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Methodology of Shape Design for Component Using Optimal Design System

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최적설계 시스템을 이용한 부품에 대한 형상설계 방법론

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Abstract This paper describes a methodology for shape design using an optimal design system, whereas generally a three dimensional analysis is required for such designs. An automatic finite element mesh generation technique, which is based on fuzzy knowledge processing and computational geometry techniques, is incorporated into the system, together with a commercial FE analysis code and a commercial solid modeler. Also, with the aid of multilayer neural networks, the present system allows us to automatically obtain a design window, in which a number of satisfactory design solutions exist in a multi-dimensional design parameter space. The developed optimal design system is successfully applied to evaluate the structures that are used. This study used a stress gauge to measure the maximum stress affecting the parts of the side housing bracket which are most vulnerable to cracking. Thereafter, we used a tool to interpret the maximum stress value, while maintaining the same stress as that exerted on the spot. Furthermore, a stress analysis was performed with the typical shape maintained intact, SM490 used for the material and the minimizing weight safety coefficient set to 3, while keeping the maximum stress the same as or smaller than the allowable stress. In this paper, a side housing bracket with a comparably simple structure for 36 tons was optimized, however if the method developed in this study were applied to side housing brackets of different classes (tons), their quality would be greatly improved

요 약 본 논문은 최적설계 시스템을 이용한 형상설계 방법론에 대해 설명하고 있으며, 일반적으로 3차원 해석은 설계를 위해 반드시 필요하다. 퍼지지식처리 수법과 계산기하학적 기법에 바탕을 둔 자동화된 유한요소 메쉬 생성 기법은 상용화된 유한요소해석코드와 솔리드모델러와 함께 시스템에 결합되어 있다. 또한, 다층형 신경망의 도움과 함께 개발된 시스템은 다차원 설계변수 공간에 존재하는 여러 만족하는 설계해인 디자인윈도우를 얻을 수 있게 해준다. 개발된 최적화 설계 시스템 사용된 부품을 평가하는데 성공적으로 적용하였다. 사이드 하우징 브라켓을 현장에서 사용되어지는 굴삭기의 힘과 유압브레이커의 작용하는 응력을 응력 게이지로 사이드 하우징 브라켓의 크랙 발생부위에 부착하여 최대응력이 얼마나 걸리는지를 측정하였다. 적용하는 대상을 현장에서와 동일한 조건하에서 최대응력이 허용응력보다 같거나 적게 하고, 기존형상 유지, 재질은 SM490, 중량 최소화 안전계수는 3으로 하여, 최대응력 값에 대한 해석을 수행하였다. 구조가 비교적 간단한 36톤용 사이드 하우징 브라켓을 최적화하였지만, 다른 클래스의(톤수 별) 사이드 하우징 브라켓 적용 시 품질향상에 크게 기여하리라 생각된다.

Keywords : Computational geometry technique, Design window, Finite element analysis, Neural network, Optimal design

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1. Introduction

Loads for pre-processing and post-processing are increasing rapidly in accordance with an increase of scale and complexity of analysis models to be solved. Particularly, the mesh generation process, which influences computational accuracy as efficiency and whose fully automation is very difficult in three-dimensional (3D) cases, has become the most critical issue in a whole process of the finite element analyses. In this respect, various researches [1-3] have been performed on the development of automatic mesh generation techniques. Among mesh generation methods, the tree model method [4] can generate graded meshes and it uses a reasonably small amount of computer time and storage. However, it is, by nature, not possible to arbitrarily control the changing rate of mesh size with respect to location, so that some smaller projection and notch etc. are sometimes omitted. Also, domain decomposition method [5] does not always succeed, and a designation of such subdomains is very tedious for uses in 3D cases. To meet these problems, evolutional computer technologies like the fuzzy theory and the neural network seem to play key roles. This paper focus on the artificial neural network, and optimal design problem need to be solved.

The system consists of two main portions. The one is an automated finite element analysis system, while the other is a design window search system using the multilayer neural network [6]. Here the design window means an area of satisfactory solutions in a permissible design parameter space. In practical situations, a design window concept seems design window more useful than on optimized solution obtained under some restricted conditions.

