>-</td>
<td>-</td>
<td>69.36</td>
</tr>
<tr>
<td>0.316</td>
<td>-</td>
<td>49.88</td>
<td>-</td>
<td>55.02</td>
</tr>
<tr>
<td>0.408</td>
<td>-</td>
<td>-</td>
<td>64.79</td>
<td>82.95</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$C_T$(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_N$</td>
</tr>
<tr>
<td>0.250</td>
</tr>
<tr>
<td>0.316</td>
</tr>
<tr>
<td>0.408</td>
</tr>
</tbody>
</table>

The four optimal hull forms obtained from Case – I to Case – IV are used for the evaluation of the wave drag and total drag for a speed range that corresponds to $F_N = 0.2 – 0.42$. Fig. 5.5 shows the wave drag coefficient curves for the original hull form and four optimal hull forms, and Fig. 5.14 shows the total drag coefficient curves for the original hull form and four optimal hull forms.

It can be clearly seen from Table 5.2 and Figs. 5.5 – 5.6 that the optimal hull forms determined for single design speed (Case – I, Case – II, and Case – III) result in a large drag reduction within a narrow range including its design speed while a large drag increase in the other speeds in comparison with the original hull form. On the other hand, the optimal hull form determined for a given design speed range (Case – IV) results in a consistent drag reduction in the whole speed range in comparison with the original hull. However, it should be noted that the single design speed optimization usually results in a larger drag reduction at its design speed than the given speed range optimization. It
should also be noted that the hull form determined in Case – IV actually have a larger drag reduction at $F_N = 0.316$ than the hull form obtained in Case – II even though the hull form is optimized for a single design speed $F_N = 0.316$ in Case – II. This interesting fact is due to the drawback of the gradient-based optimization technique that can only predicts a local minimum or maximum value in the optimization process. In addition, it also should be noticed that an increase of wetted surface area could provide an additional increase in terms of forces (e.g. Wave Drag Force($R_W$) and Total Drag Force($R_T$)). However, it is ruled out here according to the aim of this application that confirm the capability of the NURBS surface representation.

The body plan, profile plan and waterline plan of four optimal hull forms obtained in Case – I to Case – IV are plotted in Fig. 5.7 to Fig. 5.10, respectively. The hull form is not allowed to change after the midship section in the optimization process. Therefore, the change of the hull lines can be clearly observed by comparing the left half and the right half of the lines in each figure since the original Wigley hull form is symmetric about the midship section. Figs. 5.7 – 5.9 show that in the single design speed optimization case a
Figure 5.6: Total drag coefficient ($C_T$) for the initial Wigley hull form and 4 optimal hull forms determined from Case – I to Case – IV

bulbous bow is generated and it becomes larger and larger with the increase of the ship speed. These three optimal hull forms have similar characteristics. On the other hand, the hull form obtained in Case – IV is quite different from these obtained in Case – I – Case – III. A very different bulbous bow and forward perpendicular are generated in the Case – IV. This also explains why the hull form optimized with a speed range can have a consistent drag reduction in the whole speed range.

Fig. 5.11 shows the 3-D view of the optimal hull surfaces and the pressure contours evaluated at three given Froude numbers. Specifically, the left column of the Fig. 5.11 shows the hull form determined from the single design speed optimization and the pressure contours evaluated at their corresponding design speed ($F_N = 0.25, 0.316, 0.408$). The right column of Fig. 5.11 shows the hull form determined from the given speed range optimization and the pressure contours evaluated at three given speeds ($F_N = 0.25, 0.316, 0.408$), respectively. It should be noted that the ship bow in Fig. 5.11 is plotted on the left hand side of the figure for a better view of the bow and the front part of the hull. The change of the optimal hull forms with respect to the optimization criteria can be clearly observed.
Figure 5.7: Body plan, profile plan and waterline plan of the optimal hull form obtained in Case – I

Figure 5.8: Body plan, profile plan and waterline plan of the optimal hull form obtained in Case – II
Figure 5.9: Body plan, profile plan and waterline plan of the optimal hull form obtained in Case – III

Figure 5.10: Body plan, profile plan and waterline plan of the optimal hull form obtained in Case – IV
from Fig. 5.11.

Case – I  

$F_N = 0.25$

Case – II  

$F_N = 0.316$

Case – III  

$F_N = 0.408$

Figure 5.11: Pressure contours evaluated for 4 Optimal hull forms determined from Case – I to Case – IV
5.1.2 Optimization for minimum total resistance \((R_T)\) at model-scale

It is emphasized that the optimal hull form does depend on the choice of objective function. It was also noticed from previous application that the consideration for a variation of the wetted surface area needs to be made. Therefore, the use of a drag force \((R_T\) or \(R_W\)) are considered as an objective function instead of scalarization, a single objective function consists with a several objectives terms. This implies that the new objective function \(f(\vec{\beta})\) is easily obtained by replacing \(C_T\) with \(R_T\) in Eq. (5.2). As a result, the optimal hull form is determined by minimizing the objective function \(f\) defined as follow:

\[
f(\vec{\beta}) = W_1 \cdot \left( \frac{\nabla_i - \nabla_0}{\nabla_0} \right)^2 + \sum_{j=1}^{n} \cdot \left( W_j^2 \frac{R_T^j}{R_T^0} \right)
\]

,where \(\nabla\) is displacement of hull and subscript 0 and \(i\) represent the initial and the \(i\)th iteration during the whole optimization procedure.

As mentioned from the previous application, any variation of volume during the optimization cycle may result in an increase of objective function value from the first term in Eq. (5.3). This represent that volume constraint condition is applied straightforwardly in this application. Again, the model-scale Wigley hull \((L = 3m)\) is employed as an initial hull form to obtain the optimum hull form which yields in minimum total resistance.

A brief summary of the present application is given in Table 5.3. In order to compare the different effect of the objective function the same gradient-based optimization algorithm and the design variables are adapted to minimize the objective function defined by Eq. (5.3). The required gradients \(f_{\vec{\beta}}\) are evaluated via a central finite difference scheme. Also, the 4 cases (named as \(Case-I, Case-II, Case-III, and Case-IV\)) are considered. The hull is optimized for a single design speed in the first three cases that correspond to \(F_N = 0.25, 0.316, 0.408\), respectively. In the \(Case-IV\), the hull is optimized for a given speed range that corresponds to the minimization of the sum of the total resistances evaluated at \(F_N = 0.25, 0.316, 0.408\), respectively.

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Table 5.3: Definition of $R_T$ optimization for the Wigley hull

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>The Wigley Hull</td>
<td>Eq. (5.1) &amp; Model-Scale($L = 3m$)</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$R_T$</td>
<td>Eq. (5.3)</td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume</td>
<td>Scalarization</td>
</tr>
<tr>
<td>Design Variables</td>
<td>NURBS</td>
<td>53 variables</td>
</tr>
<tr>
<td></td>
<td>Control-Points</td>
<td>1-DOF : 12, 2-DOF : 16, 3-DOF : 3</td>
</tr>
<tr>
<td>Surface Representation</td>
<td>NURBS Surface</td>
<td>90 NURBS Control-Points</td>
</tr>
<tr>
<td>Optimization Algorithm</td>
<td>Gradient</td>
<td>Central Difference(2−Order)</td>
</tr>
<tr>
<td>Gridgeneration</td>
<td>FRGEN3D</td>
<td>Each step</td>
</tr>
<tr>
<td>Flow Solver</td>
<td>SSF</td>
<td>Neumann-Michell linear flow model</td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Fore Body</td>
<td>Linear free-surface</td>
</tr>
<tr>
<td>Design Speed</td>
<td>3</td>
<td>$F_N = 0.25, 0.316, 0.408$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 Single-Speed ($\text{Case} – I – III$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Multi-Speed ($\text{Case} – IV$)</td>
</tr>
</tbody>
</table>

The convergence history for the displacement, the wetted surface area, wave resistance, and total resistance are plotted in Fig. 5.12 for $\text{Case} – I$, $\text{Case} – II$, $\text{Case} – III$ and $\text{Case} – IV$, respectively. As it is also shown from Fig. 5.12 that the number of iterations needed to reach the convergence are 32, 42, 23 and 29 for $\text{Case} – I$, $\text{Case} – II$, $\text{Case} – III$ and $\text{Case} – IV$, respectively, and the changes of the displacement in all cases are less than $0.5\%$. The reduction of the wave resistance ($R_W$) and the total resistance ($R_T$) are listed in the Table 5.4.

The four optimal hull forms obtained from $\text{Case} – I$ to $\text{Case} – IV$ are used for the evaluation of the wave drag and total drag for a speed range that corresponds to $F_N = 0.2 – 0.42$. Fig. 5.13 shows the wave resistance curves for the original hull form and four optimal hull forms, and Fig. 5.14 shows the total resistance curves for the original hull form and four optimal hull forms.

As shown in the previous application, it can be clearly seen from Table 5.4 and Figs. 5.13 – 5.14 that the optimal hull forms determined for single design speed ($\text{Case} – I$, $\text{Case} – II$, and $\text{Case} – III$) result in a large drag reduction within a narrow range including its design speed while a large drag increase in the other speeds in comparison with the original hull.
Figure 5.12: Convergence history of the displacement, wetted surface area, wave resistance and total resistance for Case − I to Case − IV
Table 5.4: Reduction of drag resistance

\[ R_W(\%) \]

<table>
<thead>
<tr>
<th>( F_N )</th>
<th>Case - I</th>
<th>Case - II</th>
<th>Case - III</th>
<th>Case - IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.250</td>
<td>41.08</td>
<td>-</td>
<td>-</td>
<td>64.18</td>
</tr>
<tr>
<td>0.316</td>
<td>-</td>
<td>47.24</td>
<td>-</td>
<td>41.62</td>
</tr>
<tr>
<td>0.408</td>
<td>-</td>
<td>-</td>
<td>48.87</td>
<td>67.74</td>
</tr>
</tbody>
</table>

\[ R_T(\%) \]

<table>
<thead>
<tr>
<th>( F_N )</th>
<th>Case - I</th>
<th>Case - II</th>
<th>Case - III</th>
<th>Case - IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.250</td>
<td>85.44</td>
<td>-</td>
<td>-</td>
<td>90.01</td>
</tr>
<tr>
<td>0.316</td>
<td>-</td>
<td>82.40</td>
<td>-</td>
<td>80.53</td>
</tr>
<tr>
<td>0.408</td>
<td>-</td>
<td>-</td>
<td>82.74</td>
<td>86.46</td>
</tr>
</tbody>
</table>

Figure 5.13: Wave drag coefficient \( (R_W) \) for the initial Wigley hull form and 4 optimal hull forms determined from Case - I to Case - IV

On the other hand, the optimal hull form determined for a given design speed range \( (Case - IV) \) results in an consistent drag reduction in the whole speed range in comparison with the original hull.

