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퍼지이론과 신경망을 이용한 구조설계의 자동화 시스템

이 준 성*

Automated Structural Design System Using Fuzzy Theory and Neural Network

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ABSTRACT

퍼지이론과 계산기하학적 수법에 의한 자동요소 생성법, 해석코드 및 상용 솔리드 모델러를 유기적으로 통합한 자동화된 설계시스템을 개발하였다. 본 시스템은 여러 가지 복합현상과 관련된 실제 구조물에 대한 설계기능을 갖고 있다. 정전장 해석, 변형해석 및 모드해석 등과 같은 해석하고자 하는 물리적인 현상에 의존한 형상모델이 자동적으로 유한요소모델로 변환되어 해석을 수행한다. 또한 신경망의 기능을 도입, 통합시킴으로써 설계해의 영역을 유용하게 제시하여 준다. 개발한 시스템은 정전 마이크로머쉰의 성능 평가에 적용하여 그 효용성을 검증하였다.

Key Words : Computer Aided Engineering (CAE), Micromachine (마이크로머쉰), Fuzzy Theory (퍼지이론), Computational Geometry Technique (계산기하학적수법), Finite Element Analysis (유한요소해석), Neural Network (신경망), Design Window (디자인 윈도우)

1. Introduction

Micromachines whose size ranges 10^{-6} to 10^{-3} m are typical examples of tiny scale artifacts. They have their own missions, and are designed by different engineers in different engineering fields. However, there are some common features in their design processes. These practical structures are in general related to various coupled physical phenomena. They are required to be evaluated and designed considering the coupled phenomena. A lot of trial and error evaluations are indispensable. Such situations make it very difficult to find a satisfactory or optimized solution of practical structures, although numerous optimization algorithms have been studied.

In accordance with dramatical progress of computer technology, numerical simulation methods such as the finite element method (FEM) are recognized to be key tools in practical designs and analyses. Computer simulations allow for the testing of new designs and for the iterative opti-

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mization of existing designs without time consuming and considerable efforts to experiments. However, conventional computational analyses of practical structures are still labour-intensive and are not easy for ordinary designers and engineers to perform. It is difficult for them to find a satisfactory or optimized solution of practical structures, utilizing such conventional computer simulations tools.

The system consists of two main portions. The one is an automated FE analysis system, while the other a design window (DW) search system using the multilayer neural network(1). Here the DW means an area of satisfactory solutions in a permissible design parameter space. In practical situations, a DW concept seems more useful than one optimized solution obtained under some restricted conditions.

The present author has proposed a novel automatic FE mesh generation method for three-dimensional complex geometry(2, 3). To efficiently support design processes of practical structures, this mesh generator is integrated with one of commercial FE analysis codes MARC(4) and one of commercial solid modelers DESIGNBASE(5). With an aid of multilayer neural networks, the system also allows us to automatically obtain a multi-dimensional DW in which a number of satisfactory design solutions exist(6).

The developed system is applied to evaluate one of electrostatic micro wobble actuators(7). Through the analyses, fundamental performances of the system are discussed.

2. Outline of the System

The present automated CAE system consists of two main portions. The one is an automated FE analysis system, while the other a DW search system supported by the multilayer neural network. A flow of design using the system is shown in Fig. 1. The details of these systems will be described in this chapter.

2.1 Automated FE Analyses

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. Each subprocess will be described below. The details of the mesh generation part can be found elsewhere(1, 2).

2.1.1 Definition of geometry model

A whole analysis domain is defined using one of commercial geometry modelers, DESIGNBASE (5), which has abundant libraries enabling us to easi-

