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Automated Structural Design System Using Fuzzy Theory and Neural Network

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ABSTRACT

This paper describes an automated computer-aided engineering (CAE) system for three-dimensional structures. 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. The system allows a geometry model of interest to be automatically converted to different FE models, depending on the physical phenomena of the structures to be analyzed, i.e., electrostatic analysis, stress analysis, modal analysis, and so on. Also, with the aid of multilayer neural networks, the present system allows us to obtain automatically a design window in which a number of satisfactory design solutions exist in a multi-dimensional design parameter space. The developed CAE system is successfully applied to evaluate an electrostatic micromachines.

Keywords: Computer Aided Engineering, Micromachine, Fuzzy Theory, Computational Geometry Technique, Neural Network, Design Window

1. Introduction

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 optimization 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.

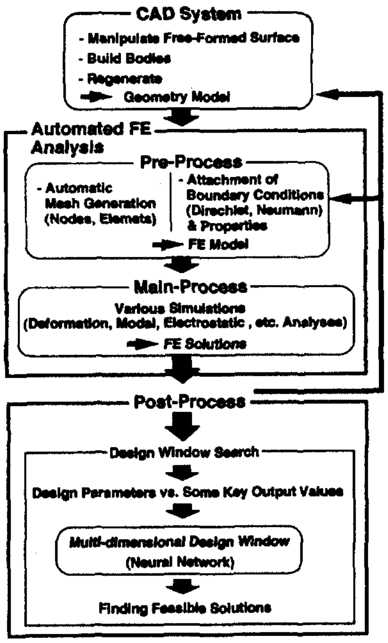


Fig. 1 Flow of automated structural design

2.1 Automated FE Analysis

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.

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 easily 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 node 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 node 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].

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, 12] 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.

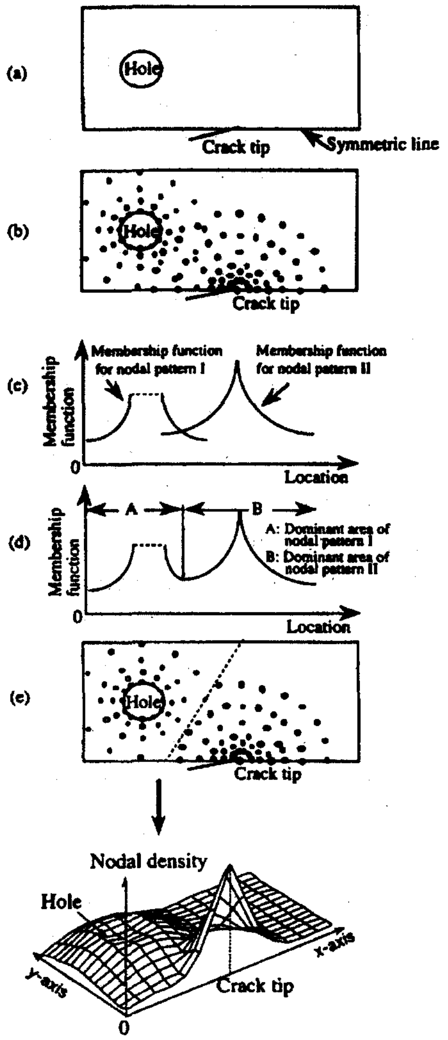


Fig. 2 Superposition of local node patterns using fuzzy knowledge processing

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, 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].

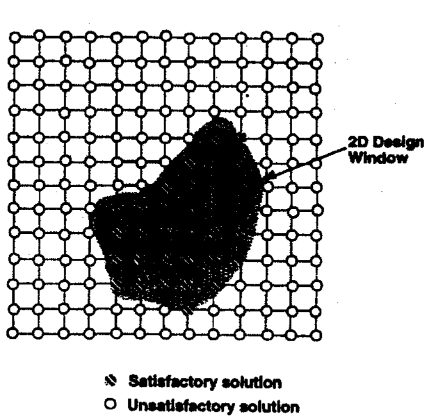


Fig. 3 Illustration of whole area search method for design window

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 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.

