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A Study on the Optimum Structural Design for Oil Tankers Using Multi-Objective Optimization

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ABSTRACT

Recently, the importance of multi-objective optimization techniques and stochastic search methods is increasing. The stochastic search methods have the concepts of the survival of the fittest and natural selection such as genetic algorithms(GA), simulated annealing(SA) and evolution strategies (ES). As many accidents of oil tankers cause marine pollution, oil tankers of double hull or mid deck structure are being built to minimize the marine pollution. For the improvement of oil tanker design technique, an efficient optimization technique is proposed in this study.

Multi-objective optimization problem of weight and cost of double hull and mid deck tanker is formulated. Discrete design variables are used considering real manufacturing, and the concept of relative production cost is also introduced.

The ES method is used as an optimization technique, and the ES algorithm was developed to generate a more efficient Pareto optimal set.

1. Introduction

Most of oil tankers built these days are double hull type or mid-deck type which are developed to prevent marine pollution in case of accident. This paper aims at the presentation of superior design point for minimum weight and minimum cost using multi-objective optimization technique. Since ship structural design is an optimization problem with many non-linear constraints, it has been traditionally performed by direct search methods with penalty functions. The direct search methods, however, cannot grant the consistent solutions because of the convergence to the local minimum, and also cannot treat discrete design variables effectively.

For the first time, multi-objective optimization problem was studied by Pareto[1] in 1896. Since 1970's, there have been many researches on this subject. Many of the early efforts to solve such multiple objective problems by conventional single objective methods are directed towards deriving a single objective from the multiple objectives on the basis of compromise or trade-off.

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To overcome these problems, the introduction of the stochastic search methods such as genetic algorithms(GA), simulated annealing(SA) and evolution strategies(ES) is indispensable. GA is the algorithm which is based on the principle of the survival of the fittest and natural selection, SA imitates the stabilization process of metal structure in metal engineering, that is to say, is the algorithm that simulates the forming process of the most stable molecular structure in given temperature(environment). ES combines the generation and mutation of GA with the annealing of SA.

In this paper, ES is chosen among these methods to perform optimum design. When (1+1)ES is used, it has the feature of direct search method which has less possibility of escaping from local minimum. In single objective optimization problem, linking (1+1)ES and $(\mu+\lambda)$ES has the advantage of reducing time to search the global optimum point. In multi-objective optimization problem, if $(\mu+\lambda)$ES controls the number of μ (parent numbers) according to the number of Pareto points, it gives the better results. In this paper, it is shown that ES is available for actual ship design, and what the results are achieved.

2. Basic algorithm of Evolution Strategies (ES)

The theory of ES was proposed by Rechenberg[5], developed and verified by Schwefel[6] and which has been used until now.

2.1 Survival of the Fittest : the (1+1)ES Method

It is the method that uses the law of the survival of the fittest. That is based on a population consisting of one parent individual and one child individual, created by adding normally distributed random numbers to every individual of the vector. The better of both individuals serves as an ancestor of the following iteration(generation).

2.2 Elimination of the Worst : the $(\mu+1)$ES Method

With the introduction of μ parents instead of only one, imitation of sexual reproduction is possible, and consequently, realized with the additional recombination. Two parents $a(x_a,\sigma_a)$ and $b(x_b,\sigma_b)$ are internally chosen in population P', and $a'(x',\sigma')$ is produced.

The selection step removes the least-fit individual(the offspring or parents) from the population before the next generation starts, producing one new descendant.

2.3 The $(\mu+\lambda)$ES and (μ, λ)ES Methods

As $(\mu+\lambda)$ ES suggests, μ parents produce λ offspring and the whole population is reduced again to the μ parents of the next generation; in other words, the selection operates on the joined set of parents and offspring. Thus parents survive until they are superseded by better offspring. In (μ,λ)ES, only the offspring undergo selection, whereas the ancestors are forgotten; hence $\lambda > \mu$ must be valid.

The major difference with $(\mu+1)$ES result from the handling of the internal strategy vector σ which now is incorporated into the genetic information of the individual and no longer controlled by 1/5 success rule.