The body plan, profile plan and waterline plan of four optimal hull forms obtained in Case - I to Case - IV are plotted in Fig. 5.15 to Fig. 5.18, respectively. The hull form is
Figure 5.14: Total drag coefficient \( (R_T) \) for the initial Wigley hull form and 4 optimal hull forms determined from Case – I to Case – IV

not allowed to change behind the midship section in the optimization process. Therefore, the change of the hull lines can be clearly observed by comparing the left half and the right half of the lines in each figure since the original Wigley hull form is symmetric about the midship section. Figs. 5.15 – 5.17 show that in the single design speed optimization case a bulbous bow is generated and it becomes larger and lager with the increase of the ship speed. Case – I and Case – III optimal hull forms have similar characteristics. On the other hand, the hull form obtained in Case – II and Case – IV is quite different from these obtained in Case – I and Case – III. A little different bulbous bow are generated in the Case – II and a large bulbous bow is formed in the lower part at the bow region. This aspect shows that the present optimization technique provide the current conventional design of optimal hull forms. In addition, it also can be observed that Case – II and Case – IV results in positive rake which potentially advantageous.[47]

Since two different kinds of the objective function has been applied to the classical Wigley hull form, the comparison is now possible to observe the different effect according to the choice of objective function. Figs. 5.19 – 5.20 display the wave and total resistance
for a speed range that corresponds to $F_N = 0.2 - 0.42$ from the optimization result based on total drag coefficient reduction ($C_T$: Case $- IV$) and the optimization result based on total resistance reduction ($R_T$: Case $- IV$), respectively. In Fig. 5.19 shows that the result using total resistance is slightly larger wave resistance than the other. In other words, a lower reduction is accomplished by use of total resistance as objective function in terms of wave resistance. However, a larger drag reduction has been achieved in terms of total resistance when the objective function consist with total resistance. This consequence can easily explained by the relation between total drag coefficient and total resistance as follow.

$$C_T = \frac{R_T}{0.5\rho S V_S^2}$$

(5.4)

Here, $\rho$, $S$ and $V_S$ denote density, wetted surface area and the speed of ship. It can
Figure 5.16: Body plan, profile plan and waterline plan of the optimal hull form obtained in Case – II

be obviously found that any increase of wetted surface area results in increment of total resistance in a given total drag coefficient from Eq. (5.4). This indicates that the objective function based on total resistance is guiding the optimal solution not to increase wetted surface area during optimization investigation. However, there is no handling in the other objective function which is utilized by total drag coefficient to prevent growth of the wetted surface area. In fact, it is clearly shown that surface area has been increased about 4% from the result in Fig. 5.4. Moreover, a large deformation can be observed over the bow region in Fig. 5.10. On the other hand, a variation is within ±0.5% from the result based on total resistance in Fig. 5.12. Therefore, the objective function based on total resistance is suitable to take into account the additional consideration about wetted surface area.
5.1.3 Comparison Study about Variation Area

In this section, the variation area is extended to the stern area of the given Wigley initial hull, so the optimal hull forms can be compared according to the variation area. Table 5.5 shows a brief summary of the present application. In order to study different effect according to scale, two different scale are applied to the present optimization tool. Ship length $3\text{m}$ is applied for a model-scale of the initial Wigley hull, and $122\text{m}$ for a full-scale of ship. Additionally, two different variation of hull surface are utilized for the purpose of a comparison study. It is necessary to name each case for convenience. First, the case which is allowed a variation only in the bow area is Bow – Only case, and the other which involved in a variation of both bow and stern regions is Bow & Stern. 31 design variables are selected to alter the position of the control points for the NURBS surface for the Bow – Only optimization, and 45 design variables are used for the Bow & Stern
optimization, where 25 design variables are in the bow area and 20 in the stern. The ship length are taken as both the model-scale and the full-scale, corresponding $L = 3m$ and $L = 122m$ respectively. The gradient-based algorithm guides to find the position of the optimal point in the computational $N_{variable} - space$, and the requisite gradients $f_{\alpha \beta}$ is based on a central finite difference scheme. Since the optimization using multi-design speed provides better reduction over a given speed range than single-design speed case as pointed out in earlier two examples, only multi-design speed($F_N = 0.25, 0.316, 0.408$) case is considered in the present application. Therefore, the same objective function which consists with four terms, one displacement and three resistance at each speed, in order to build a scalar form.

- Optimization for Model-Scale
The convergence history of the wave resistance and total resistance are plotted in Fig. 5.21 for the *Bow – Only* case and *Bow & Stern* at model-scale. As it is also shown in Fig. 5.21, the number of iterations needed to converge are 29 and 26. In addition, the
Table 5.5: Definition of optimization for the Wigley hull for different variation area

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>The Wigley Hull</td>
<td>Eq. (5.1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1. Model-Scale($L = 3m$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Full-Scale($L = 122m$)</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$RT$</td>
<td>Eq. (5.3)</td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume Scalarization</td>
<td></td>
</tr>
<tr>
<td>Design Variables</td>
<td>NURBS 45 variables</td>
<td></td>
</tr>
<tr>
<td>Control-Points</td>
<td>Fore Body : 25, Aft Body : 20</td>
<td></td>
</tr>
<tr>
<td>Surface Representation</td>
<td>NURBS Surface 90 NURBS Control-Points</td>
<td></td>
</tr>
<tr>
<td>Optimization Algorithm</td>
<td>Gradient Central Difference(2−Order)</td>
<td></td>
</tr>
<tr>
<td>Gridgeneration</td>
<td>$FRGEN3D$</td>
<td>Neumann-Michell linear flow model</td>
</tr>
<tr>
<td>Flow Solver</td>
<td>$SSF$</td>
<td>Linear free-surface</td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Fore &amp; Aft Body</td>
<td></td>
</tr>
<tr>
<td>Design Speed</td>
<td>3</td>
<td>$F_N = 0.25, 0.316, 0.408$</td>
</tr>
<tr>
<td></td>
<td>1 Multi-Speed</td>
<td></td>
</tr>
</tbody>
</table>

difference of the displacement and the wetted surface in both cases are less than ±0.4% and ±0.05%, respectively. A reduction of the wave resistance ($R_W$) and the total resistance ($R_T$) of model-scale are listed in the Table 5.6.

As displayed in Fig. 5.21 and Table 5.6, the largest reduction of wave resistance and total resistance are obtained at $F_N = 0.316$ among the three design speeds both for the Bow-Only and the Bow & Stern cases. In addition, much higher reduction is accomplished by the Bow & Stern case as expected.

This implies that deforming the stern area exhibits another aspect of the way to reduce the wave resistance. In fact, only the bow wave is changed from the Bow-Only case while no change occurs behind the ship hull. However, Bow & Stern optimization reduces the wave both around bow and behind the hull body. Therefore, a better optimum solution can be obtained by an alteration of the hull surface for the bow and the stern, concurrently. This aspect will be explained again later in this section with the verification by FEFLO. The wave and total resistance coefficient($C_W$ & $C_T$) and the corresponding wave and total
Figure 5.21: Convergence history of the wave resistance ($R_W$) and total resistance ($R_T$) for the Bow – Only and Bow & Stern cases at model-scale.

Table 5.6: Reduction of resistance for model-scale (Initial Hull=100%)

<table>
<thead>
<tr>
<th></th>
<th>$F_N$</th>
<th>0.25</th>
<th>0.316</th>
<th>0.408</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_W$</td>
<td>Bow – Only</td>
<td>75.1</td>
<td>69.4</td>
<td>89.6</td>
</tr>
<tr>
<td></td>
<td>Bow &amp; Stern</td>
<td>49.4</td>
<td>25.1</td>
<td>66.5</td>
</tr>
<tr>
<td>$R_T$</td>
<td>Bow – Only</td>
<td>92.8</td>
<td>85.4</td>
<td>93.1</td>
</tr>
<tr>
<td></td>
<td>Bow &amp; Stern</td>
<td>88.5</td>
<td>75.9</td>
<td>86.4</td>
</tr>
</tbody>
</table>
resistance ($R_W$ & $R_T$) are shown in Fig. 5.22. It shows that optimal hull form for both the Bow – Only and Bow & Stern cases yield in the reduction over the given speed range. It is strongly recommended from the previous two applications and the Percival et al.(2001)[3] that using multi-design speed yields in a better drag reduction over the given speed range than a single design speed although a single design speed optimization provides a larger reduction within narrow bound including its design speed. Additionally, it can be also found that the Bow & Stern case provides a larger reduction than the Bow – Only case not only at the three design speeds but throughout the whole speed range. The largest wave drag reduction is achieved up to 30% and 75% for the Bow – Only and Bow & Stern cases, and 15% and 25% of the corresponding largest total drag reduction.

The body plan, profile plan and waterline plan of the two optimal hull forms are plotted in Fig. 5.18 and Fig. 5.23. Comparing with the initial Wigley hull, a bigger bow appears in the lower body for the both cases. Moreover, much larger deformation grows to minimize
the resistance in the lower stern area for the Bow & Stern case.

In the literature [36], it was illustrated that the wave system for a double-wedge-shape hull body with parallel part in the middle is divided into 5 systems: a) symmetric disturbance of surface, b) Bow wave system, c) forward shoulder wave system, d) after shoulder wave system and e) stern wave system.

This implies that, total wave system for the Wigley hull is mainly combination of the 5 wave systems. Moreover, each of these 5 waves are independently affected by a particular part of hull body. For example, bow shape of the hull is mostly governing a bow wave system and stern hull form is handling a stern wave system other than the other part of hull form. This means that bow wave system and forward shoulder wave system can be affected by a variation of the surface in the bow area, and stern wave system can be altered mostly by a modification of the surface hull around the stern. This fact explains that the
Table 5.7: Reduction of resistance for full-scale (Initial hull=100%)

<table>
<thead>
<tr>
<th>$F_N$</th>
<th>0.25</th>
<th>0.316</th>
<th>0.408</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow – Only</td>
<td>70.0</td>
<td>63.1</td>
<td>89.5</td>
</tr>
<tr>
<td>Bow &amp; Stern</td>
<td>26.0</td>
<td>20.8</td>
<td>68.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$F_N$</th>
<th>0.25</th>
<th>0.316</th>
<th>0.408</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow – Only</td>
<td>87.1</td>
<td>80.3</td>
<td>93.5</td>
</tr>
<tr>
<td>Bow &amp; Stern</td>
<td>69.0</td>
<td>58.5</td>
<td>80.9</td>
</tr>
</tbody>
</table>

Bow & Stern case which allow the modification both for bow and stern area leads higher reduction than Bow – Only case. In addition, making use of an alteration of stern area can be practically applied for optimization of self-propulsion and wake-field.

- Optimization for Full-Scale

The convergence history of wave resistance and total resistance are plotted in Fig. 5.24 for the case of Bow – Only and Bow & Stern at model-scale. The number of iterations to converge are 21 and 26, respectively. And the difference of the displacement and the wetted surface in all cases are less than ±0.35% and ±2.0%, respectively. The reduction of the wave resistance ($R_W$) and the total resistance ($R_T$) of full-scale are listed in the Table 5.7.

As displayed in Fig. 5.24 and Table 5.7, the largest reduction of the wave resistance and the total resistance are obtained at $F_N = 0.316$ among the three design speeds both for the Bow – Only and the Bow & Stern cases. Similar to the model-scale, much higher reduction is accomplished by the Bow & Stern case.

The wave and total resistance coefficient ($C_W$ & $C_T$) and the corresponding wave and total resistance ($R_W$ & $R_T$) are shown in Fig. 5.25. It shows that optimal hull form for both the Bow – Only and Bow & Stern present in the reduction over the given speed range. Thus, it is inevitable to make use of multi-design speed instead of several single design speed in order to obtain reduction over the whole speed range. Additionally, it can
be also found that the Bow & Stern case provides a larger reduction than the Bow – Only case not only at the three design speed but over the speed range. The largest wave drag reduction is achieved upto 37% and 80% for Bow – Only and Bow & Stern cases, and 20% and 42% of the corresponding largest total drag reduction.

The body plan, profile plan and waterline plan of the two optimal hull forms for full-scale are plotted in Fig. 5.26 and Fig. 5.27. Especially, there is no predominant change for the Bow – Only case in Fig. 5.26 even though this optimal hull form yields in 37% and 20% reduction of the wave and total resistance.

