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Lifting Lug by the Change of form Using Multivariate Functions: An Optimal Design Study

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다변수 함수를 이용한 형상 변화에 따른 리프팅 러그의 최적 설계에 관한 연구

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ABSTRACT

In this paper, we proposed an optimal design for determining the shape of a lifting lug freely by applying a multivariate function to the D-type lug, which is commonly used in shipyards. We derived the optimal aspect ratio of the lug through structural analysis and analyzed the safety and behavior of the lug aspect ratio. As a result, two types of final candidates, both lighter than the existing lug weight, were suitable for the ratio. They were found to have the greatest force at an angle of 45 degrees when a load of 100 tons was imposed. When the horizontal and vertical feature ratio of the lug was 1:3, it showed excellent results in terms of safety rates while maintaining weight reduction and functional aspects.

Key Words : Aspect Ratio(종횡비), Lifting Lug(인양 고리), Safety Factor(안전율), Fitness(적합도), Pop-Size(집단 크기), Mutation(돌연변이), Generation(세대), Crossover(교배/교차)

1. Introduction

In shipbuilding and offshore engineering, an essential aspect in the building and fabrication of ships is the salvaging and turnover of blocks. The number of lifting lugs for this process increases as the size of the structures at the block level increases. Because lug costs are of the production, installation, and removal processes are high, an analysis on cost-saving measures through lightweight lug design is required. Previous studies have investigated improving the reuse rate of a lug, which consists of consumable material,[1] with a cost-saving method using an automated system that d

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etermines the best location for lug placement as well as the optimal quantity.[2-5] Additionally, in developing an automatic cutting device, feasibility studies have been conducted to solve problems such as different cutting heights from manual works using the cutter during lug removal process after block salvaging, as well as the resulting paint damage occurring on the opposite side of the lug.[6] In evaluating structural stability, previous studies have investigated proposed designs of the lug's main body, a central hole in a lug, and the final force caused by internal and external loads.[7-10] Other studies evaluated a design considering various loads[11] and the establishment of an algorithm-based optimal lug design system.[12-13] Furthermore, research has been conducted on the parametric design of a lug requiring structural improvement, analyzed its impact on various variables, and predicted the effectiveness of the developed system; however, structural analysis and a durability performance test have not been conducted regarding the design of the predicted lug. This study applies a genetic algorithm to a multivariate function for a type-D lug, commonly used in dockyards, not only deriving the optimal aspect ratio for a lug shape but also proposing the optimal structural design for a designer to freely evaluate the stability based on the lug aspect ratio from structural analysis and behavioral model analysis for lug weight reduction.

2. Structure of a D-type lug

The lugs used for ships can be categorized into A, L, T, D-types according to the block shape, load direction, and lug attachment location. The type of lugs primarily used for salvaging the heaviest ship block is the D-type, whose safety weight is > 100 tons. Fig. 1 illustrates a D-type lug.

A lug is composed of double plates, i.e., the main body and bracket. This study optimizes the structural design for the lug shape using a multivariate function of at least two variables expressing each component's shape and a genetic algorithm for approximation.

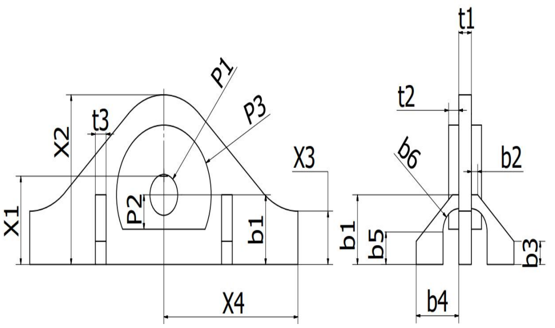


Fig. 1 Lifting lug design of D100

3. Optimization design module

3.1 Application of a genetic algorithm and multivariate function

Genetic algorithms are used for optimization problems whose object is continuous, differentiable, and freely accessible with no constraints in the search space. In genetic algorithms, decoded chromosomes, after the initial group formation and fitness test for chromosomal strengths and weaknesses, provide the object function, recalculate the fitness, select the appropriate entities to go through the reproduction process of forming the next generation group, and randomly alter the genes via crossovers for information exchange and mutations to finally introduce changes into the group. The group is formed by reproduction, crossover, and mutation for one generation, and the best solution is obtained by repeating these operations previously performed.