3. The Hybrid ES Method (HES)

There are some different properties between $(\mu+\lambda)$ES and (1+1)ES. The $(\mu+\lambda)$ ES has little probability to get local minimum value, but needs more CPU-time than (1+1)ES. In the near of the optimum point, the convergence rate of $(\mu+\lambda)$ ES is worse than (1+1) ES. So we can choose only good properties from the two method, and combine them to make the hybrid optimization method. This method is suggest by linking (1+1)ES and $(\mu+\lambda)$ ES. First, it starts with $(\mu+\lambda)$ES until goes to near the optimum point, and then turn to (1+1)ES to increase convergence rate.

4. Multi-objective optimization problem

The standard techniques for generating the Pareto set in Multicriteria optimization problems are weighting method and constraint method. The two major difficulties in the weighting method are as follows.

(1) If the Pareto curve is not convex, there does not exist any weight for which the solution to problem lies in the nonconvex part.

(2) Even if the Pareto curve is convex, an even spread of weights does not produce an even spread of pints on the Pareto curve.

The constraint method is a technique that transforms a Multicriteria objective function into a single criterion by retaining one selected objective as the primary criterion to be optimized and treating the remaining criteria as constraints. Specially, it is difficult to gain the global minimum point in the problem with local minimum point such as Test 1.

ES does not need gradient at design point but objective function and constraints, so it is easy to use and apply to non-convex problem and optimization of discrete multi-objective function.

Without any information about design space beforehand, the entire shape of the Pareto set was gained. In convex problem as well as non-convex problem, the Pareto set was partially gained by using weighting method. ES is faster than GA in computation, so ES program is robust tool for the optimization of multi-objective function.

Test 1

Minimize $F_1 = -x_1 + 5x_2$, $F_2 = x_1 + x_2$

subject to $g_1(x) = 1 - x_1^2 - x_2^2 \geq 0$, $g_2(x) = 1 - (x_1 - 1)^2 - x_2^2 \geq 0$

$g_3(x) = 1 - (x_1 - 2)^2 - x_2^2 \geq 0$, $0 \leq x_1 \leq 5.0$, $-2.0 \leq x_2 \leq 2.0$

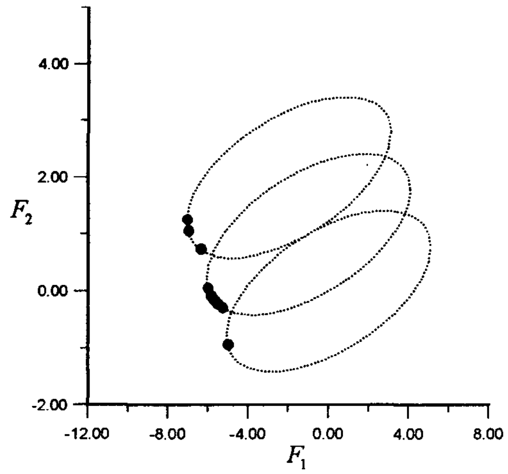


Fig.1 Test 1 ES(10+100)

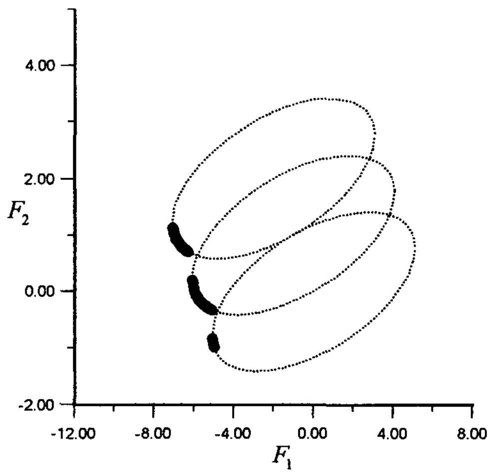


Fig.2 Test 1 ES(50+500)

Table 1 Comparison of time by ES and GA (with PC486)

