Structural Design of Micro Electrostatic Acutuator for Optical Memory Using Design Windows Searching Method

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ABSTRACT

For satisfactory design of micromachines, this paper describes a search method for a multi-dimensional design window (DW), which is defined as an area of satisfactory solutions in a feasible design parameter space. The method consists of the following two steps: (1) direct search for satisfactory design solutions using continuous evolutionary algorithm (CEA, a kind of EA), and (2) identification of DWs from the solutions using a modified K-means clustering algorithm. The obtained DWs are expected to give engineers useful information to understand a design problem, and, further, give them new ideas of design. To demonstrate practical performance of the proposed method, it was applied to a shape design of micro electrostatic actuator for optical memory.

***Keywords*: Computer-Aided Optimization, Finite Element Method, Design Window, Satisfactory design, Continuous Evolutionary Algorithm, Clustering, Micro Electrostatic Actuator

1. INTRODUCTION

Optimization algorithms have been used to find proper solutions for structural design under given constraints, and applied to various engineering applications. However, for micromachines, it seems that very few methodologies based on optimization have been developed so far. Researches on the topic are seen in [1]-[4]. Difficulties of optimization of micromachines are originated from the following characteristics of them: (a) A design parameter space is multi-dimensional, (b) a relation between design parameters and design characteristics is often nonlinear and discontinuous, (c) the design problem is often multi-objective, and (d) every requirements are not always formulated as optimization problem. To overcome these issues simultaneously, we propose here the method to search a design window (DW), which is defined as an area of satisfactory solutions in a feasible design parameter space. The DWs are expected to give engineers useful information to understand design problem, and further give them new ideas of the design.

This method consists of the following two steps: (a) direct search for satisfactory design solutions within a multi-dimensional design space using continuous evolutionary algorithm (CEA, a kind of EA)[5] and automated finite element analyses, and (b) identification of DWs from the solutions using a modified K-means clustering algorithm. In Step 1, the CEA's characteristics are fully utilized, such as multi-points search in a whole design parameter space. In Step 2, the proposed clustering method realizes automated identification without any prior knowledge on complicated multi-dimensional satisfactory design solutions. The proposed DW search method is implemented into our integrated CAE system for structural design of micromachines [6, 7], and then successfully applied to the shape design of a micro-electrostatic actuator for next generation optical memory [8].

2 DESIGN WINDOWS SEARCH METHOD

2.1 CEA-BASED SEARCH FOR SATISFACTORY DESIGN SOLUTIONS

In our previous study [9], the whole area search method (WSM) was proposed. The WSM consists of the following two phases : (a) generation of a large number of search points in a design parameter space at random, and (b) point-by-point evaluation of objective functions and constraints. However such a primitive random search method is so inefficient. On the other hand, response surface methods combined with design of experiment are often employed to reduce the number of sampling points. However, such an approximation method does not properly work for micromachines design because of severe ill-posedness of the problem and lack of design experience. To overcome these problems, the CEA based search was employed in the present study. Detailed description of the CEA can be found in [5]. Only the basic principal of the method is explained briefly here. (a) The first population is generated at random. Here, each individual in the population is represented by a real vector. Next (b) the second population is generated through several evolutionary processes such as selection, crossover, mutation according to evaluations of individuals' fittness. In the CEA, crossover and mutation are performed based on weighted addition with a probabilistic coefficient μ , which has a normal distribution with mean 0 and standard deviation σ ;

$$\mu = N(0, \sigma^2). \quad (1)$$

2.2 MODIFIED K-MEANS CLUSTERING ALGORITHM

One of popular clustering algorithms implemented into many programs is the K-means algorithm. In the algorithm, the center of each cluster iteratively moves to form the cluster according to its distance from the members of the cluster, given the number of clusters a priori. However knowing the number of clusters is not trivial task.

To overcome this, the present authors proposed a modified K-means algorithm, which contains a method to determine the optimum number of clusters based on a variation level. The algorithm is briefly explained as follows: (a) Select initial centers of K-clusters at random, at first, K=2. (b) Each data point is classified to an appropriate cluster based on a distance between the point and the cluster. The variation level E is defined as a total sum of the distances. (c) Redefine each cluster center as a mean of data points in the cluster. Repeat (b) and (c) until E is minimized. To find a proper cluster number, the variation levels E are calculated, starting from several different combinations of initial centers, and the results are compared with among others. The method to determine the proper cluster number consists of the following two steps: (d) Repeat (a) trough (c). (e) If the variational levels E obtained by using different initial centers reach the same level and do not diverge, consider that the proper cluster number is found. Otherwise increase the number of cluster, K = K+1, and go back to (a).