For lug shape optimization, a random number is set as the aspect ratio of a multivariate function of more than two independent variables associated with the purpose of conventional lug use. Equation (1) defines the optimization problem with the multivariate function:[14]

$$Optimization : F(X),\ X \in \Omega \qquad (1)$$

where $X = [X_1 \cdots X_n]^T$ is an $n \times 1$ vector, n is the dimension of x, F : $\Omega \rightarrow \Re$ is a function, and Ω is the n-dimensional solution space. The judgment criteria for optimizing the multivariate function is Equation (2):

$$\begin{aligned} F(X) &= F(X^{*}+\Delta X) \\ &= F(X^{*}) + \nabla F(X^{*})^{T}\Delta X + \frac{1}{2!}\Delta X^{T}\nabla^{2} \\ & F(X^{*})\Delta X + O_{3}(\Delta X) \end{aligned} \tag{2}$$

$F(X)$ is expanded as a Taylor series at $X=X^{*}+\Delta X$ near an arbitrary point $X^{*}\in\Omega$; $\Delta X = X - X^{*}$ For the third and higher-order terms $O_3(\Delta X)$, $\nabla F(X^{*})$ is an $n\times 1$ vector as in Equation (3):

$$\nabla F(X^{*}) = \left[\frac{\partial F(X)}{\partial_{X_1}}\ \frac{\partial^{2}F(X)}{\partial_{X_2}}\ \cdots\ \frac{\partial^{2}F(X)}{\partial_{X_n}}\right]^{T}_{|X=X^{*}} \tag{3}$$

Ignoring the higher-order terms in Equation (2) to find the maximum and minimum points of X^{*} leads to the expression in Equation (4):

$$\begin{aligned} \Delta F(X) &= F(X) - F(X^{*}) = \nabla F(X^{*})^{T}\Delta X + \frac{1}{2!} \\ & \Delta X^{T}\nabla^{2}F(X^{*})\Delta X \end{aligned} \tag{4}$$

X^{*} is a global solution if it holds for all $X\in\Omega$ and is a maximal or minimal point if it satisfies Equation (5) for all X that is $\|X-X^{*}\| \leq \delta$ for $\delta > 0$.

$$\begin{aligned} \Delta F(X) &= F(X) - F(X^{*}) \ \geq\ 0 \\ \Delta F(X) &= F(X) - F(X^{*}) \ \leq\ 0 \end{aligned} \tag{5}$$

3.2 Formulation of a D-type lug structure

For the range of the shape that can maintain the lug's functional aspects, individual variables are set at a particular ratio to generate the random numbers that have the maximal and minimal values. The independent variable for the chromosomal information using these random numbers to implement the optimal shape through crossovers is represented as Equation (6).

$$\begin{aligned} q_1 &= (q_{1max} - q_{1min})rand + q_{1min} \\ q_2 &= (q_{2max} - q_{2min})rand + q_{2min} \\ x_3 &= (x_{3max} - x_{3min})rand + x_{3min} \\ t_1 &= (t_{1max} - t_{1min})rand + t_{1min} \end{aligned} \tag{6}$$

where q_1, q_2 are arbitrary random numbers and x_3, t_1 are constants preventing the excessive collapse of the lug shape. The object function is as follows:

$$g_o(X_0),\ g_o(X_1) = fk_1,\ fk_3 \tag{7}$$

where

$$\begin{aligned} fk_1 &= \frac{Pg}{t_1\times\sigma_0\times 2\times p_1} \\ fk_3 &= 5(AR-2)^{2} + 8AR - 4 \\ P_g &= SWL(Safety\ Working\,Load) \\ \sigma_0 &= 235MPa \\ p_1 &= Lug \in side\ Size \\ AR &= (Aspect\ Ratio) \end{aligned} \tag{8}$$

Equation (8) defines the aspect ratio (AR) applied to the algorithm that indicates the value of the randomly changed lug shape. The thickness of the main body of a lug is t_1, which can be determined by Equation (9):

$$t_1 \geq \frac{P_g}{fk_1\times\sigma_0\times 2\times p_1} \tag{9}$$

To optimize lug thickness t_{1min} is applied to the object function $g_o(X_0)$ in the genetic algorithm, and the t_{1max} value is substituted with a randomized number of a maximum value for the current lug shape, which can be derived by Equation (10):

$$k_1 = \sqrt{\frac{fk_3\times p_g}{\sigma_0\times t_1}}\times 0.5 \tag{10}$$

Equation (10) can then be expressed as Equation (11) if symmetries about the aspect ratio k_1 and the horizontal axis are considered.

$$x_4 = k_1^2 \times \frac{2}{AR} \ , x_2 = x_4 \times \frac{2}{AR} \tag{11}$$

Here, the lug shape collapses if the outer radius of the lug's main body is greater than the length x_4 therefore, fk_2 is calculated by inserting a constant to obtain the outer radius R.