	ES(sec)	GA(sec)
Test 1	(10+100) 6.21	11.10
	(50+500) 60.00	110.00

5. Application to design of oil tankers

To get the good Pareto set, it is important to choose a proper terminating condition. If generation (iteration) number is not included in convergence condition, neither ES nor GA can give the good result. GA generates the Pareto set according to population size and ES also does according to the size of parent points. To make up for this weakness, all the good adaptive points are selected as new parent points among the parent and children points. Then, if the number of points are small than that of parent points, some points not Pareto set are selected randomly to compensate parents points. Strictly, this method is not $(\mu+\lambda)$ES, but it has more efficiency in time and generation of good Pareto set. Selecting all the Pareto points as parent points reduces the number of children points and increases fitness. And if the value of objective function as well as σ of selected parent points move as a group, it results in reducing calculation time. As shown in Table 2 and Fig. 6, (10+100)ES in this paper was compared with original (10+100)ES. The former has more advantage in time and result. The object of design is the midship section of double hull tanker Type 1 in Fig. 4, whose objective function is the weight and cost of midship section. The weight is converted into the material cost per unit length for the same unit and the cost into production cost per unit length .

$$f_1 = f_{material}$$

$$f_2 = f_{material} + f_{wellding} + f_{paint} + f_{cutting}$$

The design variables are as follows :

Bottom (center) longitudinal space(x_1), bottom(side) longi. space(x_2), side part longi. space(x_3), hopper tank longi. space(x_4), top side tank longi. space(x_5), deck plate thickness(x_6)

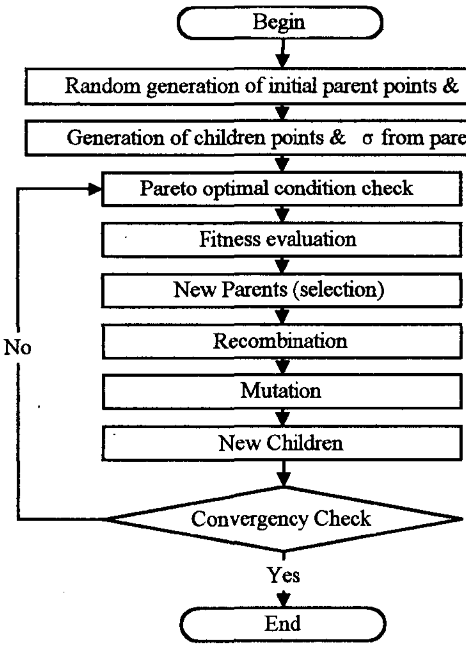


Fig.3 ES algorithm for generating Pareto optimal set

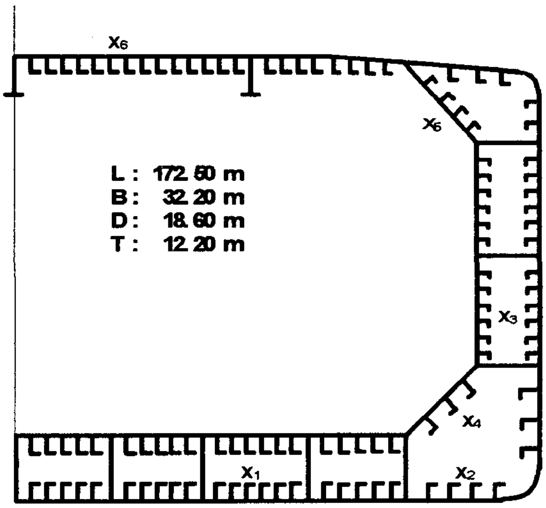


Fig. 4 Midship section of double hull oil tanker

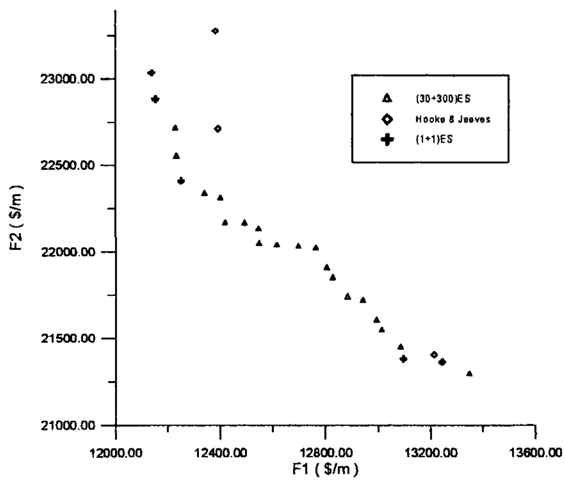


Fig. 5 Pareto sets of each methods (Type 1, Lloyd base)