2.3 IMPLEMENTATION TO INTEGRATED CAE SYSTEM

The present DW search method is implemented to the integrated CAE system for micromachines developed by the present authors [6, 7]. The detailed description of the integration mechanism can be found in [10, 11]. Only the basic idea of the mechanism is explained briefly here. The present CAE system employs object-oriented and mobile agent approaches to integrate various finite element (FE) simulation modules, optimization engines and another modules in a flexible manner in a parallel and distributed computer environment.

3 STRUCTURAL DESIGN OF MICRO ACTUATOR FOR OPTICAL MEMORY

3.1 OPERATION PRINCIPLE

Fig.1 shows the birds-eye-view of an actuator for optical memory of next generation [8]. The actuator controls one-directional nanometer-order displacement of memory pick-up lens. The actuator consists of lens, comb type electrostatic actuator, supporting bars and flame. These components except lens are made of single crystal silicon through photochemical etching processes. The main body, i.e. lens and actuator is hung to the flame by 4-supporting bars, and driven by electrostatic force between fixed comb teeth and movable ones in the y-direction.

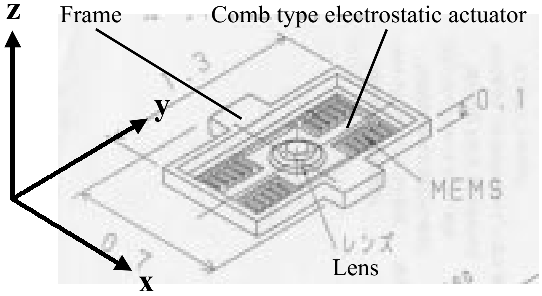


Fig. 1 Microactuator for optical memory

3.2 DESIGN REQUIREMENTS

Design requirements are set for the following physical features of the actuator: (1) range of displacement and (2) accuracy of positioning, (3) strength, (4) accuracy of chasing target memory, (5) feed-back control ability, (6) manufacturability. Table 2 summarizes these requirements described by design characteristics y_i (i=1,...,5) and their restrictions.

To evaluate the requirements (1) - (4), three-dimensional (3D) static stress analyses are performed, where step load is applied to the movable comb. To evaluate the requirement (5), 3D dynamic response analysis is performed, where air effects are considered as explained in the subsequent section.

3.3 AIR EFFECTS

A whole size of the actuator is about 1mm, while the width of each component such as comb teeth and bars is only a few micrometers. Reynolds number is estimated to be about 10^{-3} in the gap between the comb teeth. Therefore viscosity effects of air must be considered in evaluating dynamic behavior of the actuator. Air can be modeled as viscous fluid because Knudsen number is larger than 10^{-2}. The air effects were considered as added mass M', added viscosity C' and fluid resistance F'. The detailed description about M', C' and F' can be found in our previous report [12]. In a preliminary analysis [12], it was found that the air effects increase the period of vibration by 15% and decrease the amplitude of vibration by 14%. Thus the air effects are considered in the subsequent design process.

3.4 ANALYSIS MODEL

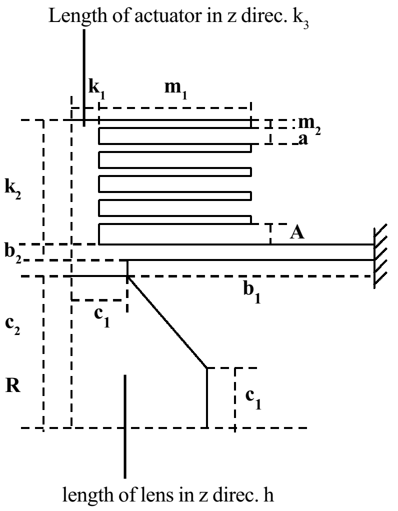
Mesh model employs ten-noded tetrahedral elements, and the total number of nodes is controlled to be less than 5000. Material properties of the single crystal of silicon and those of air (under 1 N/m^2, 20°C) given in Table 1 are used in the analysis. Fig. 2 shows all parameters defining the actuator