$$fk_2 = 0.45 = const. \ \ , \ R = fk_2 \times x_4 \tag{12}$$

The distance from the lug's bottom to the inner center circle $b_1$is expressed as Equation (13). For the $x_3$value, towing > 15 mm without the lug is considered. Additionally, to maintain the shape cut as shown in Fig. 1, the disc shape is determined to be p_2, which satisfies $p_1 < p_2 < p_3$ where p_1 and p_3 are the inner and outer radius, respectively, and q_1, q_2 from Equation (6) are used so the resulting shape will not be affected by crossover.

$$b_1 = x_2 - p_3 - 15 \tag{13}$$

$$p_1 = 44 \ , \ p_2 = p_1 \times q_1 \ , \ p_3 = p_2 \times q_2 \tag{14}$$

b_2, b_4, b_6 are substituted with the existing lug constants and b_3, b_5 are defined in Equation (15) as

$$b_3 = b_1 \times 0.553, \ b_5 = b_1 \times 0.36 - 50 \tag{15}$$

3.3 Lug shape design

The four independent variables (q_1, q_2, x_3, t_1)representing the genetic algorithm's chromosomal information include the shape-defining variables shown in Equation (16).

$$\begin{aligned} x_n &= (x_1, x_2, x_4), \ p_n = (p_1, p_2, p_3) \\ b_n &= (b_1, b_2, b_3, b_4, b_5, b_6), \ t_n = (t_1, t_2) \end{aligned} \tag{16}$$

From a fitness point of view, the possession of high chromosomal chromosomes can be seen approximating the optimal solution. However, selecting the order based on the fitness and determining the parent generation with highly-ranked chromosomes will only result in a lack of genetic diversity and premature convergence; excellent genetic information may be missed and not delivered to the next generation. To overcome this problem, a roulette wheel method, in which a higher probability of becoming a parent generation is set for higher fitness, is selected to create an algorithm that allows those of relatively low fitness values to be chosen as parent generation. Equation (17) is used for the goodness of fit.

$$fitness = \frac{(w_n - w_{1 \cdots n})^{(n*0.34)}}{\sum_{k=1}^{n} w_n} \times 100 \tag{17}$$

where w is the weight of the lug, n is the population size, and pop size and k is the generation. Table 1 presents the parameters of the genetic algorithm.

Table 1 Parameters of genetic algorithms

Variable name	Initial value
Pop size	300
Gen(k)	50
fk_1	1.4825
fk_2	0.45
σ	235
p_1	44
P_g	981000
t_2	32
t_3	34

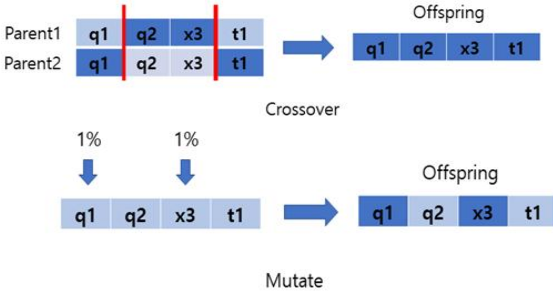


Fig. 2 Multi-point hybridization

There was no singularity in the degree of convergence for group size > 300, and the aspect ratio was optimized at the number of generations of 50. Out of the genetic operators, simple crossover, arithmetic crossover, and multi-point crossover were conducted based on four chromosomes' information to produce chromosomes with a new structure via relative crossover of the chosen chromosomes. Simple crossover can be problematic because of low-genetic diversity. Arithmetic crossover can result in premature convergence when producing mean genetic information of a parent in the children's generation as well as the lack of genetic diversity. However, the multi-point crossover has four pieces of genetic information and is judged to be ideal in lug shape determination. Thus, the multi-point crossover was applied, as shown in Fig. 2. The probability of being selected as a parent generation is high for high fitness values even in the multi-point crossover, which can also be disadvantageous because higher fitness may result in the combination of deselection. Therefore, mutations were produced for genetic diversity at a 2% probability to compensate for this problem. Additionally, crossovers and mutations influencing the changes of the former generation's excellent factors were used as an elite preserving strategy to pass the chromosomal information of the best factors onto the next generation.

