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인공지능을 이용한 3차원 구조물의 최적화 설계 : 마이크로 가속도계에 적용

Optimal Design for 3D Structures Using Artificial Intelligence : Its Application to Micro Accelerometer

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요약

본 논문은 실질적인 최적화 구조물의 설계를 위한 시스템에 대한 것으로 퍼지이론에 바탕을 둔 자동 유한요소 생성망 기술과 계산기하학적 기술, 해석코드 및 솔리드모델러를 시스템에 통합시켰다. 최적해 또는 만족해는 자동해석 시스템과 함께 탐색공간을 위한 유전자 알고리즘을 이용하여 자동적으로 탐색되어 진다. 또한, 유전자 알고리즘을 이용함으로써 본 설계 시스템은 다차원 해를 얻을 수 있다. 개발된 시스템은 터널전류에 바탕을 둔 마이크로 가속도계의 형상설계에 적용하였다.

Abstract

This paper describes an optimal design system for multi-disciplinary structural design. An automatic finite element (FE) mesh generation technique, which is based on the fuzzy knowledge processing and computational geometry technique, is incorporated into the system, together with a commercial FE analysis code and a commercial solid modelers. An optimum design solution or satisfactory solutions are then automatically searched using the genetic algorithms modified for real search space, together with the automated FE analysis system. With an aid of genetic algorithms, the present design system allows us to effectively obtain a multi-dimensional solutions. The developed system is successfully applied to the shape design of a micro accelerometer based on a tunnel current concept.

Key words : Micro Accelerometer, Finite Element Analysis, Fuzzy Knowledge Processing, Genetic Algorithm, Computational Geometry, Design Window

1. Introduction

Efficient search techniques of rational structural design solutions have attracted much attention, and various optimization algorithms have been proposed and applied to many engineering applications [1,2]. However, for structural components of modern artifacts such as nuclear structures, electronic devices or micromachines, no sufficient methodologies have been developed so far. Also, the design of structural component is an iterative process in which the aim is to achieve a structure which has adequate strength and stiffness, and is both practical and economical to manufacture : that is, in a some sense, an optimum design. The design procedure can take a very long time if approached conventionally, and it is unlikely that components will in fact be optimized in detail against all important criteria.

The use of an automated analysis system, involving FE codes together with CAD systems and FE pre- and post-processors, has provided an important step towards shortening the design process and structural optimization. Of course, to do analysis and design work, various general purpose programs such as Pro/Engineering, ABAQUS, ANSYS and so on have been used. Using these programs, however, conventional analyses of practical structures are still labour-intensive and are not easy for ordinary designers and engineers to perform. Furthermore, it is difficult for them to find a satisfactory or optimized solution of practical structures utilizing such conventional tools. A lot of trial and error evaluations are indispensable.

In case of main features of 3D structural design problems, it can be classified into the following three issues : (a) multiple coupled physical/mechanical phenomena should be taken into account in the design process, (b) intensive computational mechanics simulations are required to perform reliable and accurate evaluations of physical behaviors, (c) their structural design problems are often ill-posed, as a result of a large variety of design variables and of complex, usually discontinuous, nonlinear and multidisciplinary design goal.

In this paper, to overcome the issues mentioned above,

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the author proposed a concept of an automated design system for multidisciplinary phenomena, which in conjunction with various soft-computing and intelligent simulation techniques such as neural networks and genetic algorithms (GA), may lead to significant improvement of the quality of the final design solution. This system was applied to the design optimization of a novel tunnel current based on micro accelerometer.

2. Outline of the System

The configuration of the present system is illustrated in Fig. 1. To efficiently support design processes of practical structures such as micro- machines, the automatic FE analysis system [3], which is based on the fuzzy knowledge processing and computational geometry techniques, is integrated with a GA. By integrating a GA based optimizer, the system allows automatic search for optimum design solutions. Also, the system allows us to automatically obtain a multi-dimensional design window (DW) in which a number of satisfactory design solutions exist using multilayer neural networks [4].

Most part of the present system except the FE program is constructed on one of popular personal computers using the C++ language.

2.1 Automated FE Analyzer

One of commercial geometric modelers, Design- base [5] is employed for 3D solid structures. Material properties and boundary conditions are directly attached onto the geometry model by clicking the loops or edges that are parts of the geometric model using a mouse, and then by inputting actual values.

In the present system, nodes are first generated, and then an FE mesh is built. In general, it is not so easy to well control element size for a complex geometry. Example of node density function [6] is shown in Fig. 2. A node density distribution over a whole geometry model is constructed as follows. The present system stores several local node patterns such as the pattern suitable to well capture stress concentration, the pattern to subdivided a finite domain uniformly, and the pattern to subdivide a whole domain uniformly. An user selects some of those local node patterns, depending on their analysis purposes, and designates their relative importance and where to locate them.