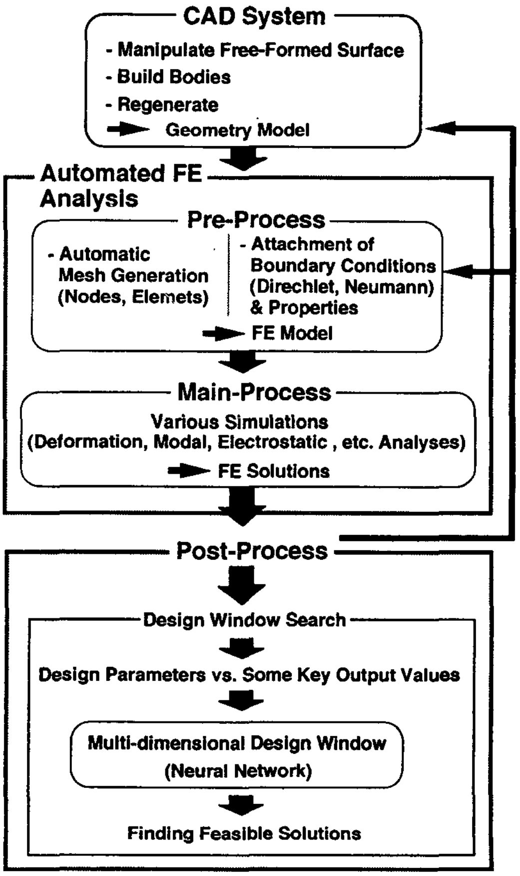


Fig. 1 Flow of automated structural design

ly operate, modify and refer to a geometry model. Any information related to a geometry model can be easily retrieved using those libraries. It should be noted here that different geometry models are constructed, depending on physical behaviors to be analyzed.

2.1.2 Attachment of material properties and boundary conditions to geometry model

Material properties and boundary conditions are directly attached onto the geometry model by clicking the loops or edges that are parts of the geometry model using a mouse, and then by inputting actual values. The present system accepts both Direchlet's and Neuman's type boundary conditions.

2.1.3 Designation of node density distributions

In the present system, nodes are first generated, and then a FE mesh is built. In general, it is difficult to well control element size for a complex geometry. A node density distribution over a whole geometry model is constructed as follows.

The system stores several local nodal patterns such as the pattern suitable to well capture stress concentration, the pattern to subdivide a finite domain uniformly, and the pattern to subdivide a whole domain uniformly. A user selects some of those local nodal patterns, depending on their analysis purposes, and specifies their relative importance and where to locate them. The process is illustrated in Fig. 2. For example, when either the crack or the hole exists solely in an infinite domain, the local nodal patterns may be regarded locally-optimum around the crack-tip or the hole. When these stress concentration sources exist closely to each other in the analysis domain, extra nodes have to be removed from the superposed region of both patterns. In the present method, a global distribution of node density over the whole analysis domain is then automatically calculated through their superposition using the fuzzy knowledge processing$^{(8, 9)}$. When designers do not want any special meshing, they can adopt uniformly subdivided mesh.

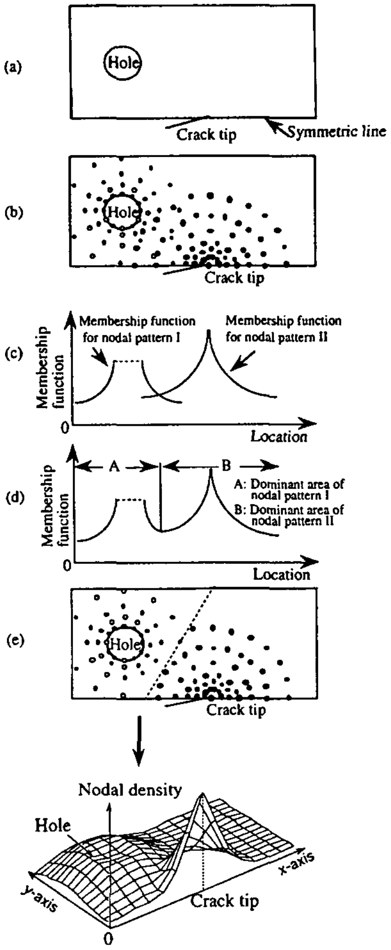


Fig. 2 Superposition of local node patterns using fuzzy knowledge processing

2.1.4 Node and element generation

Node generation is one of time consuming processes in automatic mesh generation. Here, the bucketing method$^{(10)}$ is adopted to generate nodes which satisfy the distribution of node density over a whole analysis domain.

The Delaunay triangulation method$^{(11)}$ is used to generate tetrahedral elements from numerous nodes produced within a geometry.

2.1.5 Attachment of material properties and boundary conditions to FE mesh

Through the interactive operations mentioned in section 2.1.2, a user designates material properties and boundary conditions onto parts of the geometry model. Then these are automatically attached onto appropriate 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 finite element model consisting of mesh, material properties and boundary conditions is created.