Table 1. Material properties

Silicon [110]
Mass Density (kg/m^3) : 2328
Young's modulus (GPa): 170
Poisson's ratio: 0.2
Yield stress (GPa): 2.0

Air (under 1 N/m^2, 20℃)
Mass Density (kg/m^3) : 1.205
Kinematic Viscosity(kg/m^2) : $15.01x10^{-3}$
Re : 1.0

Param.	Dim.[mm]
b_1	0.20
b_2	0.015
k_1	0.05
k_2	0.30
k_3	0.06
m_1	0.30
m_2	0.015
A	0.050
R	0.40
h	0.25
c_1	$(2^{1/2}-1)R$
c_2	0.050
a	$(k_2-A-5m_2)/4$
h_w	0.0020
h_n	$a-m_2-h_{u0}$



h_w: wide gap between fixed comb tooth and movable comb tooth,
h_n: narrow gap between fixed comb tooth and movable comb tooth.

Fig. 2 Shape parameters of the basic design

shape. As a result of the preliminary study [12], parameters b_1, b_2, k_2, k_3, m_1 are employed as design parameters.

3.5 FORMULATION FOR SATISFACTORY DESIGN

Five kinds of functions of satisfaction are empirically defined corresponding to the five design requirements. Here the score 10 means that the requirement is fully satisfied, while the half score of 5 means that the requirement is satisfied and that the solution is acceptable. Details of the functions can be found in [2]. Then the following max-min optimization problem was formulated.

$$f(b_1, b_2, k_2, k_3, m_1) = min\{\phi_1,.., \phi_5\} \Rightarrow max \quad (6)$$

where ϕ_i denotes i-th satisfactory function. When f exceeds the score of 5, it is regarded that some of the satisfactory solutions are obtained.

4. RESULTS AND DISCUSSIONS

4.1 SATISFACTORY DESIGN SOLUTIONS SEARCH

In the process of searching satisfactory solutions, the first generation is generated, referring the basic design shown in Fig. 1 according to expression (1). A population of each generation consists of 200 individuals, and the total number of generations is 40. Since the search is an expensive computational task, the search was performed on a cluster of 25-PCs (Pentium133MHz) is employed. It took about two days. More than 80% of the searching time was consumed to perform FE analyses for the individuals. f exceeds 5 at 25th generation, and after that, satisfactory design solutions began to appear. Finally 179 satisfactory design solutions were obtained out of total search points of 16000. The highest score of f was 6.35.

4.2 IDENTIFICATION OF DWS

As a result of clustering, 179 satisfactory solutions were divided into 4-DWs. The DWs are called as DW_1(63), DW_2(46), DW_3(42), DW_4(28), where each number in bracket denotes the number of solutions classified into each DW. The solution with the highest score of f is included in DW_3.

Since the DWs exist in a 5D design parameter space, it is very difficult to visualize and discuss about them directly. Therefore, in this paper, a mean vector of each DW_i(i=1,…,4) is chosen as typical satisfactory solution *Typei* (i=1,...,4). *Type1*,…,*Type4* are defined as candidates of a final design solution. Their shapes are illustrated in Fig. 3.

4.3 DISCUSSIONS

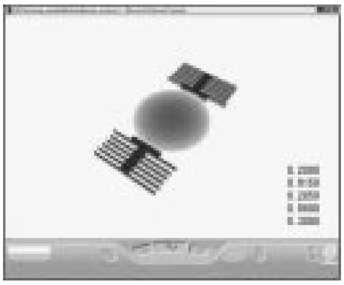
(1) Shapes *Type1* has longer supporting bars and comb teeth, and is narrower in y-length than the other types. *Type2* has shorter supporting bars and teeth, and wider in y-length than the other types. On the other hands, *Type3* has longer teeth than supporting bars. So it is difficult to fabricate *Type3* because the flame becomes to be complicated. *Type4* has shorter teeth than supporting bars.