Node generation is one of time consuming processes in automatic mesh generation. In the present study, the bucketing method [7] is adopted to generate nodes which satisfy the distribution of node density over a whole analysis domain.

The Delaunay triangulation method [8] is utilized to generate tetrahedral elements from numerous nodes given in a geometry. The speed of element generation by the Delaunay triangulation method is proportional to the number of nodes.

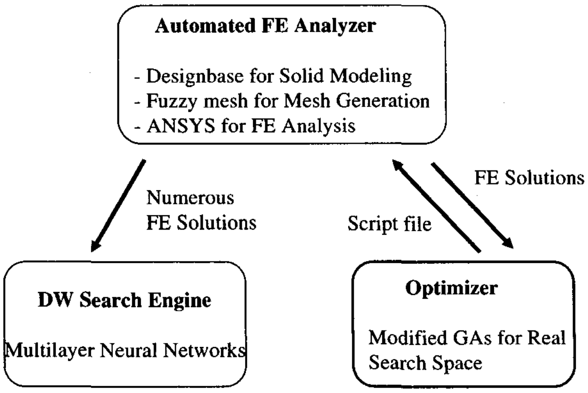
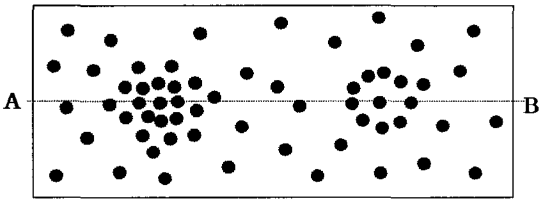
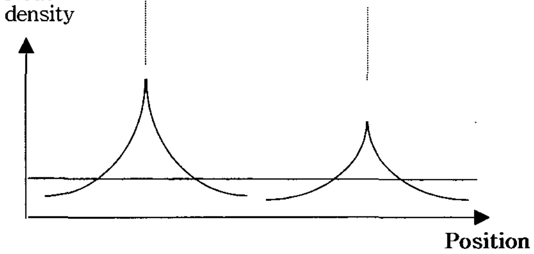


Fig. 1. System configuration



(a) Node distribution



(b) Node density function along line A-B

Fig. 2. Example of node density function

Then these are automatically attached on nodes, edges, faces and volume of elements. Such automatic conversion can be performed owing to the special data structure of finite elements such that each part of element knows which geometry part it belongs to. Finally, a complete FE model consisting of mesh, material properties and boundary conditions is obtained.

2.2 DW Search Engine

The DW is a schematic drawing of an area of satisfactory solutions in a permissible multi- dimensional design parameter space. The DW seems more useful in practical situations than one optimum solution determined under limited consideration. Among several algorithms, the Whole-area Search Method (WSM) is employed here. As shown in Fig. 3, 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. Therefore, the present author used a novel method to efficiently search the DW using the multilayer neural network [4].

This method consists of three subprocesses as shown in Fig. 4. At first, using the automated FE system, 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 [4].

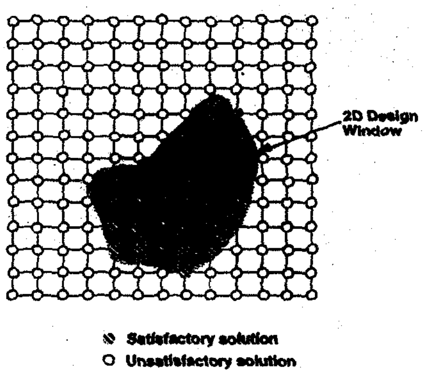


Fig. 3. Design Window in 2D parameter space

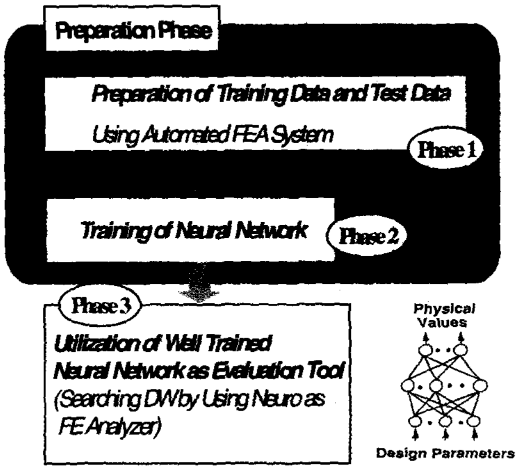


Fig. 4. Procedure of DW search using neural network

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.