2.1.6 FE analyses

The present system automatically converts geometry models of concern to various FE models, depending on physical phenomena to be analyzed, i.e. stress analysis, eigen value analysis, thermal conduction analysis, electrostatic analysis, and so on. The current version of the system produces FE models of quadratic tetrahedral elements, which are compatible to one of commercial FE codes, MARC(4). FE analyses are automatically performed.

2.2 Design Window Analysis Using Multilayer Neural Network

The design window (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(6).

This method consists of three subprocesses as shown in Fig. 4. At first, using the automated FE system described in section 2.1, numerous FE

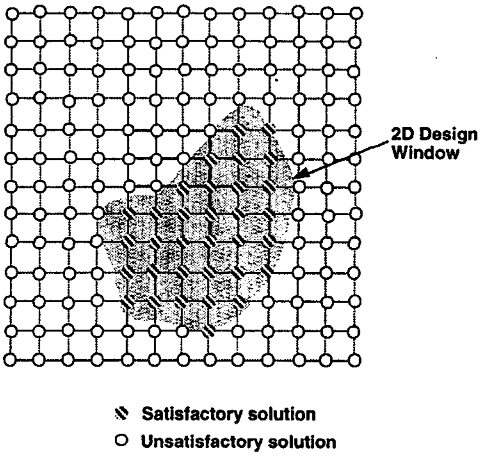


Fig. 3 Illustration of whole area search method for design window

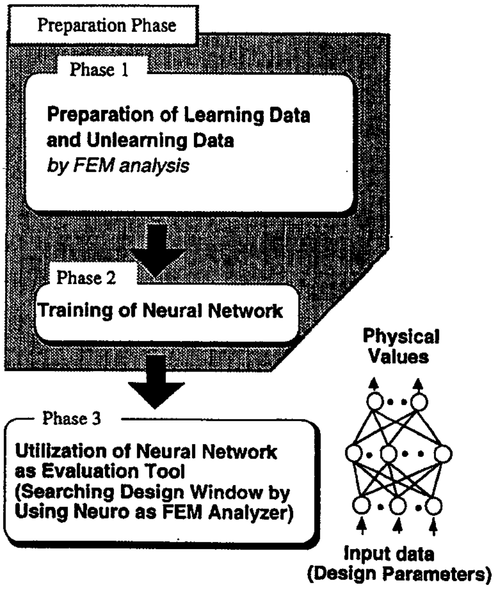
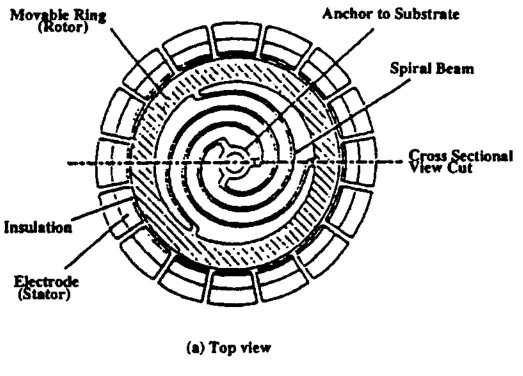


Fig. 4 Schematic view of procedure of design window search using neural network

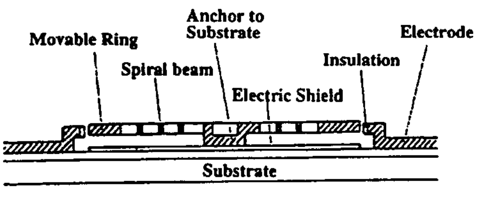
analyses are performed to prepare training data sets and test data sets for the neural network, each of which is a coupled data set of assumed design parameters vs. calculated physical values. The neural network is then trained using the training data sets. Here the design parameters assumed are given 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(6). 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. Electrostatic Micro Wobble Actuator

The present CAE system is applied to one of electrostatic micro wobble actuators(7). The micro actuator considered in the present study is designed as a part of a highly accurate positioning device(7). This actuator uses an electrostatic force as other micro-motors do, and its fabrication process is almost the same as those in ref.(12). Compared with similar devices, the micro wobble actuator has several advantages such as high performance, high reliability and high productivity.



(a) Top view



(b) Cross section view

Fig. 5 Structure of micro wobble actuator

Materials employed here are silicon and silicon compounds, which are well known as materials for semiconductor devices.