The Bow & Stern case results in a large deformation both in bow and stern area. Comparing with the initial Wigley hull. A very bigger bow appears in the lower body, and notable deformation over a stern area leads to minimize the resistance in the lower stern area. As mentioned from the model-scale optimization, each of the two large deformations
Figure 5.25: Comparison of drag coefficients ($C_W$ & $C_T$) and drag resistances ($R_W$ & $R_T$) for Bow – Only case and Bow & Stern case at full-scale

conducts not only its related wave system to reduce resistance but also the interference between the bow wave system and the stern wave system, between the bow wave system and the forward shoulder wave system and between the bow wave system and the after shoulder wave system. Even the Bow – Only case considering all of 4 interferences, a allowed surface modification is confined within bow area. However, it is possible that an adjustment of hull surface for both bow and stern area according to the interferences between 4 wave systems. This explains that a larger drag reduction is accomplished by the Bow & Stern case.

- Validation using advanced CFD tool(FEFLO)

Several different cases are applied to the present form optimization for the initial Wigley hull via simple flow solver. First of all, it is necessary to validate with an advanced flow solver in order to ensure the optimized performance. Secondly, the advanced flow solver (FEFLO) provides a higher resolution of the flow field solution so that further analysis can
Figure 5.26: Body plan, profile plan and waterline plan of the optimal hull form obtained from the Bow – Only case at full-scale

Figure 5.27: Body plan, profile plan and waterline plan of the optimal hull form obtained from the Bow & Stern case at full-scale
be carried out.

Hence, an advanced CFD tool, FEFLO based on Euler/RANS equations and nonlinear free surface conditions, is utilized to evaluate the wave drag for the original hull and the optimal hulls. The overall scheme of this free surface solver combines a finite-element, projection-type three-dimensional incompressible flow solver with a finite element, two-dimensional advection equation solver for the free surface equation. It has been shown that FEFLO provides a good agreement for for various hull forms in the literatures.[6, 25] In order to validate, the initial Wigley hull and the optimized hull for both Bow – Only and Bow & Stern cases at model-scale are selected. Larger hull deformation were detected at model-scale as shown in Figs. 5.18 – 5.23, it is better validate using the result from the model-scale.

Fig. 5.28 shows the comparison of the wave drag evaluated for the original hull, Bow – Only optimal hull, and the Bow & Stern optimal hull using simple CFD tool (SSF) and the advanced CFD tool (FEFLO). It can be seen from Fig. 5.28 that the wave drags evaluated for the original hull form and the optimal hull forms using simple CFD tool and advanced CFD tool exhibits the same tendencies. This comparison shows that the simple CFD tool is well suited for the hydrodynamic optimization.

Fig. 5.29 displays the wave profiles at three design speed for the initial Wigley hull,
Bow – Only case and Bow & Stern cases. Even a peak of the bow wave becoming little higher than the initial Wigley hull, each wave profile of the two optimal hull forms show a less oscillation, which is potentially wave drag, around body hull at $F_N = 0.25$ and $F_N = 0.316$. On the other hand, a wave profile at $F_N = 0.408$ has been reduced a little. Particularly, a modification of hull form affects before the stern part for the Bow – Only case at all three design speeds. However, the wave profiles have been changed over the whole body even further to the downstream for the Bow & Stern case. This interesting fact explains the interferences between wave systems, as mentioned earlier. Modification of hull surface at bow area is interfacing with bow and forward shoulder wave systems, and after shoulder wave and stern wave system are affected by the modification around stern area. As shown in Fig. 5.29, the hull form optimized by bow and stern alteration shows less wave over the computational domain than the others. Therefore, the largest drag reduction has been achieved by the Bow & Stern case.

It should be noticed that interferences of wave system is also easily found from wave patterns. Wave patterns of the three design speeds for three cases are presented in Figs. 5.30–5.32. As shown in Fig. 5.30, the optimal hull form of the Bow – Only case provides less wave pattern around hull body while there is no critical change over the whole flow domain. However, it shows that significant modification for both near the hull body and in the domain from the Bow & Stern optimized hull form. Particularly, the transverse wave is clearly changed into less oscillation and the divergent wave is turned into very small wave. The combination of the bow and stern modification helps to generate less wave through the interferences of 4 wave systems. This aspect also can be found at $F_N = 0.316$ in Fig. 5.31. The Bow – Only case provides less wave near the hull body, particularly divergent wave around stern, while it does not clearly change wave behind the stern. On the contrary, a distinct wave system is obtained by the Bow & Stern optimal hull form with considering that the largest drag reduction accomplished at this design speed ($F_N = 0.316$). Even though the wave around hull is similar to the wave of Bow – Only case, much less wave is generated behind stern. Both divergent and transverse waves yields in a prominently small.
Figure 5.29: Wave profile using FEFLO at 3 design speeds

Fig. 5.32 shows the wave system over the flow domain at $F_N = 0.408$. Since the wave length is ship length, this case does not provides the reduction of wave clearly, especially the Bow – Only case. A little reduction of divergent wave behind the hull and near the mid-body is detected from the both cases.
5.1.4 Comparison study about optimization algorithms

In this section, the present optimization technique is utilized with employing several optimization algorithms. The gradient-based algorithm is applied for the case of local optimization. A drawback of gradient-based already stated in Figs. 5.5 – 5.6 from the application of the Wigley hull using the total drag coefficient as an objective function. Generally, the
classical local optimization techniques have difficulties in dealing with global optimization problems. One of the main reasons of their failure is that they can easily be entrapped in local minima. Furthermore, these techniques cannot generate or even use the global information needed to find the global minimum for a function with multiple local minima. In fact, the feasible design spaces of ship hull form optimization problem is very non-convex due to
the presence of nonlinear geometrical, nonlinear PDEs, and functional constraints that have to be enforced to prevent unrealistic results and provide a realistic design. For that reason, it is necessary to develop global optimization technique. Mainly two algorithms, Genetic Algorithm (GA) & Particle Swarm Optimization (PSO), are applied. Additionally, GA has been developed also multi-objective algorithm using Pareto-front technique. Therefore, a
Table 5.8: Definition of optimization application

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>The Wigley Hull</td>
<td>Eq. (5.1) &amp; Full-Scale($L = 122m$)</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$R_T$</td>
<td>Eq. (5.3)</td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume</td>
<td>Scalarization</td>
</tr>
<tr>
<td>Design Variables</td>
<td>NURBS</td>
<td>31 variables</td>
</tr>
<tr>
<td>Control-Points</td>
<td></td>
<td>1-DOF : 21, 2-DOF : 5</td>
</tr>
<tr>
<td>Surface Representation</td>
<td>NURBS Surface</td>
<td>90 NURBS Control-Points</td>
</tr>
<tr>
<td>Optimization Algorithm</td>
<td>1. Gradient</td>
<td>Central Difference($2 - Order$)</td>
</tr>
<tr>
<td></td>
<td>2. GA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. PSO</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. MOGA</td>
<td>2 Objective Functions</td>
</tr>
<tr>
<td>Grid generation</td>
<td>FRGEN3D</td>
<td>Each step</td>
</tr>
<tr>
<td>Flow Solver</td>
<td>SSF</td>
<td>Neumann-Michell linear flow model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Linear free-surface</td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Fore Body</td>
<td></td>
</tr>
<tr>
<td>Design Speed</td>
<td>2</td>
<td>$F_N = 0.25&amp;0.316$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Multi-Speed</td>
</tr>
</tbody>
</table>

A brief summary of the present application is given in Table 5.8. Since the main aim of the present application is to compare several optimization algorithms, it is necessary to keep the same computational environments. The full-scale of the initial Wigley hull is employed to be modified the hull surface during optimization cycle in order to minimize the total drag resistance, displacement constraints condition is applied by scalarization of the objective function. 90 control points are used to represent the NURBS surface of the Wigley hull, 26 points on bow area out of 90 control points is used as design variables. One multi-design speed combined with two design speed, $F_N = 0.25, 0.316$, selected. A simple flow computer code(SSSF) is employed to analyze the performance of modified hull during optimization task. A grid generation utility(FRGEN3D) is applied to generate new hull form given by optimization cycle through NURBS surface representation. In addition, initial individual of global optimization algorithms is twice of the given number of design variables. This initial individual are distributed over the feasible domain by random-manner in GA and
MOGA, at the center of each face in PSO. At last, two total drag resistances at design speed $F_N = 0.25$ and $F_N = 0.408$ represents two objective functions.

Reduction of the wave resistance($R_W$) and the total drag resistance($R_T$) is given in Table 5.9. The number of iterations for gradient method is 16 to converge, and it have been reached to maximum iterations or generations, 50, for global optimization algorithms. And the both variations of displacement and wetted surface area are within ±0.5%. It is clearly found that local search technique provides less reduction comparing to the other global search methods. 5 results obtained from global search methods look similar reduction. Since Pareto-front method is utilized to search the best optimal solution in the given feasible domain for MOGA, a group of optimal individuals are obtained as a result. To take advantage of Pareto-front, 3 individual are selected to compare the performance of the final optimal hull form from multi-objective genetic algorithm. 3 individuals consist with the one($Ind – 1$) which provides relatively larger drag reduction at the given design speed $F_N = 0.25$, the second individual($Ind – 2$) shows somewhat better performance at
$F_N = 0.408$, finally the last one (Ind – 3) satisfies reasonable drag reduction for both design speeds. These three individuals and the rest of individuals obtained by the genetic search technique are depicted in Fig. 5.33. All 3 individuals are showing that both each objective function values are decreased compare with initial values of objective functions. Moreover, there are many individuals whose objective function values are less than the initial, any of these can be a candidate for a optimal solution. This is the very distinctive advantage of the Pareto-front approach.

Curves of the drag coefficients ($C_W$ & $C_T$) and the resistances ($R_W$ & $R_T$) for the given speed range is displayed in Fig. 5.34. As mentioned from Table 5.9, the result of the gradient method shows less drag reduction over the given speed range than other results.
Figure 5.34: Comparison of drag coefficients ($C_W$ & $C_T$) and drag resistances ($R_W$ & $R_T$) according to optimization algorithms obtained from global search algorithms. The curve for MOGA is represent $Ind - 3$ which provides a reasonable reduction for two objective functions. Overall, three results of global optimization display very similar reductions over the given speed range while there is small gap among each other.

Figs. 5.35 – 5.37 present comparison of the body plan, profile plan and waterline plan, respectively. Each optimal hull form provides apparently unique hull form. Overall, the result from PSO yields in the largest deformation in breadth direction as shown in Fig. 5.35 and Fig. 5.37.

In conclusion from the comparison of several optimizations, it is highly recommend to use global search technique for hydrodynamic hull form optimization. With making use of global optimization algorithms into hull form design, additional reductions in terms of both the wave resistance ($R_W$) and the total resistance ($R_T$) have been accomplished upto 15% and 10%, respectively.

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5.1.5 Optimization Using Parametric Hull Form Representation for the Wigley Hull Form

Upto the now, all of the optimization applications for the Wigley hull have been applied by making use of NURBS control points as design variables. On the contrary, a new approach to represent the given Wigley hull form is adapted in this section by utilizing the idea of parametric hull form representation technique. In this manner, the hull surface is modified through the variation of parameters so that newly generated hull surface is analyzed via a simple flow solver($SSF$) in order to search optimal solution of the hull form.