2.3 Modified GA Algorithm

In optimum or satisfactory design problems of modern artifacts such as nuclear structures, electronic devices and micromachines, the GAs, have attracted much attention, and have been applied to various inverse problems and optimum designs [9]. For continuous search space problems, the conventional GAs, however, tend to converge slowly, and their accuracy may strongly depend on the bit length of binary code employed. Therefore some of the present author proposed a new GAs modified for the real search space, and this formulation was used as an optimization engine.

```
k = 0 ;
Initialize P(k) ;
k = k + 1 ;
do
    Recombinate P(k) ;
    Mutate P(k) ;
    Evaluate P(k) ;
    Select P(k);
while terminal condition is not satisfied
```

Fig. 5. Fundamental structure of GAs

The fundamental structure of GA is shown in Fig. 5. First, a population of individuals, each represented by a vector, is initially (generation t=0) generated at random, i.e.,

$$P(k) = \{u_1(k), \cdots\cdots, u_\lambda \in (k)\} \in \mathbf{I}^\lambda \qquad (1)$$

where $\lambda \in \mathbf{N}$ and $\mathbf{I}$ represent the population size of parental individuals and the space of individual respectively. The population then evolves towards better regions of the search space by means of randomized processes of recombination, mutation and selection though either recombination or mutation operator is not implemented in some algorithms. In the recombination operator $\mathbf{r} : \mathbf{I}^\lambda \rightarrow \mathbf{I}^\nu$, λ parental individuals breed $\nu (\in \mathbf{N})$ offspring individuals by combining part of information from the parental individuals. The mutation $\mathbf{m} : \mathbf{I}^\nu \rightarrow \mathbf{I}^\lambda$, then, forms new individuals by making large alterations with small possibility to the offspring individuals regardless of their inherent information. With the evaluation of fitness for all the individuals, the selection operator $\mathbf{s} : \mathbf{I}^\nu \cup \mathbf{I}^{\nu+\lambda} \rightarrow \mathbf{I}^\lambda$ favorably selects individuals of higher fitness to produce more often than those of lower fitness. These reproductive operations form one generation of the evolutionary process, which corresponds to one iteration in the algorithm, and the iteration is repeated until a given terminal criterion is satisfied.

Selection in canonical genetic algorithms emphasizes a probabilistic survival rule mixed with a fitness dependent chance to have different partners for producing more or less spring. By deriving an analogy to the game-theoretic multi-armed bandit problem, Holland identifies a necessity to use proportional selection in order to optimize the trade-off between further exploiting promising regions of the search space while at the same time also exploring other regions [10]. For proportional selection

S : $I^{\lambda} \rightarrow I^{\lambda}$, the reproduction probabilities of individuals $\mathbf{u}_i$ are given by their relative fitness, i.e. $i \in \{1, \ldots, \lambda\}$:

$$P_s(u_i^k) = \frac{\Phi(u_i^k)}{\sum_{j=1}^{\lambda} \Phi(u_i^k)}. \tag{2}$$

Sampling λ individuals according to this probability distribution yields the next generation of parents.

3. Design of Micro Accelerometer

3.1 Operation Principles and Fabrication of Micro Accelerometer

The present system was applied to a novel, tunneling current based micro accelerometer [11]. The cross-section of the device are shown in Fig.6. In the fabrication process, bonded silicon on insulator is used as starting material. The proof mass is a 3 ㎛ thick Si cantilever (A) which is suspended 4 ㎛ above the Si substrate (B), and 200 nm wide gap (C) to about 2 nm until tunneling occurs. Added mass (D) is necessary to obtain required sensitivity of the accelerometer, and it can be bonded to the plate using the surface activated bonding technology being developed by Suga [12].

A cantilever with a small gap in the end was proposed for the realization of the micro accelerometer. A tunnel current that goes across the gap is observed to detect the change of the distance of the gap. The gap is created by the technique of focused ion beam is shone onto a suspended silicon bridge to make a cut at an angle of 45 degrees.

The cantilever is pulled down by an electrostatic force from the substrate to the position at which the gap comes to a specific distance. When the tip of the cantilever moves due to an acceleration, the amount of a tunnel current across the gap changes. The change is given to the voltage of capacitor, so that the gap is maintained at a constant distance. The amount of feed back is read out as an indicator of the acceleration.

The first version of layout had a uniform cantilever. It turned out to be too light to cause an enough deflection. Then the cantilever was redesigned to have a lumped mass supported by two arms in both sides. A picture of this layout is shown in Fig. 7.