The basic structure of the present actuator is illustrated in Fig. 5. Fig. 5(a) is its schematic plane view, and Fig. 5(b) its cross-section view. The material properties and the dimensions of the present actuator are illustrated in ref.(7, 13).

4. Results and Discussions

The details of the automated FE analysis part can be found elsewhere(13).

4.1 Automated FE Analyses

To examine fundamental performances of the present micro wobble actuator, the following behaviors had to be analyzed :

(1)In-plane deformation of the ring with the three spiral beams caused due to an electrostatic force.

(2)Electrostatic analysis of the air gap between the ring and one of the electrodes.

Assuming the reference configuration and dimensions, the above phenomena were analyzed (13).

In-plane deformation was analyzed to evaluate the quantitative relationship between a rotation angle and a torque necessary to rotate the rotor within the elastic limit of the beams. It can be seen from the ref.(13) that the rotation angle of the rotor is limited at about 62 degrees because of the elastic limit. Also tells us that the starting torque required is 0.42×10^{-9} Nm.

When one of the electrodes is excited, the rotor is electrostatically attracted, and comes to contact with the insulator on the inner surface of the electrode. When the next electrode is excited, the rotor revolves without slipping. It can be seen from the ref.(14) that the starting torque is proportional to the square of driving voltage, and that the 2D analytical solution is four to five times larger than the 3D FE one. Such a significant difference may be caused due to the omit of electrical leakage in the 2D analytical solution. Considering that the torque of 0.42×10^{-9} Nm is necessary to start rotating the rotor, it was obvious that a driving voltage exceeding 170 V is indispensable.

4.2 Design Window Evaluation

Here we demonstrate how the DW search method is utilized. As one of examples, some dimensions of the actuator to be operatable are schematically drawn as a DW.

4.2.1 Design parameters and geometrical constraints

Design parameters and geometrical constraints of the electrostatic micro wobble actuator considered here are as follows :

Width of the ring (Wr) : 20 - 30 μm
Thickness of the rotor (Tr) : 2.0 - 2.5 μm
Gap width between the rotor and stators (G) : 2.0 - 5.0 μm
Thickness of the insulator (Ti) : 0.2 -1.8 μm

Design criteria employed are as follows :

(1) The wobble actuator can rotate within the limit of elasticity, i.e. the maximum equivalent stress $\sigma_{\max}$ is less than the yield stress σ_{ys}.

(2) In order to rotate the rotor, the starting torque calculated from the electrostatic analysis τ_e is larger than that calculated from the in-plane deformation analysis of the rotor τ_s.

4.2.2 Network topology and training conditions

A multilayer neural network employed is of three-layered type as shown in Fig. 6. The network has four 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(1), the network gradually tends to produce the appropriate output data, which are similar to the teaching ones. The two units in the output layer output two kinds of starting torques, i.e. τ_s and τ_e. The four design parameters, Wr, Tr, Ti and G are the input data for the network.

In the present example, 81 training patterns are prepared, i.e. all the combinations of (Wr = 20, 25, 30), (Tr = 2, 2.25, 2.5), (Ti = 0.2, 1, 1.8), (G=2, 3.5, 5). On the other hand, 10 test patterns are prepared to check a generalization capability. They are randomly selected within a possible range of each design parameter. All the input data and output data are normalized to a unit range from 0.05 to 0.95.

Fig. 7 shows the history of learning process in the case that a constant of the sigmoid function U_0 is taken to be 0.6. Here the following mean error of estimation is employed for both training and test patterns :

$$Mean\ Error = \frac{1}{nt}\sum_{p=1}^{t}\sum_{k=1}^{n}\left|T_{pk} - O_{pk}\right| \tag{1}$$

where

n : the number of output units
t : the number of training or test data sets
T_{pk} : teacher signal to the k-th unit in the output layer for the p-th training or test pattern
O_{pk} : output signal from the k-th unit in the output layer for the p-th training or test pattern

The well trained network is obtained at 200,000 learning iterations, when the mean error of estimation for the test patterns reaches the minimum value of 0.005. With this criterion, the estimation accuracy of the starting torque is confirmed to be within 0.5%.