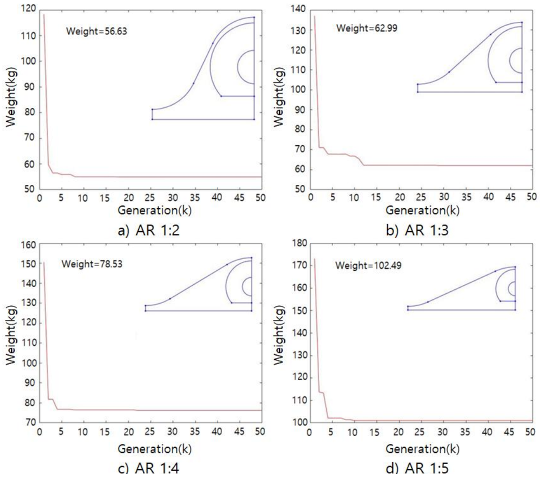
3.4 Aspect ratio in the genetic algorithm

The results from the genetic algorithm using MATLAB R2016a are provided in Table 2. Four candidate groups of shape ratios were selected so that they do not impair the lug functions.

Fig. 3 shows a graph of the lug weight versus the aspect ratio. The y-axis represents the lug weight and the x-axis represents the number of generations. In Fig. 3(a), although convergence occurs when the weight and the number of generations were 56.63 kg and 8, respectively, for the AR 1:2, the shape is unfit for lug's structural function. In Fig. 3(b), with an AR of 1:3, the convergence is reached for the initial number of generations and the weight, 4 and 62 kg, respectively. However, the weight decreases when the number of generations is 10 and then converges when it is 13. In Fig. 3(c), with an AR of 1:4, from the convergence perspective, it can be observed that the graph flattens and stabilizes, rendering this AR a suitable target for structural analysis. Additionally, in Fig. 3(d), with an AR of 1:5, convergence occurs past the weight of the conventional lug at 90.4 kg; thus, this AR is inadequate. In conclusion, the final candidates for the optimal lug aspect ratio based on the algorithm are those shown in Figs. 3(b) and (c), for which structural analyses were performed.

Table 2 Results of lug parameters according to aspect ratio

Aspect ratio		1:2	1:3	1:4	1:5
Lug parameter (mm)	p_1	44	44	44	44
	p_2	76.72	76.72	77.04	76.88
	p_3	115.92	120.01	122.42	120.96
	x_1	147.99	80.34	25.37	-33.85
	x_2	269.07	247.2	253.65	270.81
	x_3	26.44	28.04	25.35	22.78
	x_4	269.07	370.80	507.3	677.01
	R	121.08	166.86	228.29	304.65
	t_1	46.54	46.91	49.37	49.94
	t_2	32	32	32	32
	t_3	34	34	34	34
	b_1	138.15	112.19	116.24	134.84
	b_2	20	20	20	20
	b_3	76.4	62.04	64.28	74.57
	b_4	135	135	135	135
	b_5	0	0	0	0
	b_6	50	50	50	50
weight		56.63	62.99	78.53	102.49



a) AR 1:2 b) AR 1:3

c) AR 1:4 d) AR 1:5

Fig. 3 Lugs geometry of each aspect ratio

4. Structural analysis of lug candidates

The final two candidates' optimized AR ratios that reduce the lug weight while maintaining lug functionality using the genetic algorithm were AR 1:3 and 1:4. To conduct a strength analysis of the selected candidate AR for a 100-ton D-type lug, the commercial finite element analysis software ANSYS 2020 R21 was used. The lug was remodeled as shown in Fig. 4 using the dimensions shown in Fig. 1 and AR 1:3 and AR 1:4. The details of the analysis are presented in Table 2.

The conventional lug used as the reference in this study is a D100 safety load of 100-ton lug (90.4 kg). Considering the characteristics of a hull block, the range of the loading area necessary for salvage is 180˚. The lug material and, therefore, the material used for the test included general mild steel with a modulus of elasticity (E) of 205.8 GPa, a minimum yield stress (σ) of 235 MPa and a Poisson ratio (ν) of 0.3. At 45˚, a maximum of 981 kN was applied. To carefully describe the lug's behavioral phenomena, a horizontal and vertical square grid was created to have a total of 18219 nodes and 4558 elements, and a shell element with six degrees of freedom was applied to each node.

Fig. 5 shows the fracture phenomena at an AR of 1:3 for each angle (in-plane 0˚, 45˚, 90˚; out-of-plane 10˚, 20˚, 30˚).