The present author has proposed a new automatic finite element mesh generation method for three-dimensional complex geometry [7,8]. To efficiency support design processes of practical structures, this mesh generator is integrated with one of commercial finite element analysis code and one of commercial solid modeler. With an aid of of multilayer neural networks, the system also allows us to automatically obtain a multi-dimentional design window in which a number of satisfactory design solutions exist. The developed system is applied to evaluate one of practical structures.

2. Outline of the System

2.1 Automated finite element analysis

The present optimal design system consists of two main portions. The one is an automated finite element analysis system, while the other a design window search system supported by the multi-layer neural network. A flow of design using the system is shown in Fig. 1.

The developed CAE system allows designers to evaluate detailed physical behaviors of structures through some simple interactive operations to their geometry models. In other words, designers do not have to deal with mesh data when they operate the system.

2.2 Adaptive meshing method

The adaptive mesh generation techniques can be roughly divided into two main categories as categorized in Reference [9]. The first category consists of the mesh enrichment strategies in which more DOFs are added locally in a region with great solution errors. There are three methods in this category. The most common method is the h-version, which achieves solution accuracy by progressive element subdivision selectively reducing element sizes at places of greater solution errors [10]. The quadtree and octree approaches, which spatially decompose a computational domain into rectangular or hexahedral cells, are examples of the h-version mesh refinement schemes [11]. The p-version keeps the mesh fixed and solution accuracy is achieved by increasing hierarchically the order of element interpolation functions. The h-p-version is the combination of the h- and p-version [12]. Fully automatic implementation of the h-p-version refinement scheme has not been achieved yet. In this paper, it is applied the p-version and the h-p-version as shown in Fig. 2.

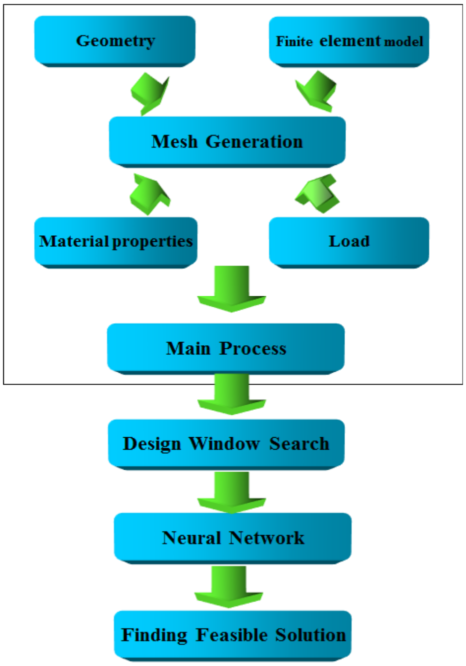


Fig. 1. Flow of optimal design process

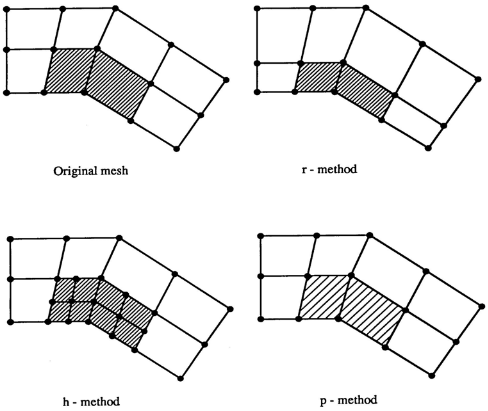


Fig. 2. Adaptive mesh technique

2.3 Fuzzy control of node position

The fuzzy rules employed here can be generalized as :

RULE^i : IF p is A^i , THEN q is B^i

where RULE^i is the i-th fuzzy rule, A^i and B^i the fuzzy variables, p the value of node, and $\triangle p$ the difference of the current and the next values of p, i.e. $|p(n+1)-p(n)|$(n : the iteration number of node), respectively. The labels of the fuzzy variables are defined as follows.

As for A^i,

LARGE → p is much larger than 1.0.
MEDIUM → p is larger than 1.0.
SMALL → p is little larger than 1.0.

As for B^i,

LARGE → q is positive and large.
MEDIUM → q is positive and medium.
SMALL → q is positive and small.