4.2.3 DW search

DWs are searched using the trained neural network. The sizes of the micro wobble actuator to be operatable are searched, considering both in-plane deformation of the rotor and the electrostatic phenomena. To rotate the rotor, τ_e has to be larger than τ_s. Both torques for different design parameters can be promptly evaluated using the trained neural network. Fig. 8 shows the DW in the Wr, G and Ti space when the voltage 120 V is applied and Tr ranges from 2 to 2.5 mm. The number of searched points in this DW is 85. On the other hand, no satisfactory solutions are found when 100 V is applied. That is, a DW is null. Fig. 9 shows the DW in the G, Tr and Ti space, when the driving voltage is 150 V and Wr ranges from 20 to 30 mm. This DW is much larger than that for 120 V.

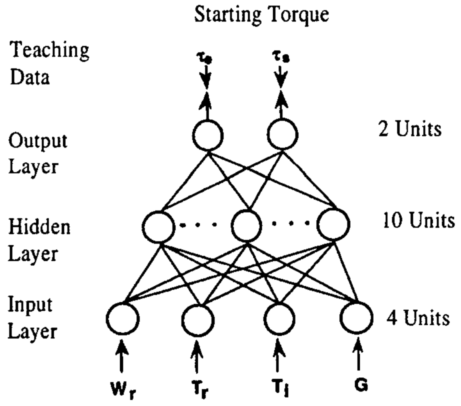


Fig. 6 Network toplogy and its input/output data

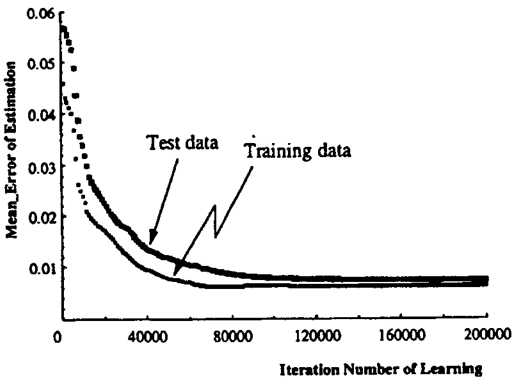
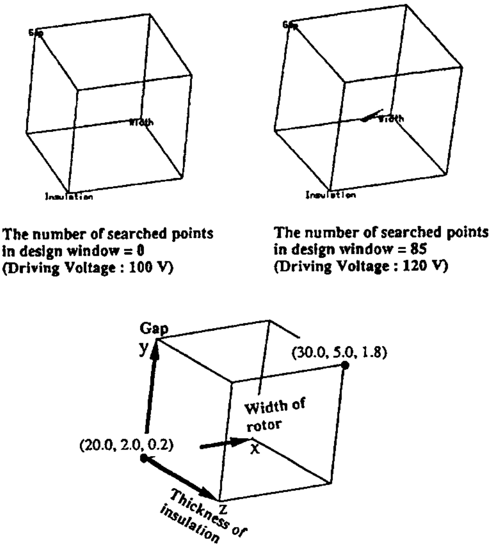


Fig. 7 Convergence of training process



The number of searched points in design window = 0 (Driving Voltage : 100 V)

The number of searched points in design window = 85 (Driving Voltage : 120 V)

Starting Torque (Electrostatic Analysis) >
Starting Torque (Stress Analysis)

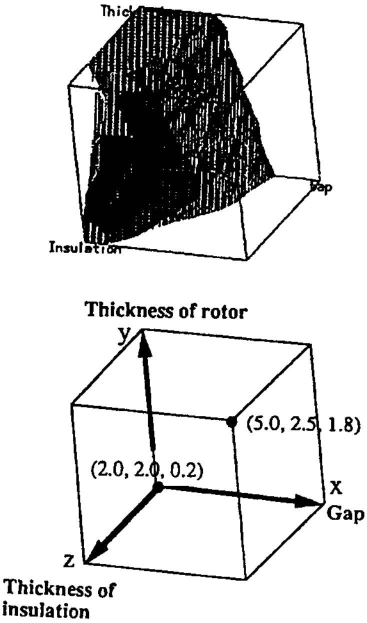
Thickness of rotor : 2.0 - 2.5 μm

The number of searching points = 65, 536

Fig. 8 Design windows for 100 and 120 V

5. Conclusions

A novel structural 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 DW search approach supported by the multilayer



The number of searched points in design window = 18,420
(Driving Voltage : 150 V)
Width of rotor : 20 - 30 μm

Fig. 9 Dwign window for 150 V

neural network is also described. This CAE system is successfully applied to the evaluation of performances of an electrostatic micro wobble actuator.

Acknowledgement

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