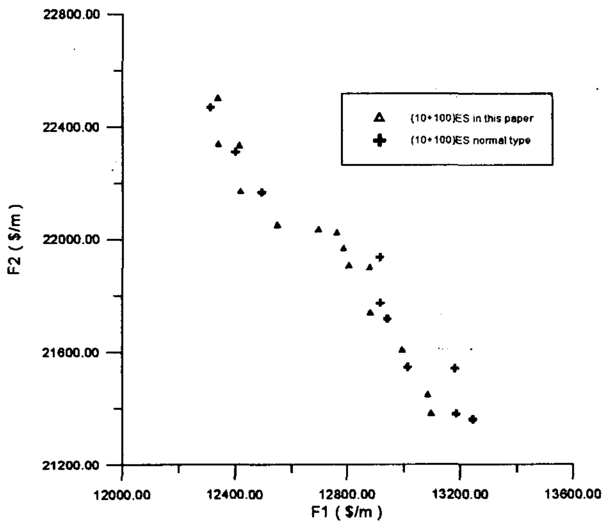


Fig. 6 Two types of ES with Pareto set

The values of deck plate thickness are calculated with discrete value(0.5 mm). The values of longi. spaces are determined from 600 mm to 950 mm by the number of longitudinals (an example of x_1 : 620, 660, 690, 740, 780, etc.). All dimensions except that of deck plate are minimum value by rule according to the variation of longi. space. The constraint conditions are minimum dimension of deck and minimum section modulus of deck and bottom by rule. In Fig. 5 and Table 2 there are Pareto set which compare Hooke & Jeeves direct search method(HJ) and (1+1)ES using weighting method with (30+300)ES in respect of time and performance.

Weighting factor is selected 11 cases (k = 0.0, 0.1, 0.2, ..., 1.0). Since the direct search method have difficulty in dealing with discrete design variables, only the deck plate thickness was used as a design variable, discrete variables of longi. spaces were used as parametric variables, in optimization algorithm. As expected, HJ searched four of eleven points and (1+1)ES did five. All of these points are not acceptable as Pareto point. HJ is faster than others, but it searched one Pareto point and even that point is not global minimum. (1+1)ES searched four Pareto points, but it has disadvantage in time. Above two method are strongly depended on initial point. On the contrary, (30+300)ES is independent on initial point and it extracts rapidly good result. The direct search method such as HJ and (1+1)ES is not available for multi-objective optimum design.

Double hull tanker has so many merits that design is easy for the similarity to conventional tanker. It is good for maintenance and management of cargo hold, and lighter than mid-deck tanker. But it has more the risk of explosion, may lose buoyancy in an accident, and may have disadvantage such as a lot of oil flow. Mid-deck tanker has the merit to have little oil flow and not to lose buoyancy in an accident, but it has more difficulties in maintaining and managing the cargo holds. Also its weight tends to increase. Fig. 7 ~ Fig. 10 show that, in each ship type, type 2 is more effective than type3 in the respect of weight or cost, and double hull type is more effective than mid-deck type. Deck thickness of type 2 is bigger than that of type 3, because type 3 has one more longitudinal bulkhead than type 2. But total midship area and welding length of type 2 are smaller than type 3. In the respect of weight and cost, type 2 must be selected more than type 3, and double hull type more than mid deck type.