As shown in Fig. 3, trapezoid type membership functions are utilized as those of labels of A^i and B^i from the viewpoint of simplicity.

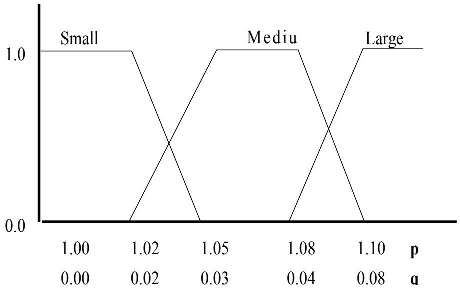


Fig. 3. Membership functions of labels of $A^i(p)$ and $B^i(q)$

2.4 Design window

The design window (DW) is a schematic drawing of an area of satisfactory solutions in a permissible multi-dimensional design parameter space. The design window seems more useful in practical situations than one optimum solution determined under limited consideration. Among several algorithms, the Whole-area Search Method (WSM) [13] is employed here.

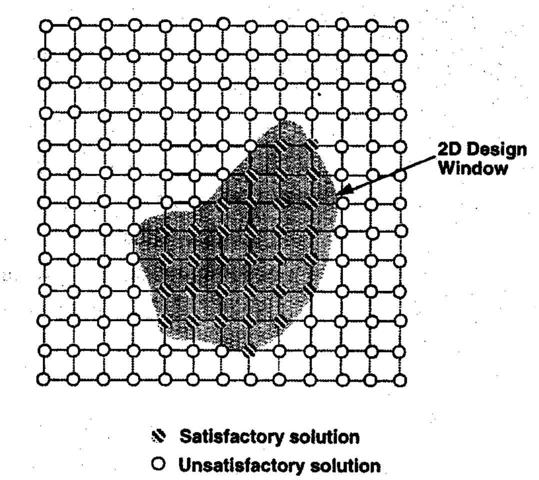


Fig. 4. Whole area search method for design window

As shown in Fig. 4, a lattice is first generated in the design parameter space that is empirically determined by a user. All the lattice points are then examined one by one whether they satisfy design criteria or not. The WSM is the most flexible and robust, but the number of lattice points to be examined tends to be extremely huge.

2.5 Neural network

An neural network architecture comprises massively parallel adaptive processing elements with hierarchically structured interconnected networks. A processing unit of the artificial neural network has multiple input slots and a single out slot. The relationship between the input and output signals is usually formulated as follows [13]:

$$o_j = f(U_j) = \frac{1}{1+\exp(-2U_j/U_0)}, \tag{1}$$

$$U_j = \sum_{j=1}^{i} W_{ji} \times I_i - \theta_j, \tag{2}$$

where O_j is the output signal of the j_{th} unit, U_j is the internal potential of the j_{th} unit, f() is the activation function (i.e., a sigmoid function here), U_0 is the constant of the sigmoid function, W_{ji} is the connection weight between the i_{th} and j_{th} units, I_i, is the input signal from the i_{th} to the j_{th} units, Θj is the threshold value of the jth unit, and is the number of input signals. All the units of an ordinary multilayer neural network are formed into multiple layers-that is, an input layer, intermediate layers, and an output layer, with only feedforward connections between successive layers.

This method consists of three subprocesses as shown in Fig. 5.