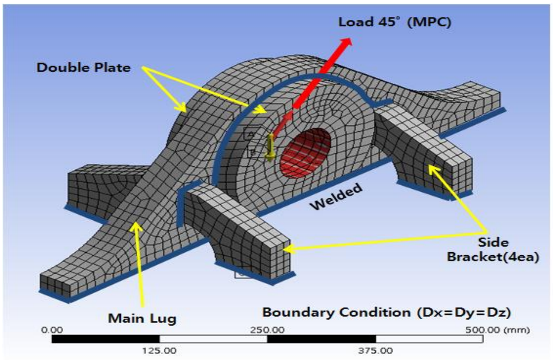


Fig. 4 FE Model and boundary condition

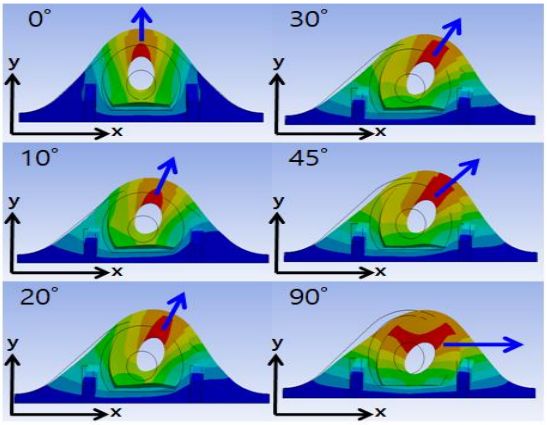


Fig. 5 Stress distribution plot by angle (AR 1:3)

Table 3 Structural analysis results and safety factor of aspect ratio 1:3

Force(N)	Load angle	Yield stress(MPa)	Safety factor
981000	0˚	90.511	11.1
	10˚	106.9	10.7
	20˚	120.52	10.1
	30˚	135.55	9.3
	45˚	159.87	8.1
	90˚	127.92	9.5

Table 3 presents the final strength for each load angle and safety ratio. As the angle increases from 0°, the final strength also increases. At 45°, the maximal load is 159.87 MPa, and the weight reduction is 27.41 kg compared with the conventional lug weight while not exceeding the allowable limits. Fig. 6 shows the lug fracture behavior when angle-wise loads are applied for the shape with an AR of 1:4. For the in-plane load (0°, 45°, 90°) and out-of-plane load (10°, 20°, 30°), the load direction and displacement are shown, and it can be observed that the load value obtained at 45° is near the maximal strength value. Table 4 shows the results for AR 1:4.

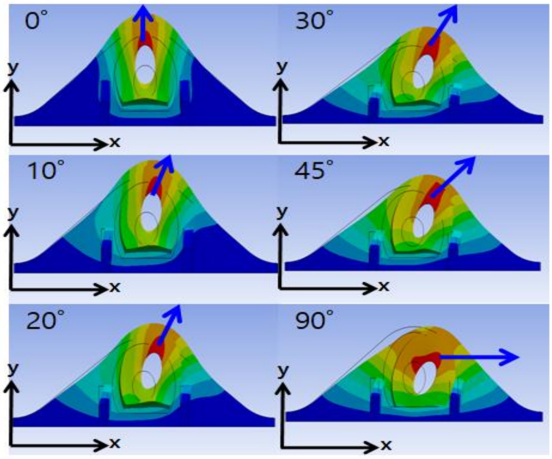


Fig. 6 Stress distribution plot by angle (AR 1:4)

Table 4 Structural analysis results and safety factor of aspect ratio 1:4

Force(N)	Load angle	Yield stress(MPa)	Safety factor
981000	0°	89.765	11.7
	10°	101.01	11.5
	20°	113.09	11
	30°	126.53	10.2
	45°	148.42	8.9
	90°	109.42	10.1

For AR 1:4, the final strength was 148.42 MPa at 45°, and the safety ratio was 8.9, which confirms that weight reduction was optimized at 11.87 kg compared with the conventional weight while not exceeding the allowable limits

4. Conclusion

This study regards the typical lifting lug, D100, currently used in shipyards. We applied a genetic algorithm to a multivariate function, obtained the optimal shape ratios as results, selected two candidate groups that were fit for optimization as final candidates, and accordingly designed the lug's structural aspects. Finally, we performed structural analyses to identify the behavioral phenomena for each loading angle and derived the following results:

1. The results from the genetic algorithm showed that the final candidate groups that can reliably perform lug functions while being more lightweight than conventional lugs were those that were fit for optimization when the aspect rati (x_2, x_4) was 1:3 and 1:4.
2. The load (100 tons) applied to a lug showed maximal force at 45°. Safety factors were 8.1 and 8.9 for AR 1:3 and 1:4, respectively, indicating that a large weight difference does not result in a significant difference in the safety factor.
3. Conclusively, our results show that the weight reduction compared with the conventional lug was the largest for AR 1:3. The final strength and safety factor depended more on the lug thickness than the aspect ratio after the aspect ratio for maintaining lug functions has been considered.

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