Table 2 Comparison of search time (with PC486)

Method	Time (sec)
HJ	215
(1+1)ES	9421
(30+300)ES	648
(10+100)ES normal type	241
(10+100)ES in this paper	202

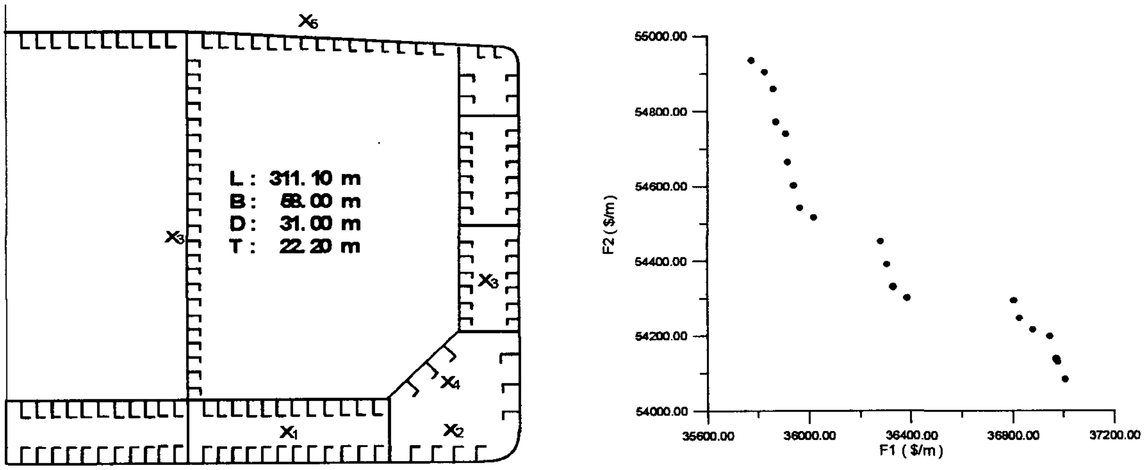


Fig. 7 Midship section of double hull oil tanker and calculation result (Type 3, DnV base)

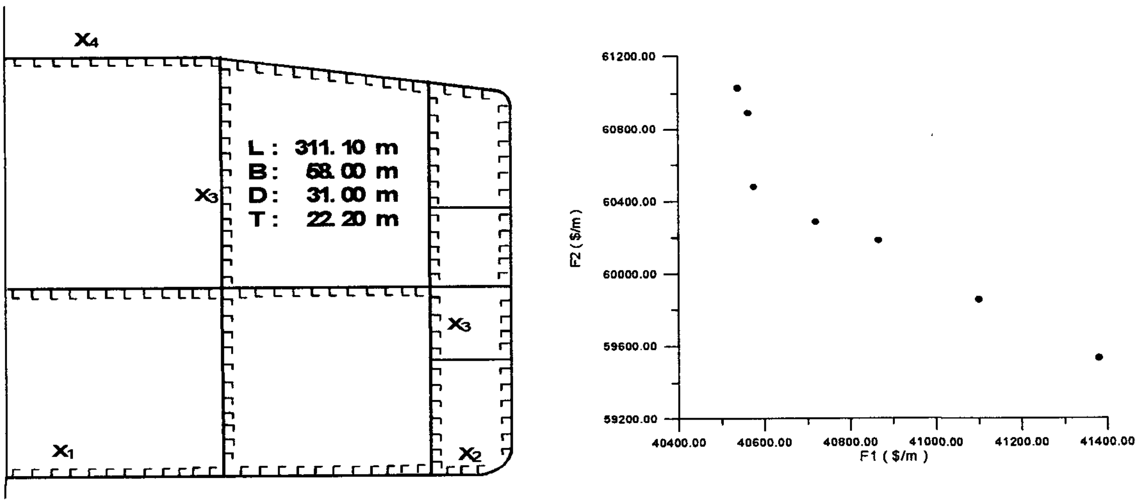
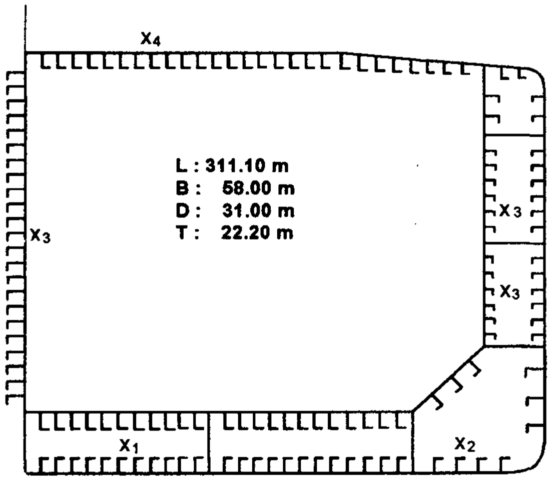


