Optimum design of voice coil motor with constant torque coefficients using evolution strategy

Chang Seop Koh and Osama A. Mohammed
Department of Electrical & Computer Engineering, Florida International University, Miami, Florida 33199

Jun-o Kim and Song-yop Hahn
Department of Electrical Engineering, Seoul National University, Seoul 151-742, Korea

An effective optimum design method is presented. The method combines the three-dimensional boundary element method with the (1+1) evolution strategy. The reduced scalar potential formulation with the magnetic surface charge as the unknown variable is used under the assumption that the yokes are not saturated. It is found, through the numerical example, that the global optimum shape of the magnet can be easily found within a reasonable number of generations. More elaborate design can be achieved by increasing the number of design variables.

I. INTRODUCTION

The voice coil motor (VCM) is widely used in high speed and accurate position control actuators such as magnetic disk drives. In the design process of a VCM, the constant torque coefficient characteristic is very important.[1–3] The torque coefficient of a rotary-type VCM with flat coil changes along the positions of the rotor, which impairs high speed and accurate position control use. This fact comes from the uneven distribution of magnetic induction in the air gap. One possible solution is to optimize the shape of the permanent magnet of the VCM.

Several attempts have been made to offer a simulation and design tool for this purpose.[1–3] However, they are not sufficient to predict accurately the carriage motion in the disk drives because the VCM is either analyzed by the equivalent circuit model,[2,3] or by the two-dimensional finite element method,[1] although it has a full three-dimensional configuration. Furthermore, these previous attempts do not offer any guidance for the optimization of the dimension and shape of the VCM.

In this paper, an efficient optimum design algorithm, that combines the boundary element analysis and the (1+1) evolution strategy, is presented to find an optimum shape of a VCM that gives constant torque coefficients. The three-dimensional boundary element method is utilized to analyze the dynamic characteristics of a VCM.

II. CHARACTERISTICS ANALYSIS

The VCM is a kind of linear dc motor where the carriage reciprocates by the force induced by the interaction of the coil current and the magnetic flux generated by the permanent magnets in the air gap. Figure 1 shows the configuration of a VCM analyzed and designed in this paper. This is a rotary-type VCM with flat coil, where the two permanent magnets are magnetized upward and downward, respectively, and the magnetic flux passes through both yokes.

The VCM is excited by only the ferrite permanent magnet whose remanent magnetic flux density is 0.42 T. Hence, the pure steel yokes can be assumed to be unsaturated. Using this assumption, the reduced magnetic scalar potential formulation is utilized because the permanent magnets can be easily taken into consideration and the resultant system matrix becomes relatively small.[4] The unknown state variables are, in this case, equivalent magnetic surface charges defined as follows:

$$\rho(r) = -\frac{\partial\varphi(r)}{\partial n} + H_a(r)\cdot n, \tag{1}$$

where r is the position vector, $\varphi(r)$ is the reduced magnetic scalar potential, H_a is the incident magnetic field intensity created by the permanent magnets and given by

$$H_a(r_s) = \frac{1}{4\pi}\sum_{k=1}^{2}\int_{S_k}\frac{M(r)\cdot n(r)(r_s - r)}{|r_s - r|^3}\,ds, \tag{2}$$

where M is the magnetization vector, S_k is the surface of the kth magnet, and n is the outward unit normal vector.

The boundary integral equation is derived by using the scalar Green's identity from Maxwell's equations. If the condition of zero summation of the magnetic surface charges is

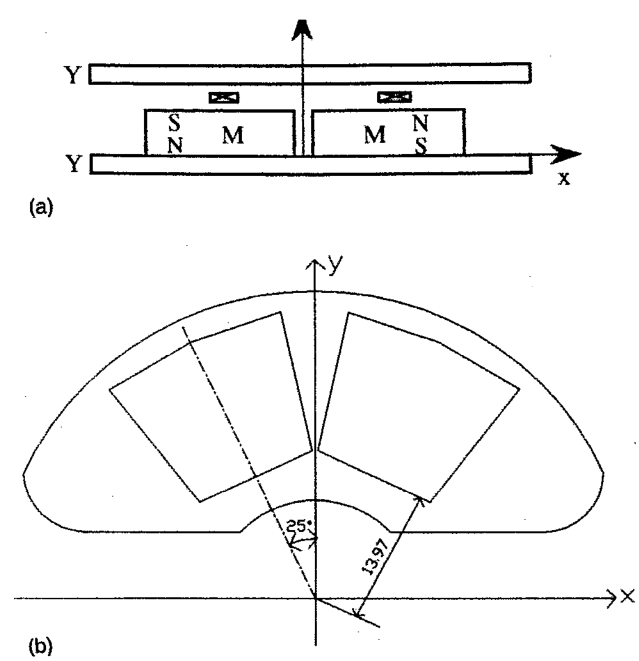

FIG. 1. The VCM configuration. Cross-sectional view (a) and top view (b).