The parametric representation technique has been introduced by Perez et al.[22] in order to provide fair lines of hull form. Therefore, the NURBS surface modeling technique is necessary component once the hull offsets are obtained. This parametric representation approach is based on works with the sectional area curve(SAC), waterplane and section curve(i.e., longitudinal profile) at the given stations of hull. In order to generate the sectional area
curve and waterplane curve using mathematical expression, each curve is divided into 2 part, one of them for the aft-body and the other for fore-body. Finally, half-breadth sectional curve is obtained using the data from the sectional area curve and waterplane curve. The point of the given curves is possible to modify through the alteration of parameters which are commonly used by naval architect. A detail is explain the Chapter 3: Surface
Table 5.10: Definition of optimization application

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>The Wigley Hull</td>
<td>Eq. (5.1) &amp; Full-Scale(L = 122m)</td>
</tr>
<tr>
<td>Objective Function</td>
<td>(R_T)</td>
<td>Eq. (5.3)</td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume</td>
<td>Scalarization</td>
</tr>
<tr>
<td>Design Variables</td>
<td>Parameter</td>
<td>10 variables</td>
</tr>
<tr>
<td>Surface Representation</td>
<td>NURBS Surface</td>
<td>(31 \times 41) control net</td>
</tr>
<tr>
<td>Optimization Algorithm</td>
<td>MOGA</td>
<td>2 Objective Functions</td>
</tr>
<tr>
<td>Grid generation</td>
<td>(FRGEN3D)</td>
<td>Each step</td>
</tr>
<tr>
<td>Flow Solver</td>
<td>(SSF)</td>
<td>Neumann-Michell linear flow model</td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Whole Surface</td>
<td>Linear free-surface</td>
</tr>
<tr>
<td>Design Speed</td>
<td>2</td>
<td>(F_N = 0.25, 0.408)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Multi-Speed</td>
</tr>
</tbody>
</table>

A brief summary of the present application is given in Table 5.10. The full-scale of the modified initial Wigley hull is employed to minimize the total drag resistance, displacement constraints condition is applied by scalarization of the objective function. Since parametric hull representation provides control points for NURBS surface, \(31 \times 41\) NURBS surface net is obtained from parametric hull form. One multi-design speed combined with two design speed, \(F_N = 0.25, 0.408\), selected. A simple flow computer code(SSF) is adapted to guide to minimize the performance of modified hull during optimization task. A grid generation utility(\(FRGEN3D\)) is applied to generate new hull form given by optimization cycle through NURBS surface representation which is obtained by the present parametric technique.

In the present application, 10 parameters are adapted as design variables to deform the initial Wigley hull form as follow:

- **Sectional area curve**
  Maximum midship area(\(Ax\))
  Longitudinal position of maximum midship area(\(LCX\))
  Entrance angle in bow(\(\alpha_e\))
Because of making use of parameters to optimize the given Wigley hull, parametric study can be carried out in order either to investigate the effect of each parameter or to ensure local solution is contained within the prescribed maximum and minimum bound. Fig. 5.38 depicts effect of each parameter’s variations in terms of the total resistance. Above all, the single variation of the longitudinal position of maximum midship does not provide any improvement of the total resistance at all. The largest drag reduction is obtained by the modification of the maximum half-breadth ($Bx$). Finally, the total resistance curve is displayed in Fig. 5.39 for the optimization result using all of the 10 parameters. In order to compare the resistance with NURBS control points optimization, the resistance curve which has been shown in Fig. 5.25 is plotted. In fact, the performance of the optimal hull form by parametric hull representation technique shows less drag reduction. Consequently, the less reduction is due to the restrained modification from the parametric hull representation. In other word, modification of NURBS control points (i.e., conventional modeling techniques) are very flexible since there are no inherent restrictions with regard to geometry. However, the amount of design variables becomes high which provides an expensive computational costs or time-consuming task. But parametric modeling techniques yields in the less number of design variables and also guarantees fairness of the optimal hull form. This is the most noticeable advantage of parametric approach. The body, profile and waterline plan of the optimal hull form by parametric hull representation technique is displayed in Fig. 5.40. It
should be stressed that all lines are fulfilled in term of fairness. Additionally, the initial and modified parameters and sectional area curves are presented in Table 5.11 and Fig. 5.41. Since longitudinal position of maximum midship area shifted toward stern, modified SAC is asymmetrical unlikely the original SAC of the Wigley hull. In addition, it should be noticed that displacement is prescribed condition to obtain modified hull form, there is almost no variation for displacement. Finally, performance improvement in terms of the wave and total resistance ($R_W$ & $RT$) is provided in Table 5.12.
Figure 5.38: Parametric study

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Figure 5.39: Whole parameter result

Figure 5.40: Body Plan, Profile Plan and Waterline Plan of the Optimal Hull form Parametric Hull Optimization
In this section, the present optimization technique is applied to the Korean Research Institute for Ships and Ocean Engineering (KRISO) container ship (KCS) as a case of modern container ships. The KCS hull form was for the first time selected in the Gothenburg 2000 workshop for a modern slender ship case as a replacement for the Series 60 ($C_b = 0.6$) model in the earlier workshop. Fig. 5.42 and Table 5.13 presents an overview of the KCS hull form and main particulars, respectively. The ship length between perpendiculars ($L_{pp}$) is 230m and 7.2786m for full and model scales, respectively. The model draft ($T$) is 0.3418m and the model wetted surface area ($S_{wet}$) is 9.4379$m^2$ and the block coefficient ($C_b$) is 0.65. It may helpful to consider some important features of a geometry of the KCS, At first, a long bulbous bow toward upstream is enough to keep drawing interests from the shape optimization community of marine vehicles. The other notable feature of the KCS is that existence of an extended stern overhang, which is conditionally wet transom. This type of stern is commonly seen in recent container ship designs, and it produces complicated flow in the stern and wake wave fields. Even though the static waterline shape is normal, at operational speeds, it results in a conditionally wet transom. Several works for the KCS hull has been presented in the literature in terms of not only the optimization but also the CFD flow solvers[15,16,23,46]. The most controversial topic in the KCS shape optimization at present is the stern optimization for wake field in the extension of self-propulsion.
Table 5.13: Main particulars of the KRISO container ship (KCS)-model scale

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length $L_{pp}$ (m)</td>
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</tr>
<tr>
<td>Breadth $B$ (m)</td>
<td>1.019</td>
</tr>
<tr>
<td>Draft $T$ (m)</td>
<td>0.342</td>
</tr>
<tr>
<td>Wetted surface area (m$^2$)</td>
<td>9.438</td>
</tr>
<tr>
<td>Block coefficient $C_b$</td>
<td>0.65</td>
</tr>
<tr>
<td>Froude number ($F_N$)</td>
<td>0.26</td>
</tr>
</tbody>
</table>

5.2.1 Optimization using SSF

A brief summary of the present application is given in Table 5.14. The full-scale of KCS hull is used to minimize the wave drag coefficient, displacement constraints condition is applied by the sectional area curve generation. Since parametric hull representation provide a new sectional area curve, shifting method is applied to obtain a new hull surface. Therefore, it is necessary to use initial hull surface rather than to generate new hull surface by the grid generation tool. For this reason, the initial hull surface is used to obtain a new surface grid at each iteration by movement which easily computed from two SAC (the initial & modified). One single design speed ($F_N = 0.26$) is selected. At first, a simple flow computer code (SSF) is adapted to guide to minimize the performance of modified hull during optimization task.

In the present application, 7 parameters are adapted as design variables to deform the initial hull form as follow:

- **Sectional area curve**
- Entrance angle in bow ($\alpha_e$)
- Trailing angle in stern ($\alpha_s$)
- Longitudinal position of parallel part for Fore-body ($X_{pf}$)
- Longitudinal position of parallel part for Aft-body ($X_{pa}$)
Table 5.14: Definition of optimization application to KCS using SSF

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>KCS</td>
<td>Full-Scale($L = 200m$)</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$C_W$</td>
<td></td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume</td>
<td>By Parameter for SAC</td>
</tr>
<tr>
<td>Design Variables</td>
<td>Parameter</td>
<td>7 variables</td>
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<td>Optimization Algorithm</td>
<td>Gradient</td>
<td>Local</td>
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<td></td>
<td>$GA &amp; PSO$</td>
<td>Global</td>
</tr>
<tr>
<td>Gridgeneration</td>
<td>Shifting</td>
<td>Using initial surface</td>
</tr>
<tr>
<td>Flow Solver</td>
<td>SSF</td>
<td>Neumann-Michell linear flow model</td>
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<td></td>
<td></td>
<td>Linear free-surface</td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Whole Surface</td>
<td></td>
</tr>
<tr>
<td>Design Speed</td>
<td>1</td>
<td>$F_N = 0.26$</td>
</tr>
</tbody>
</table>

Nondimensional area of the fixed station for Fore-body ($A_f$)

Nondimensional area of the fixed station for Aft-body ($A_a$)

- **Profile plan**

  Bulb-Height($H_b$)

  In order to compare the optimal result according to optimization algorithms, two global optimization approaches are applied by making use of both the Genetic Algorithm($GA$) and the Particle Swarm Optimization($PSO$) and one local search technique are utilized by making use of the gradient method. Since 7 design variables are selected to minimize wave drag coefficient as mentioned earlier, 14 individuals or particles are generated as a initial generation or swarm in order to search the global optimal solution in the feasible domain. Additionally, it is not necessary to use resistance value as an objective function because there is no large deformation which possibly provides a large variation of wetted surface area and volume. In fact, the variation of the final optimal solutions for the two global optimization technique are less than 0.3% and 0.05% for the volume and the wetted surface area, respectively.

  Fig. 5.43 shows variation of the sectional area curve for the optimal hull from the 3 different optimization algorithms as well as the initial hull. There are large variation particularly for the aft-body while small modification appears on bow region and before
parallel part in the mid-ship for fore-body. The sectional area curve are very similar between two algorithms worth mentioning in passing. Overall, the two optimal hull forms which are obtained by the global technique show that area is reduced in the very entrance part and increased in the forward shoulder. For the aft-body, significantly increased area appears in after shoulder and reduced area in stern area. This result can be easily found in Fig. 5.44 which depicts longitudinal profiles of the two optimal hull forms and the initial hull form of the given container ship. It also shows that the bulb height ($H_b$) of the both cases are resulted in higher position than the initial. From the Figs. 5.43 – 5.44, it needs to be emphasized that the both final optimal surfaces show very fair surfaces which are obtained by making use of shifting technique from the sectional area curve.

Fig. 5.45 shows the wave profiles at the given design speed ($F_N = 0.26$) using FEFLO. The wave profiles of two final optimum hull forms are similar each other and reduce the peak at the bow wave than the initial KCS hull and so the wave on the mid ship. The stern wave and the wave behind the hulls are also reduced and shifted a little toward upstream. The wave pattern of the three optimal hulls and the initial are plotted in Fig. 5.46 at the given design speed. Especially, waves near the parallel part are reduced compared with the wave pattern of the initial hull. And the complexity around the bow wave of the initial is disappeared in the results of the GA and PSO.

Finally, the curve of the wave drag coefficient ($C_W$) are computed in Fig. 5.48. Over the presented speed range, wave drag shows a reduction. It should also be added that the wave drag reductions of the optimal hull forms of GA and PSO are 16.16% and 16.15%, respectively, as shown in Table 5.15.

### Table 5.15: Reduction of wave drag coefficient ($C_W$) (Initial Hull=100%)

<table>
<thead>
<tr>
<th>Gradeint</th>
<th>$\nabla$</th>
<th>$S_wet$</th>
<th>$C_W$</th>
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<tbody>
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<td>100.15</td>
<td>100.10</td>
<td>94.01</td>
</tr>
<tr>
<td>GA</td>
<td>100.26</td>
<td>100.05</td>
<td>83.84</td>
</tr>
<tr>
<td>PSO</td>
<td>100.26</td>
<td>100.05</td>
<td>83.85</td>
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</tbody>
</table>
Figure 5.43: Comparison of sectional area curve

Figure 5.44: Comparison of body plan

Figure 5.45: Comparison of wave profile at $V_{Design} \left(F_N = 0.26\right)$
Figure 5.46: Comparison of wave pattern at $V_{Design}(F_N = 0.26)$

Figure 5.47: Comparison of wave pattern at $V_{Design}(F_N = 0.26)$ (zoom-in)
5.2.2 Optimization using *FEFLO*

As given in Table 5.14, the full-scale of KCS hull is used to minimize the wave drag coefficient, displacement constraints condition is applied by the sectional area curve generation. As mentioned in the previous section, the initial hull surface is used to obtain a new surface grid at each iteration by movement which easily computed from the two the initial and modified SAC. One single design speed \( (F_N = 0.26) \) is selected. In this section, an advanced flow computer code(*FEFLO*) is utilized to search the optimum solution which provides the minimum performance of modified hull during optimization task.

