A Genetic Algorithm Combined with Finite Element Method for Robust Design of Actuators

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Abstract—This paper describes a design optimization procedure based on a genetic algorithm combined with the finite element method. It adopts the concepts of Orthogonal Array for design parameter settings, and Signal-to-Noise Ratio (S/N) for evaluating the individual fitness. Taking advantage of the unique features of genetic algorithms, the robust solution is achieved by a rapid global search. The approach is applied to the robust design problem of a magnet actuator to demonstrate its effectiveness.

Index Terms—Actuators, finite element analysis, genetic algorithms, robust design.

I. INTRODUCTION

WITH RECENT advances in artificial intelligence, genetic algorithms (GA's), as searching procedures based on the mechanisms of natural selection and genetics, have been recognized as efficient and effective tools in design optimization, and exhibit a high rate of global convergence across the broad spectrum of optimization problems [1]. The method has been used, for instance, in optimal design of electrical machines with various degree of success [2]. In practice, however, difficulty arises when the number of design variables is large or the evaluation of the product performance is time consuming. Effective use of such techniques to solve practical engineering problems is therefore still an area of research.

If a solution obtained by conventional optimization technique is very sensitive to small perturbations [3] of its parameter values, it may not be of practical use. On the other hand, if the product performance is highly dependant on tight tolerance control of design parameters, such a product will be very difficult to produce because of the limited precision of manufacturing tools, and the variability of working environment, and so on. Therefore, compared to other optimization techniques, robust design aims at achieving not only the optimal design target, but also the insensitiveness of product performance to noise factors (uncontrollable factors) which may be caused by variability due to manufacturing or environmental conditions.

Actuators are used in large quantities in applications varying from household appliances to space technology; their design optimization assumes great importance. Taking these products by way of example, application of robust design methodology can
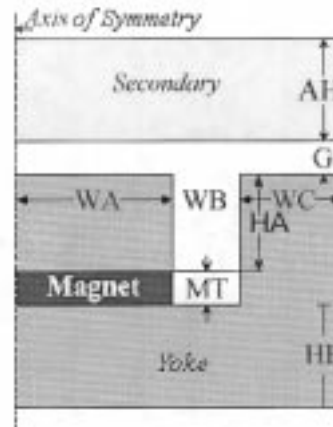
Fig. 1.   Half of vertical cross sectional of actuator.

make the performance insensitive to variability in operation conditions and variance in geometric dimensions due to manufacturing variability, thus improving the product reliability.

The finite element method (FEM) is nowadays routinely used for analyzing and evaluating the performance of electromagnetic devices, accounting for the effects of nonlinearity and geometric complexity of the physical problems. In this paper, an optimization technique, using a GA based optimizer and FEM based simulator, is introduced and applied to the robust design of actuators. Adopting concepts of Orthogonal Array (OA) and Signal-to-Noise (S/N) Ratio [4], the advantage of GA is fully utilized and the robust solution is achieved by a rapid global search.

II. DESCRIPTION OF DESIGN PROBLEM

The description of the optimization problem is given below. The problem relates to an actuator, which is the key component of a latch mechanism. The cross-sectional view of the axisymmetric actuator is shown in Fig. 1 in which the symbols for the parametric model of the actuator are also indicated. Nonlinearity in the material properties of the secondary, yoke and magnet are taken into account in the FEM simulation. The design problem is subject to three constraints. the total height of actuator, the outer diameter, and the volume of the magnet should be maintained constant.

The objective of the design problem is to achieve a design target, which is represented as the electromagnetic force on the secondary, and its insensitivity to uncontrollable factors. Finite Element Analysis is applied to fmd the electromagnetic force in the actuator at every particular setting of the parameters.

TABLE I
ORTHOGONAL ARRAY $L2^3$

Setting	Factor A	Factor B	Factor C
1	Level 1	Level 1	Level 1
2	Level 1	Level 2	Level 2
3	Level 2	Level 1	Level 2
4	Level 2	Level 2	Level 1

In the design study, the radius of magnet WA, and the height of bottom yoke HB, are selected as control factors which are design parameters, and the variability in secondary height AH, and variability in WB are treated as noise factors which are uncontrollable factors. Additionally, variability in HB is also critical and treated as a noise factor besides a control factor. All control factors were used to construct the chromosome in GA and all noise factors were combined with control factors to establish the actuator. All these factors were processed as variable for robust performance. The design constraints, such as the fixed width and length of the whole actuator, fixed magnet material volume, are also applied.

III. THE GENETIC ALGORITHM

A genetic algorithm has been developed to search for the robust design solution of the actuator. The genetic algorithm implemented uses binary representation. Appending strings forms the individuals and delineates the design parameters, therefore a coding process is carried out.

The presented algorithm is based on roulette wheel selection, single position crossover, bit mutation, fitness scaling and elitist selection. The population size, binary bit string length and number of generations are set depending on time consumption for computation using finite element method.