3.2 Design Requirements

Table 1 summarizes the detailed design requirements for the present micro accelerometer. They include requirements for dynamic and static behaviors of the device, its strength, cost and sensitivity. The purpose of the present design process was to find any structure configurations which would stisfy all the design requirements given in Table 1. For each requirement an empirical normalized satisfaction function was formulated.

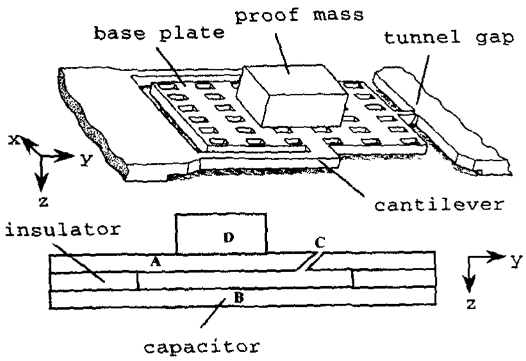


Fig. 6. Concept for a micro accelerometer

Fig. 7. Layout of a micro accelerometer

Table 1. Design requirement for micro accelerometer

1	Dynamic range	$f_1 > 1$ kHz
2	Mode 1 dominance	$f_1 \ll f_2$
3	Directivity	$d_3 \gg d_2, d_1$
4	Max. deflection	$d_3 < 2$ nm
5	Economy	Area < 400㎛×400㎛
6	Strength	$\sigma_{max} < \sigma_{ys}$
7	Max. applied voltage	$V \leq 15V$
8	Controllability (sensitivity)	Compensation voltage per a_3=1 g, $\Delta V \approx 0.3V$

* Notes; f_i : *Eigen frequency of mode* i
d_i : z-displacement at tunnel gap for a_i=1g
a_i : acceleration in the direction of xi axis

Fig. 8 shows *four of eight functions*. The score greater than 5 means that the requirement is satisfied, while the score of 10 means full satisfaction. The following optimization problem was formulated :

$$f(A_1, A_2, \ldots, A_n) = \min\{y1, y2, \ldots, y8\} \rightarrow max,$$

where Ai denotes i-th design parameter specified for the problem, and yj is a value of satisfaction function. This problem was solved by the GAs modified for the real search space.

4. Analysis Results

To demonstrate actual performances of the present system, the system was applied to a tunneling current based micro accelerometer. Fig. 9 shows a geometry model of 3D accelerometer using Designbase.

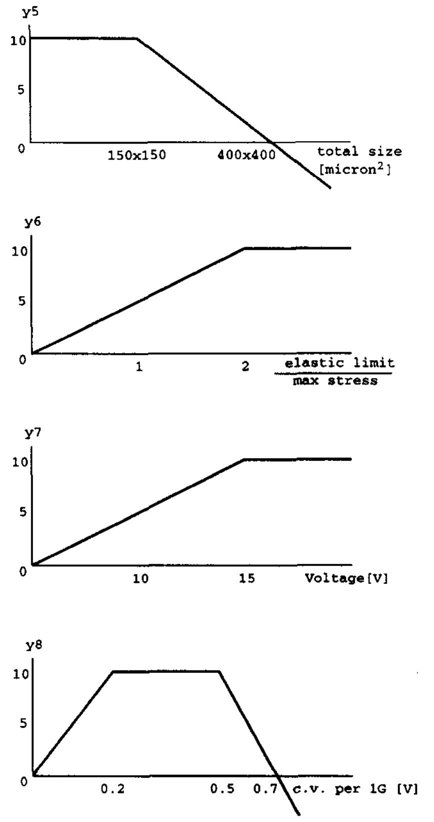


Fig. 8. Example of satisfaction functions for design requirements

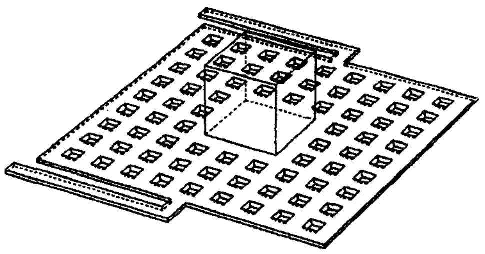


Fig. 9. Example of geometry model

Fig. 10 shows a typical FE mesh, which consists of 9,042 tetrahedral quadratic elements and 19,342 nodes. Among the whole process, interactive operations to be done by an user are performed in a reasonably short time of 3~4 minutes. Fig. 11 indicates the design parameters for the present micro accelerometer. Also, Table 2 shows a range of these parameters.

In the micro accelerometer design, knowing the dynamical behavior of the cantilever is important to determine dimensions, the deflection of the cantilever must be large enough to be able to detect an acceleration. At the same time, the tunnel current tip must be placed in a position in which the primary or secondary oscillation modes do not interfere the measurement.