As used in the previous application for the KCS hull, the 7 parameters are adapted to modify the given initial hull as design variables. In order to compare the optimal result according to optimization algorithms, two global optimization approaches are applied by make use of both the Genetic Algorithm(*GA*) and the Particle Swarm Optimization(*PSO*) and one local search algorithm, gradient method, is employed, again. 14 initial individuals or particles are generated in order to search the global optimal solution in the feasible domain.
Table 5.16: Definition of optimization application to KCS using SSF

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>KCS</td>
<td>Full-Scale($L = 200m$)</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$C_W$</td>
<td></td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume</td>
<td>By Parameter for SAC</td>
</tr>
<tr>
<td>Design Variables</td>
<td>Parameter</td>
<td>7 variables</td>
</tr>
<tr>
<td>Optimization Algorithm</td>
<td>Gradient</td>
<td>Local</td>
</tr>
<tr>
<td></td>
<td>$GA &amp; PSO$</td>
<td>Global</td>
</tr>
<tr>
<td>Grid generation</td>
<td>Shifting</td>
<td>Using initial surface</td>
</tr>
<tr>
<td>Flow Solver</td>
<td>$FEFLO$</td>
<td>Incompressible Flow</td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Whole Surface</td>
<td>Nonlinear free-surface</td>
</tr>
<tr>
<td>Design Speed</td>
<td>1</td>
<td>$F_N = 0.26$</td>
</tr>
</tbody>
</table>

Fig. 5.49 shows variation of the sectional area curve for the optimal hull froms obtained by three $GA$ and $PSO$ algorithms as well as the initial hull. Unlike the topimal hulls using $SSF$, a large variation for the fore-body is appears while small modification appears on stern and behind parallel part in the mid-ship for aft-body. The sectional area curves are different between two algorithms. Overall, the two optimal hull form shows that area is reduced in the entrance part and increased in the forward shoulder. For the aft-body, slightly decreased area appears in after shoulder and larger area in stern area than the initial KCS hull. It is noticed that the final optimum hull obtained by $PSO$ yields in a little larger modification than the $GA$’s. This result can be easily found in Fig. 5.50 which displays sectional shape of the two optimal hull forms and the initial hull form of the given container ship. It also shows that the bulb height ($H_b$) of the both cases are resulted in higher position than the initial with small differences. It also needs to be mentioned that the both final optimal surfaces show very fair surfaces. This could be a main advantage of parametric surface representation approach as an high level technique. In other word, modification via parametric surface representation is restricted because of its inherent regard to geometry. Therefore, it is necessary to make use of either further geometrical parameters or other surface representation technique which is combined with the present parametric approach.

Fig. 5.51 shows the wave profiles at the given design speed ($F_N = 0.26$) using $FEFLO$. 130
The wave profiles of two final optimum hull forms are similar each other and reduce the peak at the bow wave than the initial KCS hull and so the wave on the mid ship. The stern wave and the wave behind the hulls are also reduced and shifted a little toward upstream. The wave pattern of the two optimal hulls and the initial are plotted in Fig. 5.52 at the given design speed. Particularly, waves near the parallel part are reduced compared with the wave pattern of the initial hull. And the complexity around the bow wave of the initial is disappeared in the results of the GA and PSO. Even a little different phase of the optimal hulls between either flow solvers or optimization algorithms, the wave profiles and the wave patterns are similar.

Finally, it should also be added that the wave drag reductions of the optimal hull forms of GA and PSO are 12.6% and 18.9%, respectively, as shown in Table 5.17.

<table>
<thead>
<tr>
<th></th>
<th>$\nabla$</th>
<th>$S_{\text{wet}}$</th>
<th>$C_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>100.12</td>
<td>99.91</td>
<td>99.13</td>
</tr>
<tr>
<td>GA</td>
<td>100.25</td>
<td>100.00</td>
<td>87.37</td>
</tr>
<tr>
<td>PSO</td>
<td>100.09</td>
<td>100.02</td>
<td>81.11</td>
</tr>
</tbody>
</table>
Another application to the present technique is to improve the performance of the surface combatant ship, David Taylor Model Basin Model-5415, which was selected in the Gothenburg 2000 workshop for a representative of modern navy ship. Fig. 5.54 and Table 5.18 presents an overview of the DTMB Model-5415 hull form and main particulars, respectively. The ship length between perpendiculars ($L_{pp}$) is 142$m$ and 5.719$m$ for full and model scales, respectively. The model draft ($T$) is 0.2488$m$ and the model wetted surface area ($S_{wet}$) is 4.861$m^2$ and the block coefficient ($C_b$) is 0.506. Since an existence of a sonar dome bow and transom as shown in Fig. 5.54, DTMB Model-5415 has been treated as a typical instance of
a highly complicated hull form to optimize. Some papers dedicated to shape optimization of DTMB Model-5415. Tahara et al.[11] developed an optimization module for a zonal dome and stern of DTMB Model-5415 using a Reynolds averaged Navier-Stokes (RANS) solver based on successive quadratic programming (SQP) for higher-performance optimization method by introduction of parallel computing, message passing interface (MPI) protocol. In addition, a variable-fidelity approach for multi-objective optimization was carried out in a purpose of speed up the optimization procedure using free surface RANS code by Peri and Campana[5, 48].

The experimental data are available (http://www.simman2008.dk/5415/combatant.html), the comparison between experimental result and numerical approximations, both a simple flow code(SSF) and an advanced CFD flow solver(FEFLO) are utilized to provide the performance of the hull form during optimization process, is presented in Fig. 5.55. Even though SSF which is based on Neumann-Michell linear flow model shows a somewhat larger difference than the result of FEFLO, it provides a similar tendency. On the other hand,
FEFLO, finite element based Euler/RANS flow solver provides a good agreement with experimental data. It is necessary to mention at this point that SSF is robust enough to provide a reasonable flow approximation in terms of relative difference among each modified hull form even its insufficient agreement with the experimental data in a quantitative respect. Particularly, its prominently cheap computational cost is overwhelming to any other CFD flow solvers in the shape optimization module which needs a large number of iterations.

Figure 5.54: David Taylor Model Basin (DTMB) Model-5415
Table 5.18: Main particulars of the DTMB Model-5415-model scale

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length $L_{pp}$ (m)</td>
<td>5.720</td>
</tr>
<tr>
<td>Breadth $B$ (m)</td>
<td>0.724</td>
</tr>
<tr>
<td>Draft $T$ (m)</td>
<td>0.248</td>
</tr>
<tr>
<td>Wetted surface area $(m^2)$</td>
<td>4.861</td>
</tr>
<tr>
<td>Block coefficient $C_b$</td>
<td>0.506</td>
</tr>
<tr>
<td>Froude number $(F_N)$</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Figure 5.55: Comparison of the wave drag coefficient

5.3.1 Optimization using $SSF$

Table 5.14 presents a summary of the present application. The full-scale of DTMB Model-5415 hull is used to minimize the wave drag coefficient, displacement constraints condition is applied in the generation of the sectional area curve during optimization cycle. Since parametric hull representation provide a new sectional area curve, shifting method is applied to obtain a new hull surface. The initial hull surface is used to obtain a new surface grid at each iteration by movement which easily computed from two SAC (the initial & the modified SAC). Optimization tool is applied to minimize the wave drag coefficient ($C_W$) at a single design speed ($F_N = 0.28$). At first, a simple flow computer code($SSF$) is utilized to search optimal solution for the given DTMB Model-5415.
Since it is unnecessary to use two parameters for a parallel part in the mid ship, 4 parameters are adapted as design variables to deform the initial hull form in the present application as follow:

- **Sectional area curve**
  
  Entrance angle in bow \((\alpha_e)\)

  Trailing angle in stern \((\alpha_s)\)

  Nondimensional area of the fixed station for Fore-body \((A_f)\)

  Nondimensional area of the fixed station for Fore-body \((A_a)\)

In order to compare the optimal result according to optimization algorithms, two global optimization and one local optimization approaches are applied by making use of both the Genetic Algorithm (GA), the Particle Swarm Optimization (PSO) and the gradient-based method. Since 4 design variables are selected to minimize wave drag coefficient as mentioned earlier, 8 particles for PSO are generated as a initial swarm in order to search either global optimal solution in the feasible domain. Meanwhile, the first generation for GA has 10 individuals as a default to ensure possibility of searching global optimal solution.

Additionally, it is not necessary to use resistance value as an objective function because there is no large deformation which possibly provides a large variation of wetted surface area and volume. In fact, the variation of the final optimal solutions for the three optimization technique are less than 0.05% for both the volume and the wetted surface area.

Fig. 5.56 shows the sectional area curve for the optimal hull from the three optimized hull as well as the initial hull. There is variation over the hull body. The sectional area curve are very similar between three algorithms. Overall, the three optimal hull form shows that area is reduced in the very entrance part and increased in the forward shoulder. For the aft-body, a decreased area appears in after shoulder and an increased area in stern area. This result can be easily found in Fig. 5.57 which depicts longitudinal profiles of the three optimal hull forms and the initial hull form of the given surface combatant ship. It also shows that the stern of the three optimized hull forms are resulted in a little lower position.
Table 5.19: Definition of optimization application

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>DTMB Model-5415</td>
<td>Full-Scale($L = 200m$)</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$R_T$</td>
<td></td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume</td>
<td>By Parameter for SAC</td>
</tr>
<tr>
<td>Design Variables</td>
<td>Parameter</td>
<td>4 variables</td>
</tr>
<tr>
<td>Optimization Algorithm</td>
<td>Gradient</td>
<td>Local</td>
</tr>
<tr>
<td></td>
<td>$GA &amp; PSO$</td>
<td>Global</td>
</tr>
<tr>
<td>Grid generation</td>
<td>Shifting</td>
<td>Using initial surface</td>
</tr>
<tr>
<td>Flow Solver</td>
<td>$SSF$</td>
<td>Neumann-Michell linear flow model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Linear free-surface</td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Whole Surface</td>
<td>Fixed the sonar dome</td>
</tr>
<tr>
<td>Design Speed</td>
<td>1</td>
<td>$F_N = 0.28$</td>
</tr>
</tbody>
</table>

than the initial. From the Figs. 5.56 – 5.57, it needs to be emphasized that the both final optimal surfaces show very fair surfaces which is obtained by making use of shifting technique from the sectional area curve even its complex geometry.

Fig. 5.58 shows the wave profiles at the given design speed ($F_N = 0.28$) using FEFLO. The wave profiles of three final optimum hull forms are similar each other. Since the bow area is not allowed for modification, there is no difference in the peak at the bow wave. However, less oscillated wave for the three optimal hull between bow and stern than the wave of the initial hull. In addition, the stern wave and the wave behind the hulls are also reduced and shifted a little toward upstream. The wave pattern of the three optimal hulls and the initial are plotted in Fig. 5.59 for the given design speed. Especially, waves near the parallel part are clearly reduced compared with the wave pattern of the initial hull. And the complexity around the stern wave of the initial is disappeared in the results of the optimal hulls.