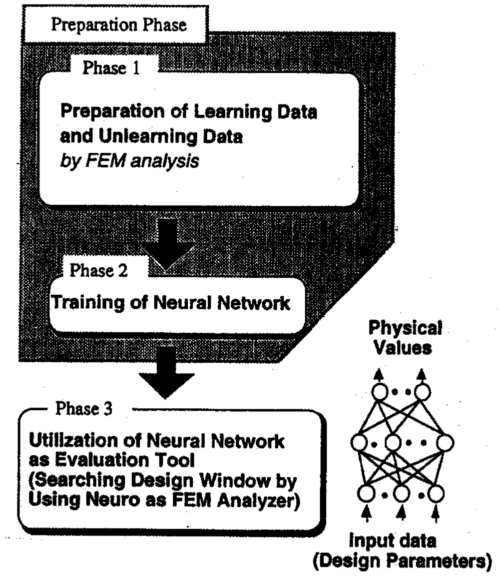


Fig. 5. Schematic view of design procedure of neural network

At first, using the automated FE system described in section 2.1, numerous FE analyses are performed to prepare training data sets and test data sets for the neural network, each of which is a coupled data set of assumed design parameters vs. calculated physical values. The neural network is then trained using the training data sets. Here the design parameters assumed are given to the input units of the network, while the physical values calculated are shown to the output units as teacher signal. A training algorithm employed here is the backpropagation [13]. After a sufficient number of training iterations, the neural network can imitate a response of the FE system. That means, the well trained network provides some appropriate physical values even for unknown values of design parameters. Finally a multi-dimensional DW is immediately searched using the well trained network together with the WSM.

3. Practical Evaluation

To examine fundamental performances of the present optimal design system, it is applied to evaluate the hydraulic breaker. The hydraulic breaker operates using the hydraulic pressure, being attached to the excavator on the construction spot, and it is widely used for excavation, road crushing, rock bed crushing, tunnelling work, underwater work and other types of the construction works. Geometric modelers are utilized to define geometries of analysis domains. One of commercial geometric modelers, ANSYS is employed for 3D solid structures and analysis.

The hydraulic breaker requires the bracket to be attached to the excavator. The types of the bracket can be categorized in large into box and side housing ones. The box bracket that is rectangular is stable in its structure, In contrast, the side housing bracket is vulnerable in structure compared with the box bracket.

This study used the stress gauge to measure the maximum stress affecting the parts of the side housing bracket most vulnerable to the cracking, and thereupon, used a tool to interpret the maximum stress value, while maintaining the same stress as on the spot.

Fig. 6, Fig. 7 and Table 1 shows respectively the breaker shape and boundary condition for analysis. In case of a housing bracket, Fig. 8 shows a typical FE mesh, it took about 30 minutes to define this geometry model by using a solid modeler. The mesh consists of 350,250 elements and 96,424 nodes. Nodes and elements are generated in about 20 minutes and in about 5 minutes, respectively. To complete this mesh, the following two node patterns are utilized ; (a) the base node pattern in which nodes are generated with uniform spacing over a whole analysis domain, (b) a special node pattern for stress concentration position of corners. Fig. 9 shows a calculated distribution of stress.

Design parameters and geometrical constraints of the bracket considered here are shown in Fig. 10.

Design criteria employed are as follow:

- The bracket of maximum equivalent stress is less than the allowable stress.