(2) Design characteristics Satisfactory functions described in subsection 3.5 are sometimes not suitable to compare the obtained candidates because the satisfactory functions were set as tentative goals to search DWs. Then relative satisfactory functions ϕ_1' - ϕ_5' are defined to compare the candidates. ϕ_i' gives score of 10 to the best candidate, and score of 1 to the worst candidate in the i-th design characteristic y_i. The radar chart of ϕ_i' is shown in Fig. 4. Fig. 4 shows that *Type1* is the most well-balanced and better solution. *Type2* has no week points. Thus *Type1* and *Type2* are regarded as more balanced solutions, though *Type3* and *Type4* are superior in some specific characteristics.

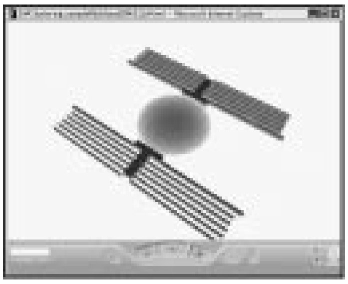
(3) Best design If a final design should have no week points, *Type1* should be chosen as the final design. If a final design should be superior in some design characteristics, *Type3* or 4 should be chosen according to needs. If difficulty in fabrication should be avoided, *Type3* should not be chosen.

5. CONCLUSIONS

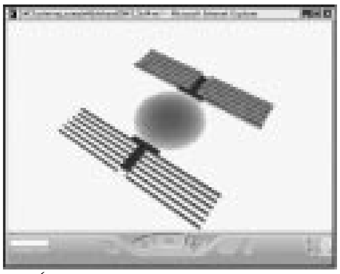
The multidimensional DWs searching method using the CEA and the modified K-means clustering algorithm were proposed. To demonstrate its practical performance, the pro-



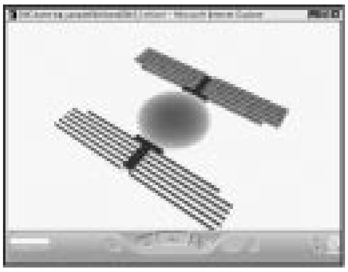
(a) Initial basic design



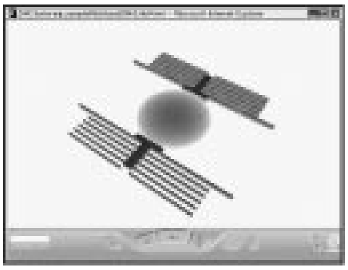
(1) Type1, center of DW1



(2) Type2, center of DW2



(3) Type3, center of DW3



(4) Type4, center of DW4

(b) Candidates of final design solution

Fig. 3 Comparison of shapes among the basic design and four designs

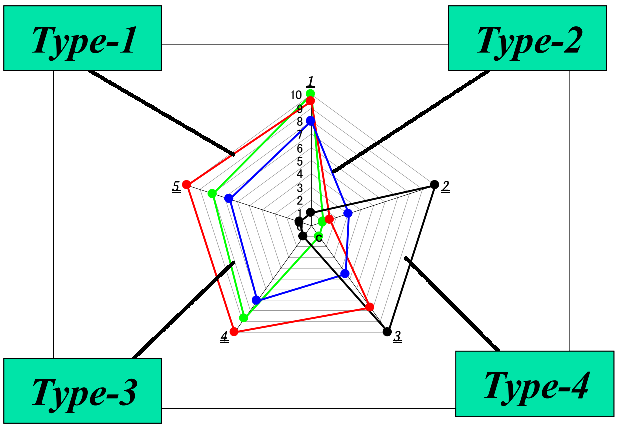


Fig. 4 Comparison of relative satisfaction values (Nos.1-5 denote each satisfaction values.)

posed method was implemented into the integrated CAE system for micromachines developed by the authors, and applied to the shape design of a micro electrostatic actuator. The CAE system was then successfully applied to the following structural design problem. The problem was a satisfactory structural design, which consists of 5-design parameters and 5-design requirements. 4-DWs were obtained. Each representative design solution in each DW has different shapes and design characteristics. The 4-typical satisfactory design solutions corresponding to the 4-DWs were discussed in detail from the viewpoints of practical engineering design. Following this numerical study, the research group of Fujitsu Research Institute Tokyo is producing the prototype of micro electrostatic actuators for optical memory.

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