Finally, the curve of the wave drag coefficient ($C_W$) are computed in Fig. 5.61. Over the presented speed range, wave drag shows a reduction except lower speed range. The largest wave drag reductions of the three optimal hull forms is achieved by $GA$, 14.57%, as shown in Table 5.20.
Figure 5.56: Comparison of sectional area curve between initial and Optimal

Figure 5.57: Comparison of section profile between Initial and Optimal

Figure 5.58: Comparison of wave profile between initial and Optimal
Figure 5.59: Comparison of wave pattern at $V_{Design}(F_N = 0.28)$

Figure 5.60: Comparison of wave pattern at $V_{Design}(F_N = 0.28)$-zoom in
Table 5.20: Reduction of wave drag coefficient ($C_W$) (Initial Hull=100%)

<table>
<thead>
<tr>
<th></th>
<th>$\nabla$</th>
<th>$S_{wet}$</th>
<th>$C_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>100.46</td>
<td>100.05</td>
<td>89.72</td>
</tr>
<tr>
<td>GA</td>
<td>100.43</td>
<td>99.99</td>
<td>85.43</td>
</tr>
<tr>
<td>PSO</td>
<td>100.43</td>
<td>99.99</td>
<td>87.15</td>
</tr>
</tbody>
</table>

5.3.2 Optimization using $FEFLO$

Fig. 5.62 shows variation of the sectional area curve for the optimal hull from the three different algorithms as well as the initial hull. A variation is detected over the whole body from the both optimal hull forms. However, no clear difference between the two optimal hulls are observed. Overall, the two optimal hull form shows that area is increased in the entrance part and reduced in the forward shoulder, it is similar to the optimal forms via $SSF$ as shown in the previous application of DTMB Model-5415. For the aft-body, slightly increased area appears in after shoulder and reduced area in stern area than the initial KCS hull. It is noticed that the final optimum hulls obtained by both methods yields in a little higher position of stern. This result can be easily found in Fig. 5.63 which displays sectional shape of the two optimal hull forms and the initial hull form of the initial DTMB Model-5415.

Fig. 5.64 shows the wave profiles at the given design speed ($F_N = 0.28$) using $FEFLO$. 

Figure 5.61: Comparison of the wave drag coefficient between initial and Optimal

Figure 5.62: Variation of the sectional area curve for the optimal hull from the three different algorithms as well as the initial hull.

Figure 5.63: Sectional shape of the two optimal hull forms and the initial hull form of the initial DTMB Model-5415.

Figure 5.64: Wave profiles at the given design speed ($F_N = 0.28$) using $FEFLO$. 

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Table 5.21: Definition of optimization application

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>DTMB Model-5415</td>
<td>Full-Scale ($L = 200, m$)</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$R_T$</td>
<td></td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume By Parameter for SAC</td>
<td></td>
</tr>
<tr>
<td>Design Variables</td>
<td>Parameter 4 variables</td>
<td></td>
</tr>
<tr>
<td>Optimization Algorithm</td>
<td>Gradient Local $GA \ &amp; PSO$</td>
<td></td>
</tr>
<tr>
<td>Grid generation</td>
<td>Shifting Using initial surface</td>
<td></td>
</tr>
<tr>
<td>Flow Solver</td>
<td>$FEFLO$ Incompressible Flow</td>
<td>Nonlinear free-surface</td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Whole Surface Fixed the sonar dome</td>
<td></td>
</tr>
<tr>
<td>Design Speed</td>
<td>$F_N = 0.28$</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.22: Reduction of wave drag coefficient ($C_W$) (Initial Hull=100%)

<table>
<thead>
<tr>
<th></th>
<th>$\nabla$</th>
<th>$S_{wet}$</th>
<th>$C_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>100.19</td>
<td>99.99</td>
<td>98.50</td>
</tr>
<tr>
<td>$GA$</td>
<td>100.43</td>
<td>99.99</td>
<td>95.13</td>
</tr>
<tr>
<td>$PSO$</td>
<td>100.43</td>
<td>99.99</td>
<td>95.05</td>
</tr>
</tbody>
</table>

The wave profiles of three final optimum hull forms are somewhat different each other. Since the bow area is not allowed for modification, there is no difference in the peak at the bow wave. However, the peak of the wave in the middle of forebody are shifted in the optimized hull forms. The $GA$’s is shifted toward upstream while the $PSO$’s is transposed downward in the stream. In addition, the stern wave and the wave behind the hulls are slightly reduced and shifted a little toward upstream. The wave pattern of the three optimal hulls and the initial are plotted in Fig. 5.65 for the given design speed. Especially, waves in the mid-body of the optimal hull via $PSO$ is clearly reduced compared with the wave pattern of the initial hull.

Finally, the curve of the wave drag coefficient ($C_W$) are computed in Fig. 5.67. Over the presented speed range, wave drag shows a reduction. the wave drag reductions of the optimal hull forms of $GA$ and $PSO$ are 4.87% and 4.95%, respectively, as shown in Table 5.22.
Figure 5.62: Comparison of sectional area curve between Initial and Optimal

Figure 5.63: Comparison of section profile between Initial and Optimal

Figure 5.64: Comparison of wave profile between Initial and Optimal
Figure 5.65: Comparison of wave pattern at $V_{Design}(F_N = 0.28)$

Figure 5.66: Comparison of wave pattern at $V_{Design}(F_N = 0.28)$-zoom in
5.4 The Series-60 Hull \((C_b = 0.6)\)

The last application in this dissertation is to improve the performance of the well-known classical hull, the Series-60 Hull \((C_b = 0.6)\). This hull has a relatively simple geometry: no bulbous bow but stern exists with plain geometry. Fig. 5.68 and Table 5.23 presents an overview of the Series-60 hull form and main particulars, respectively. The ship length between perpendiculars \((L_{pp})\) is 200m at full scale. The draft \((T)\) is 6.67m and the wetted surface area \((S_{wet})\) is 6843.9\(m^2\) and the block coefficient \((C_b)\) is 0.6.

\[
I(\vec{\beta}) = W_1 \cdot \left( \frac{\nabla_i - \nabla_0}{\nabla_0} \right)^2 + \sum_{j=1}^{n} \left( W_j R_{jT_i}^j R_{jT_0} \right)
\]

(5.5)

where \(\nabla\) is displacement of hull and subscript 0 and \(i\) represent the initial and the \(i\)-th iteration during the whole optimization procedure, respectively. Objective function values is evaluated with proper selection of weights, \(W_1\) and \(W_j\).

Particularly, combination of parameters and NURBS control points consists the design variables. This implies that the hull surface representation is possible with making use of NURBS surface and hull modification is carried out via both NURBS control points and
Table 5.23: Main particulars of the Series-60 ($C_b = 0.6$) - full scale

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length $L_{pp}$ (m)</td>
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</tr>
<tr>
<td>Breadth $B$ (m)</td>
<td>6.67</td>
</tr>
<tr>
<td>Draft $T$ (m)</td>
<td>5.33</td>
</tr>
<tr>
<td>Wetted surface area (m$^2$)</td>
<td>6843.9</td>
</tr>
<tr>
<td>Block coefficient $C_b$</td>
<td>0.60</td>
</tr>
</tbody>
</table>

geometrical parameters.

Table 5.24 describes a summary of application to the Series-60 Hull. The objective function consists with two component. One is related with volume variation and the other is the total resistance as shown in Eq (5.5). The former can be interpreted as the volume constraint condition, any difference results in growing of objective function value so that variation of displacement can be easily prevented. The latter is a summation of ratio between the modified and the initial of the total resistance at the given design speeds. A simple flow code (SSF) is utilized to examine the performance of hull and information about flow field as well as hull surface. Multi-objective genetic algorithm (MOGA) is adapted to guide from the initial hull form to the final optimal hull form using Pareto-front approach. The full scale total resistance is considered at two multiple design speeds, $F_N = 0.18$ and $F_N = 0.32$ for bench-marking example so that an advanced application with additional design speeds are going to be achieved.

In the present application, 6 parameters are adapted as design variables to deform the initial hull form as follow:

- **Sectional area curve**
  - Entrance angle in bow ($\alpha_e$)
  - Trailing angle in stern ($\alpha_s$)
Table 5.24: Definition of optimization application

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>Series-60 Hull</td>
<td>$C_b = 0.6$ &amp; Full-Scale($L = 200m$)</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$RT$</td>
<td></td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume</td>
<td>Scalarization</td>
</tr>
<tr>
<td>Design Variables</td>
<td>Parameter</td>
<td>7 variables</td>
</tr>
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<td>Surface Representation</td>
<td>NURBS Surface</td>
<td>$31 \times 41$</td>
</tr>
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<td>Optimization Algorithm</td>
<td>MOGA</td>
<td></td>
</tr>
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<td>FRGEN3D</td>
<td>Each step</td>
</tr>
<tr>
<td>Flow Solver</td>
<td>SSF</td>
<td>Neumann-Michell linear flow model</td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Whole Surface</td>
<td></td>
</tr>
<tr>
<td>Design Speed</td>
<td>2</td>
<td>$F_N = 0.18, 0.32$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 Multi-Speed</td>
</tr>
</tbody>
</table>

Longitudinal position of parallel part for Fore-body ($X_{p_f}$)

Longitudinal position of parallel part for Aft-body ($X_{p_a}$)

Longitudinal position of parallel part for Fore-body ($X_{p_f}$)

Longitudinal position of parallel part for Aft-body ($X_{p_a}$)

Nondimensional area of the fixed station for Fore-body ($A_f$)

Nondimensional area of the fixed station for Aft-body ($A_a$)

In addition, there are 3 more design variables from NURBS control points which represent the stem line over the bow. The new modified stem line is decided by the variation of these 3 during optimization process. The reason why this technique has been implemented to the present optimization module is that this geometrical property need to be considered especially for some special ship (i.e., ice-break ship). Moreover, Delhommeauthis et al. [47] showed that this line is possibly also very critical for the bow wave.

Since the presented application is adapting Multi-Objective Genetic Algorithm (MOGA) using Pareto-front approach, Fig. 5.69 shows the whole individuals including the initial, Pareto front and three final optimal solutions in terms of two objective functions. Three final optimal solutions are selected to make a comparison of a performance of the hull. The first two individuals ($Ind−1$ & $Ind−2$) represent for the reasonably best optimal individual
for each objective function, and the last one (Ind – 3) is the one result which satisfies the both objective functions.

Fig. 5.70 shows the sectional area curves of the initial and the three optimal final optimum individuals. As depicted, some notable modifications in the SAC are detected even though there is no obvious difference among the final hull forms. Reduced areas are obtained in the entrance part of the fore-body and gradually increased behind the forward shoulder. Particularly, the three SAC show different aspect in the stern. Ind – 1 shows almost same distribution of area in the stern while the Ind – 2 results in smaller area. However, the former is resulted in a slight reduction of area in the after shoulder in the aft-body while the latter is distributed with somewhat large difference in lessening. The interesting fact is that Ind – 3 which assures the reduction of both design speed has the property of Ind – 1 for the fore-body and Ind – 2 for aft-body. This fact also can be found in Figs. 5.72 – 5.74. Since the geometric parameters are employed as design variables, all the optimal results show fair surfaces. Additionally, all the optimal hull forms are resulted in a positive rake as shown in the profile plan in each figures. The reductions of the wave
resistance ($R_W$) and the total resistance ($R_T$) are presented in Table 5.25. As expected, $Ind - 1$ shows the largest reduction at the lower design speed ($F_N = 0.18$), and $Ind - 2$ at the larger ($F_N = 0.32$) while $Ind - 3$ provides the reductions for the both speeds. Finally, the drag coefficient ($C_W$&$C_T$) and the resistance ($R_W$&$R_T$) curves of the optimal hull forms are compared with the given initial Series-60 hull ($C_b = 0.6$) in Fig. 5.75.

Table 5.25: Reduction of Drag Coefficient(Initial Hull=100%)

\[
\begin{array}{|c|c|c|c|}
\hline
& Ind - 1 & Ind - 2 & Ind - 3 \\
\hline
R_W(\%) & & & \\
0.18 & 67.9 & 139.39 & 88.0 \\
0.32 & 86.3 & 78.25 & 84.2 \\
\hline
R_T(\%) & & & \\
0.18 & 94.1 & 105.0 & 97.1 \\
0.32 & 89.9 & 84.1 & 88.4 \\
\hline
\end{array}
\]

Figure 5.70: Comparison of the sectional area curve
$F_N = 0.18$

$F_N = 0.25$

$F_N = 0.32$

Figure 5.71: Comparison of the wave profile

Figure 5.72: Body Plan, Profile Plan and Waterline Plan of the Optimal Hull form Obtained in Ind – 1
5.5 Summary

In this chapter, the presented optimization technique have been illustrated to various hull form.