In the GA based optimization process, each generation consisted of 50 individuals, each one holding a vector of design parameters.

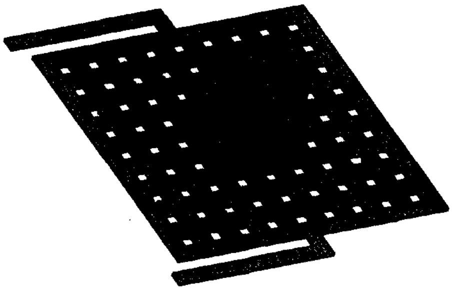
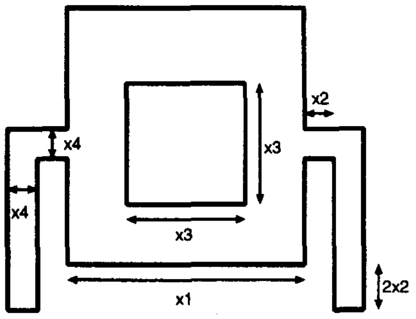


Fig. 10. Mesh for a part of micro accelerometer



x5 : height of proof mass
x6 : mass density of proof mass

Fig. 11. Definition of design parameter

Table 2. Range of design parameters

Parameter	Range
x1	150 ~ 400 [㎛]
x2	10 ~ 100 [㎛]
x3	50 ~ 350 [㎛]
x4	5 ~ 50 [㎛]
x5	2 ~ 20 [g/cm^3]
x6	10 ~ 50 [㎛]

Therefore the evaluation of all individuals in one generation required 200 automatic 3D FE analyses. In order to decrease the calculation time, the distributed computation approach feature was effectively utilized, and calculations were performed concurrently on three personal computers. This way the calculation time was reduced to roughly about 70 minutes per 1 generation. Fig. 12 shows the objective function value versus generation for 4 and 6 variables. Also, Fig. 13 presents results of the optimization process for the generation of design parameters. Satisfactory designs were found after only several hours of calculations, with further calculations leading to slightly better results.

5. Conclusions

In this paper, a concept of an automated design system for multidisciplinary structural design was proposed, and specified using the genetic algorithms. The automatic design system was built and integrated with GA based optimizer modified for a real search space. Here interactive operation operations to be done by an user can be performed in a reasonably short time even when solving complicated problems of 3D structures such as micro accelerometer. The system was successfully applied to an automated shape design of a micro accelerometer based on a tunneling current concept.

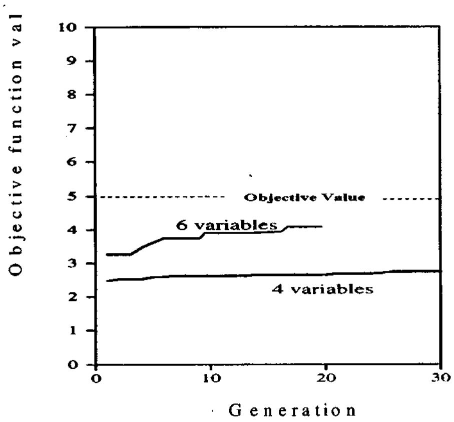


Fig. 12. Objective function value vs. generation

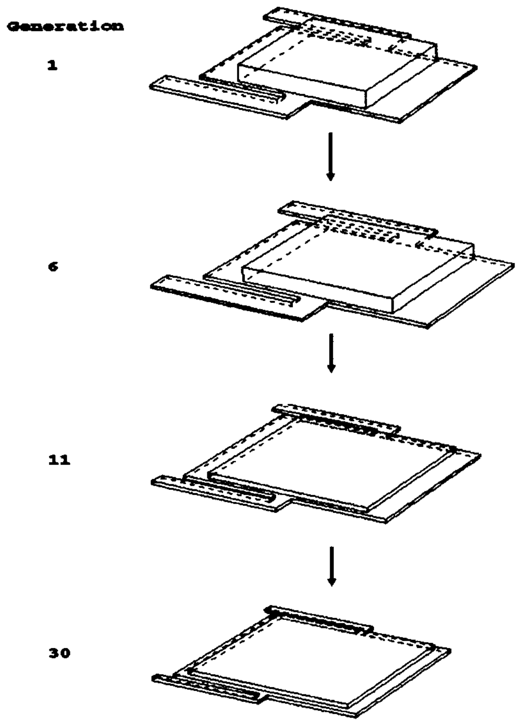


Fig. 13. Shape evolution of micro accelerometer

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