Fig. 8 Midship section of mid-deck oil tanker and calculation result (Type 3, DnV base)



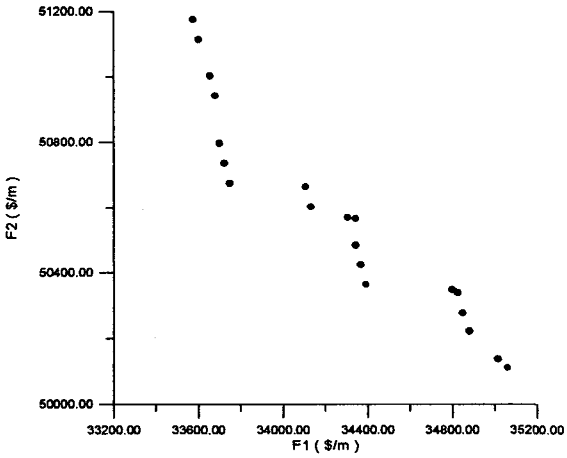
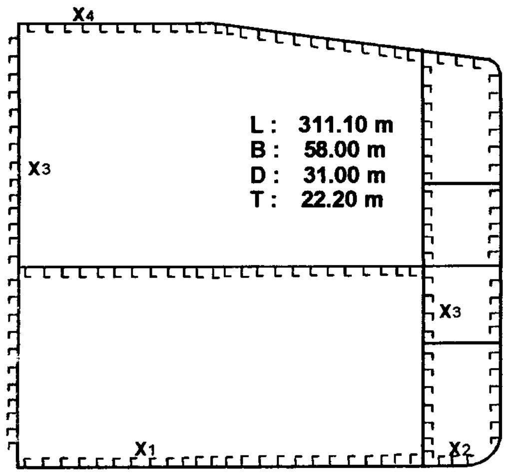


Fig. 9 Midship section of double hull oil tanker and calculation result (Type 2, DnV base)



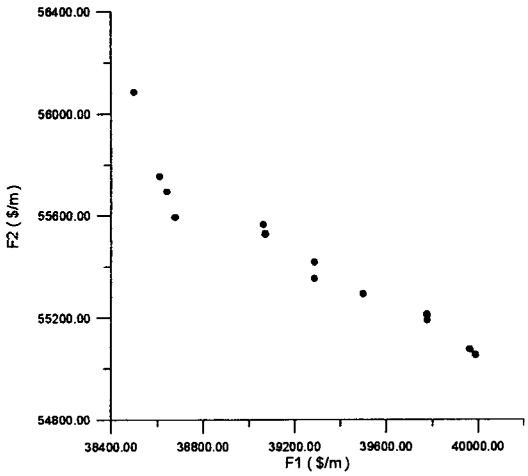


Fig. 10 Midship section of mid-deck oil tanker and calculation result (Type 2, DnV base)

6. Conclusions

New algorithms for multi-objective optimization problem are established, and the structural design of oil tankers for the protection from marine pollution has been carried out.

The main conclusions of this work can be summarized as follows :

(1) In single objective optimization problems, the hybrid optimization method(HES) is developed by linking (1+1)ES and ($\mu+\lambda$) ES considering their merits. By this approach it is possible to search the global optimum point more efficiently and rapidly than the usual stochastic search methods.

(2) The weighting method and constraint method are not available in multi-objective optimum design, because it is difficult to generate Pareto optimal set using them. However, the ES program is an effective and robust tool for multi-objective optimization problem.

(3) To get a good Pareto optimal set, all the good adaptive points should be selected as new parent points among the parent and child points. To select all the Pareto points as parent points reduces the number of child points and increases fitness.

(4) Comparing each type of the oil tanker, the double hull type is more effective than the mid-deck type and type 2(one centre longitudinal bulkhead) is more effective than type3(two centre longitudinal bulkheads) in the respect of weight or cost. The deck thickness of type 2 is bigger than that of type 3, because type 3 has one more longitudinal bulkhead than type 2. But total midship area and welding length of type 2 are smaller than type 3. Therefore type 2 is more effective.

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