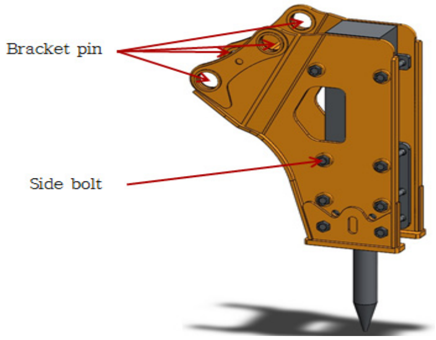


Fig. 6. Shape of breaker

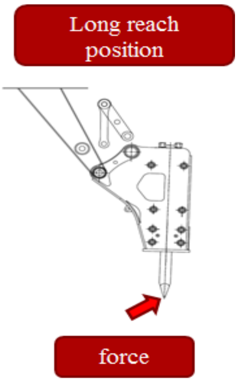


Fig. 7. Long reach

Table 1. Force of excavator

Mode	Force (kN)			
	Force	Fx	Fy	Fz
Long reach position	159.7	144.3	68.5	-

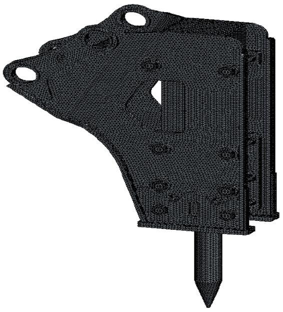


Fig. 8. Finite element model of side housing bracket

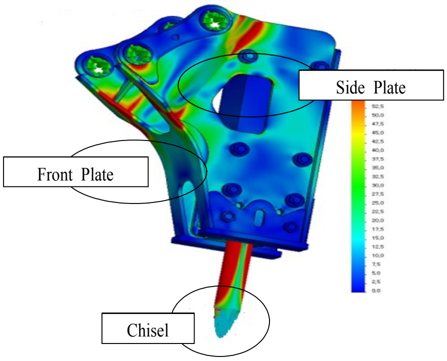
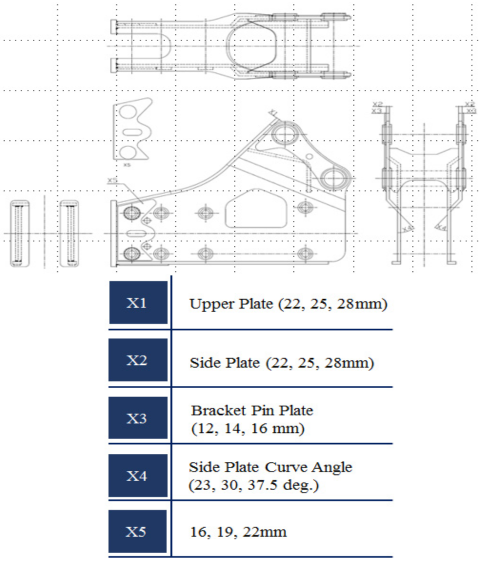


Fig. 9. Stress distribution of side housing bracket



X1	Upper Plate (22, 25, 28mm)
X2	Side Plate (22, 25, 28mm)
X3	Bracket Pin Plate (12, 14, 16 mm)
X4	Side Plate Curve Angle (23, 30, 37.5 deg.)
X5	16, 19, 22mm

Fig. 10. Design variables

The multilayer neural network employed is of three-layered type as shown in Fig. 11. The network has five units in the input layer, ten units in the hidden layer, and two units in the output layer. Through iterative training, i.e. the back propagation learning algorithm, the network gradually tends to produce the appropriate output data, which are similar to the teaching ones.

The five design parameters, X1~X5 are the input data for the network. Design windows are searched using the trained neural network. The sizes of minimum weight for bracket to be operated are searched, considering allowable stress. Table 2 shows a baseline and optimum values within elastic limit.

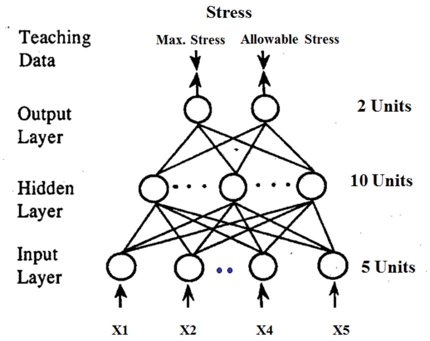


Fig. 11. Network topology and its input/output data

Table 2. Baseline and optimum value

		Lower	Initial	Optimal Sol.	Present Sol.	Upper
Design Variables	X1	22	25	25	25	28
	X2	22	22	28	28	28
	X3	12	14	16	16	16
	X4	23	37.6	23	23	37.6
	X5	16	16	16	16	22
Objective Function	Weight	-	810	949.7	950	-
Constraint	Max. stress	-	179.8	99.21	101	105

The automated analysis system was used, while the maximum stress was maintained as same as or smaller than the allowable stress with the typical shape maintained intact, the SM490 used for the material and the minimizing weight safety coefficient set at 3. On the other hand, the developed neural network system was used to minimize the defects and weight of the side housing bracket for minimizing the weight. As a result, the maximum stress was reduced 30.4% compared with the initial model. In this study, the side housing bracket with a comparably simple structure for 43 tons was optimized, but if the method developed by this study should be applied to the side housing brackets of different classes (tons), their quality would be greatly improved.

4. Conclusion

A novel optimal design system for practical structures is described in the present paper. Interactive operations to be done by a user are performed in a reasonably short time even when solving complicated problems such as micro actuators. The other processes which are time consuming and labour-intensive in conventional systems are fully automatically performed in a popular engineering workstation environment. A design window search approach supported by the multilayer neural network is also described. This design system is successfully applied to the evaluation of performances of a side housing bracket of hydraulic breaker.

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