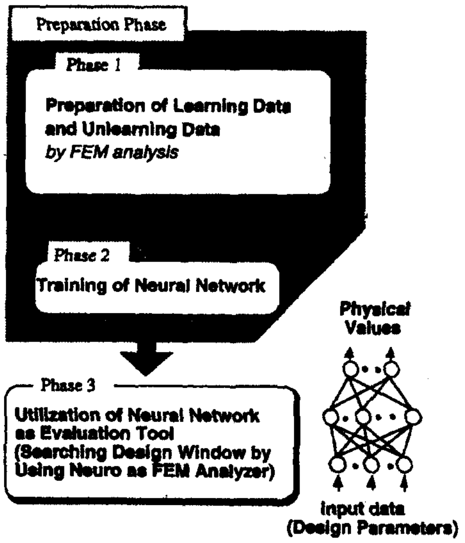
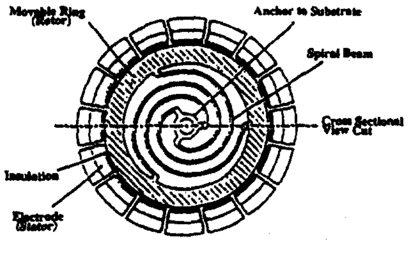


Fig. 4 Schematic view of procedure of design window search using neural network

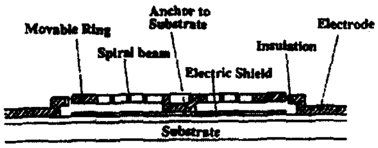
3. Electrostatic Micro Wobble Actuator

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. [13]. Compared with similar devices, the micro wobble actuator has several advantages such as high performance, high reliability and high productivity.

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, 14].



(a) Top view



(b) Cross section view

Fig. 5 Structure of micro wobble actuator

4. Results and Discussions

The details of the automated FE analysis part can be found elsewhere [14].

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 [14].

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.[14] 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

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

Design criteria employed are as follows :

(1) The wobble actuator can rotate within the limit of elasticity, i.e. the maximum equivalent stress σ_{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 backpropagation 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.

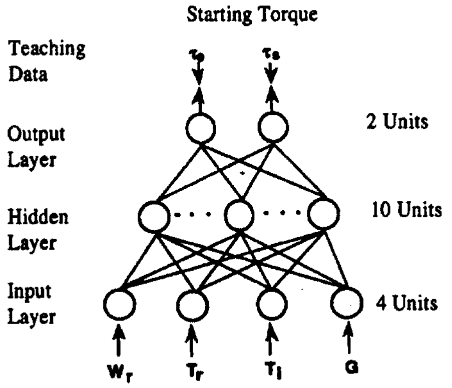


Fig. 6 Network topology and its input/output data

Fig. 7 shows the history of learning process in the case that a constant of the sigmodi function Uo is taken to be 0.6. Mean error of estimation is employed for both training and test patterns [1]. 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%.

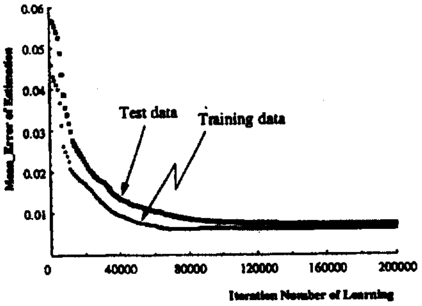


Fig. 7 Convergence of training process

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 μm. 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. 8 shows the DW in the G, Tr and Ti space, when the driving voltage is 150 V and Wr ranges from 20 to 30 μm. This DW is much larger than that for 120 V.

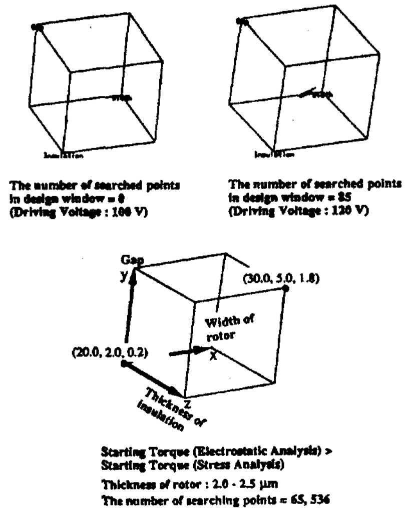


Fig. 8 Design Window for 100 and 120 V

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

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