At first, a bow region of the Wigley hull has been optimized in terms of the various objective functions. For the case of the multi-design speed using the total drag coefficient
Figure 5.75: Convergence History of the Wave Resistance \( R_W \) and Total Resistance \( R_T \) for Bow-Only Case and Bow&Stern Case at the full-scale

\( (C_T) \) at the model scale yields in 45% and 15% of the wave drag and total drag coefficients, respectively, as shown in Table 5.2. Moreover, it has been found that the making use the multi-design speed is necessary as displayed in Figs. 5.5 – 5.6 in order to improve hull performance over a design speed range. However, it also has been noticed that the consideration for the variation of wetted surface area need to be included for the evaluation of objective function during optimization process. Thus, another objective function is implemented by the total drag resistance \( (R_T) \) which includes the wetted surface area as shown in Eq. (5.3). As a result, the drag reductions of wave and total resistance have been achieved at most 50% and 20% with multi-design speed in Table 5.4. Particularly, the variation of the wetted surface area and the displacement are restricted within 0.5%. Furthermore, the optimization for the bow and stern parts has been applied with 81% and 41% of the wave and total drag \( (R_W \ & \ R_T) \) reductions for the full scale and 75% and 20% reductions for the model scale of as shown in Tables 5.7 and 5.6. In addition, validation has
been shown that the optimal hull form via a simple flow-code (SSF) reasonably provides the drag reductions using the advanced flow solver (FEFLO). Meanwhile, a study on the comparison of optimization algorithms has been carried out. One local search algorithm (Gradient-based method), two global techniques (GA and PSO) and one multi-objective optimization (MOGA), have been implemented for this study. As expected, Table 5.9 shows the two global algorithms yield in a larger reduction than the local search approach. Finally, the Wigley hull has been optimized using the proposed parametric hull representation technique. In this technique, the given hull is expressed by the three parametric curves: sectional area curve (SAC), waterline curve and the longitudinal profiles at the given stations. The optimal hull is especially in a fair shape as a result and the reductions of drag are also quite satisfactory as shown in Table 5.12.

The KCS as a case of modern container ships has been optimized in terms of the wave drag coefficient ($C_W$) by making use of the parametric hull variation. Since sectional area curve is the main parametric curve, shift approach for the given stations along the longitudinal direction has been implemented. Even with the complexity of the geometry, the optimal hulls have been obtained with a fair surface. Especially, both flow solvers, SSF and FEFLO, have been utilized to guide the given initial hull to minimize the wave drag coefficient. The reduction of the wave coefficient by both SSF and FEFLO displayed in Tables 5.15 and 5.17, respectively.

Another application is the surface combatant ship, DTMB Model-5415, as an complex hull form which has sonar dome and stern. The same optimization technique with the KCS has been adapted. Since the variation have been conducted by the geometric parameters, the optimal hull forms by the both flow solvers are in fair shapes as shown in Figs. 5.57 and 5.63.

The last application in this dissertation is the optimization for the well-known Series-60 ($C_b = 0.6$). Especially, both NURBS surface representation technique and parametric hull variation approach are employed in this application. The reduction of the wave and total resistance have been obtained smaller than any other cases as shown in Table 5.25.
However, the applied hull variation technique for this hull is certainly meaningful.
Chapter 6: Application II

Up to now, the applications have been achieved for the drag in terms of the wave and total resistance as well as coefficient. Some applications have been optimized for a single design speed by making use of 3 single-objective optimization algorithms and some cases are accomplished for a multi design speed in order to consider a given speed range by either scalarization or multi-objective optimization technique. However, for practical reasons, ship designers may want to optimize two or more objects simultaneously. The object functions can be any combinations of wave drag, self-propulsion, sea-keeping, wave-field, etc. With considering this fact, the application to the multi-objective optimization for both a wave drag reduction and an enhancement of sea-keeping performance is introduced in this chapter.

The sea-keeping performance is evaluated by a simple linearized formula (Bales’ Ranking Method) [49] of hull form parameters while wave drag coefficient is obtained by the simple CFD code (SSF).

### 6.1 Evaluation of Sea-Keeping Performance by Bales’ Rank Method

Bales [49] suggested a simple linearized formula using 6 form parameters, called Bales’ Sea-Keeping rank or Bales’ Ranking method, in order to evaluate the sea-keeping performance particularly in the early design stage. Because of its simple approximation, this approach have been validated by several hull forms and successfully achieved to the application of hull form optimization. [49,50] Initially, this quantified model is developed by 20 destroyer type hulls in long-crest, head seas condition. For generalization, the method was validated by homogeneous class of hull geometries, including destroyers, frigates, and light cruisers by using only hull form parameters. A six form parameters employed were the waterplane
coefficient forward of amidships ($C_{WF}$) and aft of amidship ($C_{WA}$), the draft-to-length ratio ($T/L$), the cut-up ratio ($c/L$), the vertical prismatic coefficient forward of amidships ($C_{VPF}$) and aft of amidship ($C_{VPF}$). Therefore, the functional relationship between the sea-keeping rank ($R$) and the six form parameters can be written as

$$R = f(C_{WF}, C_{WA}, T/L, c/L, C_{VPF}, C_{VPF})$$

$$= a_0 + a_1C_{WF} + a_2C_{WA} + a_3(T/L) + a_4(c/L) + a_5C_{VPF} + a_6C_{VPF}$$

(6.1)

The next step is to quantify the sea-keeping rank using selected 20 hull models in terms of eight sea-keeping responses. The responses selected were pitch, heave, ship-to-wave relative motion at Station 0 and 20, bottom slamming at Station 3, absolute vertical acceleration at Station 0, heave acceleration, and absolute vertical motion at Station 20. Then, the 20 hull forms were ranked from 1.0 to 10.0, by averaging eight sea-keeping responses, with best hull having 10.0. Finally, the linear relationship between the evaluated rank with six form parameters are obtained. In other words, the coefficient $a_i$, $i = 0, 1, \ldots, 6$ are evaluated by the regression analysis as

$$R = 8.422 + 45.104C_{WF} + 10.078C_{WA} - 378.465(T/L)$$

$$+ 1.273(c/L) - 23.501C_{VPF} - 15.875C_{VPF}$$

(6.2)

### 6.2 Application of Sea-Keeping Optimization to DTMB Model-5415

Table 6.1 describes a summary of the present application. The DTMB Model-5415 hull is used for a given single-objective problem, maximization of Bales’ seakeeping estimator, while displacement constraints condition is applied in the generation of the sectional area curve during optimization cycle. The surface modification is based on the SAC variation.
Table 6.1: Definition of optimization application

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>DTMB Model-5415</td>
<td>Model-Scale</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$(R)$</td>
<td>Sea-Keeping Index</td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume</td>
<td>By Parameter for SAC</td>
</tr>
<tr>
<td>Design Variables</td>
<td>Parameter</td>
<td>4 variables</td>
</tr>
<tr>
<td>Optimization Algorithm</td>
<td>GA</td>
<td></td>
</tr>
<tr>
<td>Grid generation</td>
<td>Shifting</td>
<td>Using initial surface</td>
</tr>
<tr>
<td>Flow Solver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sea-Keeping</td>
<td>Bales’ Ranking Method</td>
<td></td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Whole Surface</td>
<td>Fixed the sonar dome</td>
</tr>
</tbody>
</table>

used for the application to the single-objective optimization from the Chapter. 5. Again, 4 parameters are adapted as design variables to deform the initial hull form in the present application as follow:

- **Sectional area curve**

  Entrance angle in bow ($\alpha_e$)

  Trailing angle in stern ($\alpha_s$)

  Nondimensional area of the fixed station for Fore-body ($A_F$)

  Nondimensional area of the fixed station for Fore-body ($A_a$)

  The number of maximum generation is set as 200 while each generation has 10 individuals for 4 design variables. 10% of the best individuals are kept in each generation, and cut-off faraction and mutation rate are set 0.75 and 0.05, respectively. Since the evaluation of the Sea-Keeping rank is engaged with the simple approach which is computationally very cheap, the given application are achieved until the prescribed maximum iteration is reached with very small convergence criteria. As a result, the optimal hull form obtained by the Bales’ Sea-Keeping rank 6.04 while the initial is 5.40. Displacement is increased by 2.73% and wetted surface area yields in a slight increase of the initial hull form.

  The sectional area curve (SAC) of the initial and the optimal are compared in Fig. 6.1. The volume of forward ship ($\nabla_F$) and waterplane area of forward ship ($AWF$) is
Table 6.2: Variations of wave drag coefficient \((C_W)\) and Sea-Keeping Ranking\((R)\) (Initial Hull=100% & \(R = 5.40\))

<table>
<thead>
<tr>
<th>▽(%)</th>
<th>Swet(%)</th>
<th>Sea-Keeping Index((R))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best:Sea-Keeping</td>
<td>102.73</td>
<td>100.1</td>
</tr>
</tbody>
</table>

Figure 6.1: Comparison of SAC between initial and Optimal

decreased while the volume of aft ship \((C_{VPA})\) and waterplane area of forward ship \((C_{WF})\) is increased. Particularly, each of these variation leads to an increase of the Bales’ Sea-Keeping rank according to the Eq. (6.2). Fig. 6.2 describes the corresponding hull lines.

Since the SAC of optimal hull form shows decrease over the whole range except the stern area, it can be easily detected that sectional profiles are also shifted in the way to reduce the area from the lines.

Figure 6.2: Comparison of the lines between initial and Optimal
### Table 6.3: Definition of optimization application

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Hull</td>
<td>DTMB Model-5415</td>
<td>Model-Scale</td>
</tr>
<tr>
<td>Objective Function</td>
<td>$1.C_W$</td>
<td>Wave drag Coeff.</td>
</tr>
<tr>
<td></td>
<td>$2.(R)$</td>
<td>Sea-Keeping Index</td>
</tr>
<tr>
<td>Constraints</td>
<td>Volume</td>
<td>By Parameter for SAC</td>
</tr>
<tr>
<td>Design Variables</td>
<td>Parameter</td>
<td>4 variables</td>
</tr>
<tr>
<td>Optimization Algorithm</td>
<td>MOGA</td>
<td></td>
</tr>
<tr>
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<td>Shifting</td>
<td>Using initial surface</td>
</tr>
<tr>
<td>Flow Solver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.Drag</td>
<td>$SSF$</td>
<td>Neumann-Michell linear flow model</td>
</tr>
<tr>
<td>2.Sea-Keeping</td>
<td>Bales’ Ranking Method</td>
<td></td>
</tr>
<tr>
<td>Hull Variation</td>
<td>Whole Surface</td>
<td>Fixed the sonar dome</td>
</tr>
<tr>
<td>Design Speed</td>
<td>2</td>
<td>$F_N = 0.28 &amp; 0.45$</td>
</tr>
</tbody>
</table>

### 6.3 Application of Multi-Objective Optimization to DTMB Model-5415

In this section, the DTMB Model-5415 is used for a given multi-objective problem, minimization of the wave drag coefficient($C_W$) and maximization of Sea-Keeping Ranking($R$), while displacement constraints condition is applied in the generation of the sectional area curve during optimization cycle. Table 6.3 describes a summary of the present application. Particularly, the wave drag coefficient is minimized at the two single design speed ($F_N = 0.28 \& 0.45$) and one speed range between $F_N = 0.28$ and $F_N = 0.45$. The surface modification is based on the SAC variation with the shifting method. 4 parameters are adapted as design variables to deform the initial hull form in the present application as follow:

- **Sectional area curve**

  Entrance angle in bow ($\alpha_e$)

  Trailing angle in stern ($\alpha_s$)

  Nondimensional area of the fixed station for Fore-body ($A_f$)

  Nondimensional area of the fixed station for Fore-body ($A_o$)
Table 6.4: Objective functions for each optimization case

<table>
<thead>
<tr>
<th>Case</th>
<th>Objective Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case − 1</td>
<td>$f_{\text{obj}}^1$, $f_{\text{obj}}^3$</td>
</tr>
<tr>
<td>Case − 2</td>
<td>$f_{\text{obj}}^2$, $f_{\text{obj}}^3$</td>
</tr>
<tr>
<td>Case − 3</td>
<td>$f_{\text{obj}}^1$, $f_{\text{obj}}^2$, $f_{\text{obj}}^3$</td>
</tr>
</tbody>
</table>

In addition, three objective functions are defined as follows:

\[
f_{\text{obj}}^1 = \frac{(C_i^w - C_0^w)}{C_0^w} \text{ at } F = 0.28 \quad (6.3a)
\]

\[
f_{\text{obj}}^2 = \frac{(C_i^w - C_0^w)}{C_0^w} \text{ at } F = 0.45 \quad (6.3b)
\]

\[
f_{\text{obj}}^3 = -R \quad (6.3c)
\]

where $C_0^w$ and $C_i^w$ denote the wave drag coefficients evaluated for the initial hull form and intermediate hull form obtained during the optimization process, respectively, and $R$ is the seakeeping ranking.