The Orthogonal Array $L2^3$, which is shown in Table I, is used for the design settings of noise factors. For each design combination, four response values are calculated under each noise factor setting using the finite element method. In general, the mean response is designed to be on-target, while the standard deviation of the responses is minimized. Therefore the Signal-to-Noise (S/N) ratio [4], which is implemented in Taguchi Method, is introduced and used to evaluate the performance and standard deviation. The S/N ratio transforms several repetitions into one value, which reflects the amount of variation present and the mean response. There are several SN ratios available depending on the type of performance of products: larger-the-better (LTB), smaller-the-better (STB), and nominal-the-better (NTB). For the presented case, the S/N ratio of NTB is selected for achieving larger electromagnetic force. The corresponding S/N ratio becomes,

$$S/N = -10\log\left(\frac{1}{n-1}\sum_1^n \frac{1}{y_i^2}\right) \qquad (1)$$

where n is the number of noise factors setting and y_i is the performance value at a certain setting, which is the electromagnetic
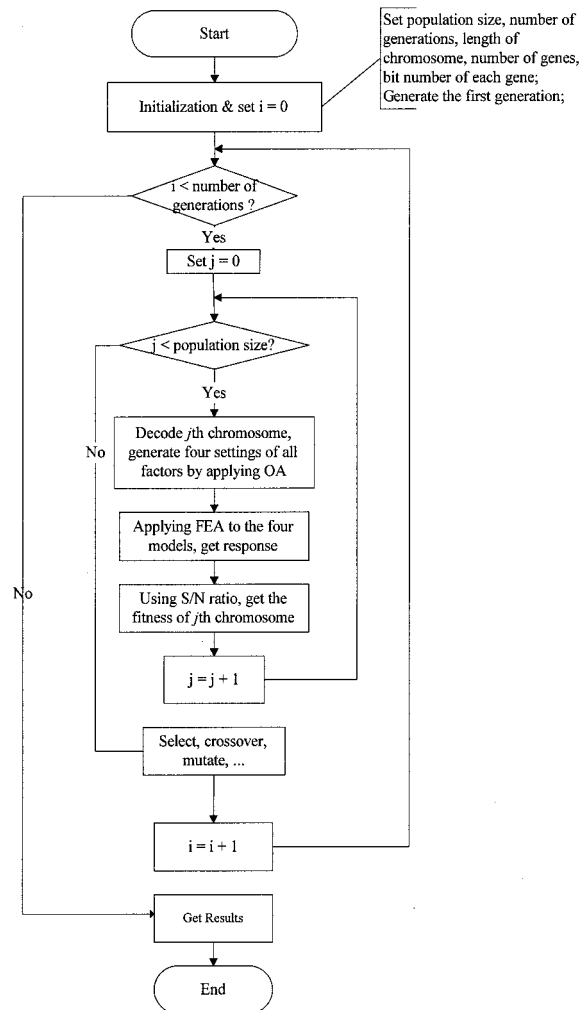

Fig. 2. Flowchart of GA operation.

force obtained using Maxwell tensor method and virtual work method based on finite element analysis of the magnetic field problem in the present study.

IV. DESIGN AND EXPERIMENTS

For this study, the number of generations is set to 50, and the bit string length to 16. Each parameter can be varied within its domain The tolerances of noise factors AH, WB, and HB are $\pm 0.5\%$, $\pm 0.5\%$, and $\pm 1\%$ and respond to two levels in Table I respectively. The flow chart of the GA operation is shown in Fig. 2.

Commercial FEA software ANSYS V5.4 is used to evaluate the product performance, which is the electromagnetic force in the presented study. A simulator driver is implemented in the GA based optimizer to interface the FEA software.

Typically, the computation time of a single design, including the time consumption for Finite Element Analysis, is less than twelve seconds on a desktop computer with a Pentium II 300 MHz microprocessor.

The algorithm will return a solution every time. A robust solution is reached after a number of generations. Fig. 3 shows the
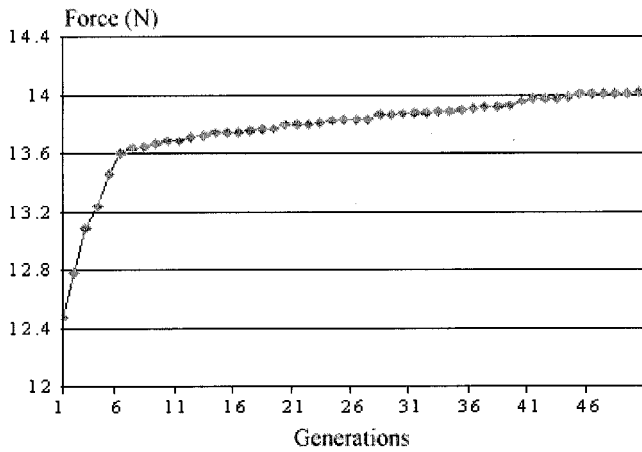
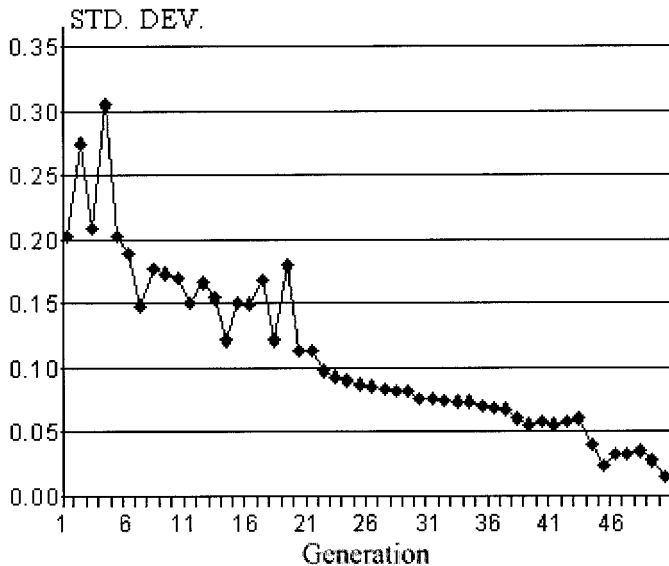Fig. 3.   Forces returned after GA operation of each generation.

Fig. 4.   Std. Deviations returned after GA operation of each generation.
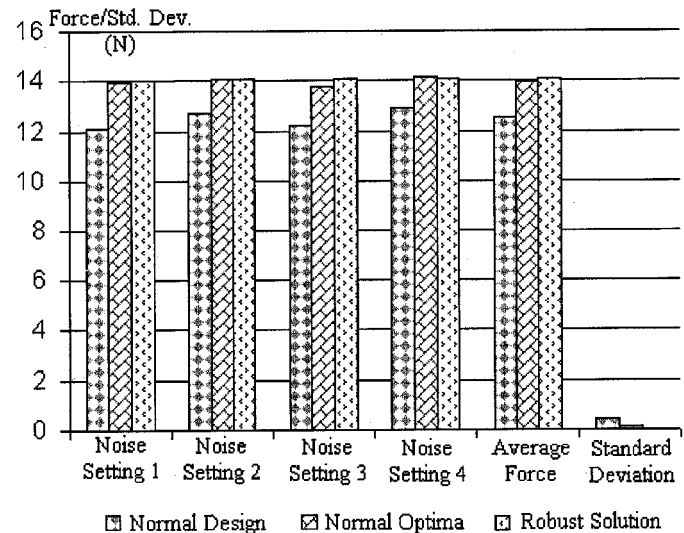

Fig. 5.   Comparison between normal design, normal optimization and robust solution. The combination of noise settings is referred to Table I.

TABLE II
RESULTS AT NORMAL DESIGN, NORMAL OPTIMIZATION AND ROBUST DESIGN

	Normal Design	Normal Optimization	Robust Solution
Noise Setting 1 (N)	12.089	13.960	14.029
Noise Setting 2 (N)	12.725	14.082	14.073
Noise Setting 3 (N)	12.213	13.813	14.068
Noise Setting 4 (N)	12.909	14.111	14.087
Mean Force (N)	12.484	13.991	14.065
Standard Dev.	0.3949	0.1359	0.0248

returned force values simulated by Finite Element Analysis after GA operation of each generation, and Fig. 4 shows the returned deviation values due to the variation of AH, WB, and HB after GA operation of each generation. From these two figures, it can be found that the electromagnetic force is markedly improved, and the deviation of actuator performance due to noise factors is profoundly reduced in the optimization process.

For comparison, a normal optimization process using Genetic Algorithm is conducted, in which the effects of noise factors are not considered, whilst the original design is also evaluated. The solution obtained from the normal optimization and that obtained using the robust concept at four noise factor settings are compared. The result of comparison is shown in Fig. 5, while the electromagnetic forces and their respective standard deviations are listed in Table II. It can be seen that the normal optimization process indeed yields better actuator performance and smaller standard deviation than the original design. However, even better performance and in particular much smaller performance variability can be achieved using the GA based robust design technique, although normal optimization design my produce larger force of certain settings of noise factors.

It will be noted that the rate of convergence is reasonably rapid in solving the robust design problem under investigation, for which FEA is used to evaluate the product performance. It takes affordable computer resources and time to complete the entire optimization process. For the case of 50 generations with 50 populations, taking into consideration the effects of noise factors, the predicted number of times of evaluations for individual's fitness is 10 000. In practice, the number of times of FEM simulations is about 3500 because of many repetitions of individuals, and computer time consumption is approximately twelve hours on a desktop computer with a 300 MHz microprocessor.

V. CONCLUSION

In this paper, it is shown that the optimization approach based on GA and FEA is effective and efficient for robust design of actuators. It is very suitable for those nonlinear electromagnetic problems, and for multi-peak problems. Such an approach can also be applicable to those problems with discrete design parameters.

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