At first, the parametric study is performed in order to observe the response of the each objective function respect to each parameter. In Figs. 6.3(a) − (c), the result of parametric study is shown according to the drag wave coefficient and the seakeeping index in terms of each parameter. Overall, the results are reasonable. For instance, the drag is improved with decreasing the entrance angle while the Bales’ Sea-Keeing rank ($R$) is decreased because of a reduction of the waterplane area.

In order to compare the optimal results according to the each objective function, three cases are selected. The first two (Case − 1 & Case − 2) are corresponding to the two single design speed at $F_N = 0.28$ and $0.45$. Meanwhile, last (Case − 3) is selected the optimal hull form which consists the Pareto front of the run with speed range. In Figs. 6.4(a) − (c), the last solutions is displayed in the criterion space in terms of $F_{\text{obj}}^1 - F_{\text{obj}}^2$, $F_{\text{obj}}^2 - F_{\text{obj}}^3$, and
\( F_{\text{obj}}^3 - F_{\text{obj}}^1 \) with the population which are generated in the course of optimization cycles. The maximum iteration number is set as 200, which yields in 1959 of the number of the total objective function evaluations. Additionally, it is not necessary to use resistance value as an objective function because there is no large deformation which possibly provides a large variation of wetted surface area and volume, as mentioned in the previous chapter.

![Parametric Study](image)

(a) \( C_W \) at \( F_N = 0.28 \)  
(b) \( C_W \) at \( F_N = 0.45 \)  
(c) Sea-Keeping Rank \((R)\)

**Figure 6.3: Parametric Study**

In fact, the variation of the final three optimal solutions are less than 0.1% the wetted surface area. Particularly, all three optimal solutions are resulted in the increase of the displacement which is favorable. The summary of 3 optimal solutions are shown in the Table 6.5. Three multi-objective optimization cases are then considered. The objective
functions used in each case are listed in Table 6.4.

The minimum drag reduction is achieved by 14.5%, and the sea-keeping ranking, $R$, is increased by 0.75. In the Fig. 6.5, the wave drag coefficient are compared for a small range of speed which includes the design speed. Additionally, the corresponding SAC are plotted in Fig. 6.6. Particularly, the case (Case – 3) which considering an improvement of the both objective functions shows that its hull form is somewhat between the other two optimal hull forms. For example, Case – 3 is almost same with Case – 1 around the mid fore-body, Case – 1 around the mid aft-body. This fact can be also detected in Fig. 6.7 which describes the lines of 3 optimal hull as well as the initial.

A comparison of the optimal hull forms according to the single-objective and multi-objective application in terms of the sea-keeping performance. The first optimal hull is the
Table 6.5: Variations of wave drag coefficient ($C_W$) and Sea-Keeping Ranking ($R$) (Initial Hull=100% & $R = 5.39$)

<table>
<thead>
<tr>
<th>Case</th>
<th>$\nabla$(%)</th>
<th>$S_{\text{wet}}$(%)</th>
<th>$C_W^1$(%)</th>
<th>$C_W^2$(%)</th>
<th>Sea-Keeping Ranking($R$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>104.4</td>
<td>100</td>
<td>87.5</td>
<td>94.9</td>
<td>5.73</td>
</tr>
<tr>
<td>Case 2</td>
<td>102.7</td>
<td>100.1</td>
<td>110.3</td>
<td>91.4</td>
<td>6.00</td>
</tr>
<tr>
<td>Case 3</td>
<td>100.0</td>
<td>100.1</td>
<td>91.1</td>
<td>94.4</td>
<td>5.73</td>
</tr>
</tbody>
</table>

Figure 6.5: Comparison of the wave drag coefficient between initial and Optimal

Figure 6.6: Comparison of SAC between initial and Optimal
result of the single-objective optimization which is obtained by using GA and the other is the optimized hull form from the multi-objective application using MOGA. A comparison of the SAC and the lines are displayed in Fig. 6.8 and Fig. 6.9. As a result, two optimal hull forms are resulted in the almost identical. In fact, the Bales’ Sea-Keeping rank of GA and MOGA hull form are 6.04 and 6.00, respectively.

Finally, a comparison of the optimal hull forms according to the single-objective and multi-objective application in terms of the wave drag coefficient. The first optimal hull is the result of the single-objective optimization which is obtained by using GA and the other is the optimized hull form from the multi-objective application using MOGA. A comparison of the SAC and the lines are displayed in Fig. 6.10 and Fig. 6.11. As a result, two optimal
hull forms show little different phase in both the SAC and the lines, particularly in the mid fore-body and in the stern area. In addition, the wave drag coefficient curves are shown in the Fig. 6.12. As expected, the result from the GA provides a slightly larger reduction at the design speed.
Figure 6.11: Comparison of the lines between $C_W$ Optimals of GA and MOGA

Figure 6.12: Comparison of the wave drag coefficient between $C_W$ Optimals of GA and MOGA
Chapter 7: Conclusions

A practical hydrodynamic optimization technique for ship hull design has been developed in terms of the surface representation and modification module and optimization algorithm module using two flow solvers, a simple potential flow code SSF based on Neumann-Michell theory and an advanced incompressible Euler/RANS flow code FEFLO based on finite element method.

Surface Representation

The NURBS surface representation technique has been used to model both the initial and the intermediate hull forms during the optimization process. Since a large number of design variables is needed to define hull form variations represented by NURBS, the grouping method is introduced to reduce the number of design variables. In particular, the dependent design variable whose position is affected by the variation of its independent variables is reduced by the grouping method based on the exponential spline technique. Furthermore, two parametric hull representation approaches are implemented for the optimization of parametric hull form design by making use of the shifting technique in order to modify the hull forms during the optimization cycle.

Optimization

The single-objective problems are optimized by using both a local search and a global search algorithm. Gradient-based method is successfully applied for the quadratic optimization problem. However, this algorithm cannot be applied to find the global solution in a design space that includes a number of local maximums and minimums such as the Griewank function. Therefore, two different global search techniques are implemented to
determine the global optimum solution. Specifically, the Genetic Algorithm (GA) is successfully utilized to provide the global solution. The Particle Swarm Optimization (PSO) is also implemented to search the global optimal solution. Both global search algorithms are very efficient. Finally, multi-objective optimization problems are considered by using the multi-objective genetic algorithm (MOGA) with Pareto Optimality by Ranking method. With this approach, a set of Pareto optimal is successfully provided for the 2-dimension multi-objective problem.

**Application-I**

At first, the bow of the Wigley hull has been optimized for various objective functions. For the case of the multi-design speed using the total drag coefficient ($C_T$) at the model scale yields in 45% and 15% of the wave drag and the total drag coefficients, respectively. It has been found that the use of the multi-design speed is necessary to provide less drag over a wide range of Froude numbers. In particular, it has been noticed that the consideration for the variation of wetted surface area must be included to evaluate the objective function during the optimization process. Thus, another objective function is implemented by the total drag resistance ($R_T$) which includes the wetted surface area. As a result, the drag reductions of the wave and the total resistance has been achieved at most 50% and 20% with multi-design speed in Table 5.4. In particular, the variation of the wetted surface area and the displacement are restricted within 0.5%. Furthermore, the optimization for the bow and stern parts has been applied with 81% and 41% of the wave and total drag ($R_W$ & $R_T$) reductions for the full scale and 75% and 20% reductions for the model scale. In addition, validation has shown that the optimal hull form via a simple flow-code (SSF) reasonably provides the drag reductions using the advanced flow solver (FEFLO). Meanwhile, a study on the comparison of optimization algorithms has been carried out. One local search algorithm (Gradient-based method), two global techniques (GA and PSO) and one multi-objective optimization (MOGA), have been implemented for this study. The two global algorithms yield in a larger reduction than the local search. Finally, the Wigley hull has been
optimized using the proposed parametric hull representation technique. In this technique, the given hull is expressed by the three parametric curves: sectional area curve (SAC), waterline curve and the longitudinal profiles at the given stations. The optimal hull is especially in a fair shape as a result and the reductions of drag are also quite satisfactory.

The KCS as an example of a modern container ship has been optimized in terms of the wave drag coefficient ($C_W$) by using the parametric hull variation. Since sectional area curve is the main parametric curve, the shift approach for the given stations along the longitudinal direction has been implemented. Even with the complexity of the geometry, the optimal hulls have been obtained with a fair surface. Especially, both flow solvers, SSF and FEFLO, have been utilized to guide the given initial hull to minimize the wave drag coefficient.

Another application is the surface combatant ship, David Taylor Model Basin Model-5415 (DTMB Model-5415) as an complex hull form which has sonar dome and stern. The same optimization technique with the KCS has been adapted. Since the variation have been conducted by the geometric parameters, the optimal hull forms by both flow solvers are in fair shapes.

At last, the application in this thesis is the optimization of the well-known Series-60 ($C_b = 0.6$). Especially, both the NURBS surface representation technique and the parametric hull variation approach are employed in this application. The reduction of the wave and total resistance has been obtained smaller than for any other applications. However, the applied hull variation technique for this hull is meaningful as a result of the use of direct (NURBS surface) and indirect (Parametric) hull representation approaches at the same time.

**Application-II**

As the last application in this dissertation, a multi-objective optimization for minimization of the wave drag coefficient and improvement of the sea-keeping performance in the long crested, head seas is selected. Bales’ Sea-Keeping ranking method has been applied
to determine a sea-keeping index during the optimization cycles while a simple flow solver (SSF) has been employed to evaluate the drag. As an initial hull, a navy surface combatant (DTMB Model-5415) has been optimized to reduce the wave drag and to improve the sea-keeping index, simultaneously. Additionally, a parametric study has been performed in order not only to observe the response of each objective function with respect to each parameter but also to check whether the surface representation technique properly produces new hull forms. Overall, the results are reasonable and provide a clear relationship with different objective functions. Finally, the optimization has been achieved by using two single design speeds and one design speed range for the wave drag coefficient. Therefore, 3 objective functions are considered for the case of design speed while 2 objective functions are optimized for the case of single speed. As a result, 3 hull forms have been obtained which are somewhat different in the fore-body and similar in the aft-body. As expected, two single design cases provide the maximum drag reduction at the given speed as well as sea-keeping performance. However, the case with multi-design speed provides a better reduction within the given speed range.
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Bibliography


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Curriculum Vitae

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