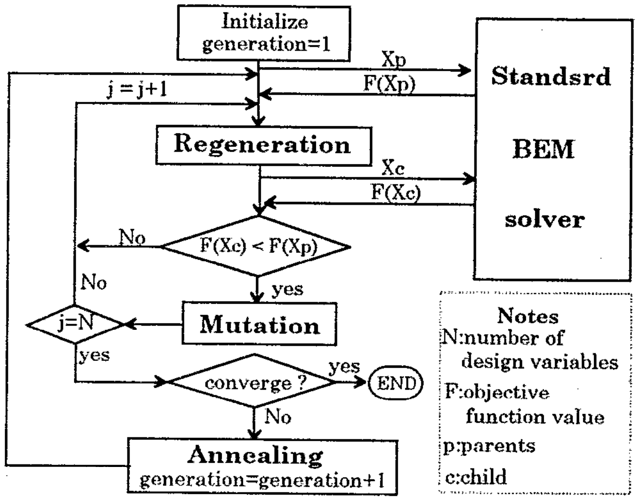

FIG. 2. Flow chart of the (1+1) evolution strategy.

introduced based on a penalty function method,[4] the constrained boundary integral equation can be obtained as follows:

$$\left[1-\left(1-\frac{1}{\mu}\right)\frac{\Omega}{4\pi}\right]\rho(r_p)-\left(1-\frac{1}{\mu}\right)\int_\Gamma \frac{(r_p-r)\cdot n}{4\pi|r_p-r|^3}\,\rho(r)ds$$

$$+\frac{1}{A}\int_\Gamma \rho(r)ds=H_a(r_p)n(r_p), \tag{3}$$

where Ω is the interior solid angle at r_p, μ and Γ are the relative magnetic permeability and the boundary surface of the yoke, respectively, and A is the area of Γ.

Discretizing the surface and applying the Galerkin formulation for Eq. (3) yield the following matrix equation:

$$[K]\{\rho\}=\{f\}. \tag{4}$$

Once Eq. (4) is solved, the magnetic induction in the air gap can be evaluated using the equation

$$B(r_p)=\mu_0 H_a(r_p)+\mu_0\left(1-\frac{1}{\mu}\right)\int_\Gamma \frac{(r_p-r)\cdot n}{4\pi|r_p-r|^3}\,\rho(r)ds. \tag{5}$$

All the integrals for Eqs. (4) and (5) are computed numerically using the Gauss–Radau or Gauss–Legendre integration formulas.

III. OPTIMIZATION ALGORITHM

In order to find an optimum shape for the magnets, the (1+1) evolution strategy is adapted. The method, which is one of the stochastic optimization algorithms, combines the genetic algorithm that copies the natural principles of mutation and selection with the simulated annealing process in thermodynamics.[5] The three major processes; regeneration, mutation, and annealing, are repeated until the optimum design is achieved as summarized in Fig. 2.

The new design variables vector X_c (child in a generation) are generated from the old design variables vector X_p (parent in a generation) by the rule;

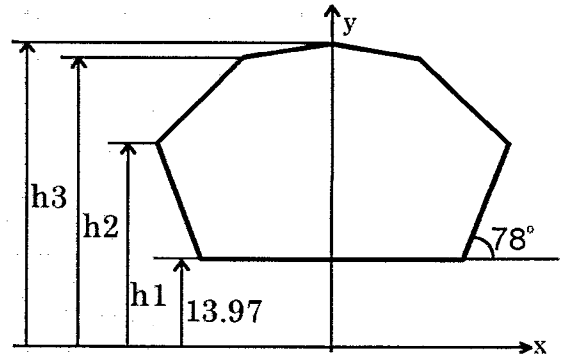

FIG. 3. Design variables.

$$X_{ci}=X_{pi}+\alpha R, \quad i=1,2,\ldots,N, \tag{6}$$

where N is the dimension of the design variables vector, α is the step length, and R is a random number with uniform distribution.

After computing the objective function values, $F(X_p)$ and $F(X_c)$, corresponding to the old and new design variable vectors, respectively, a new parent in the next generation is decided by the following rule to simulate the mutation:

$$X_p=\begin{cases} X_c & \text{if } F(X_c)<F(X_p) \\ X_p & \text{if } F(X_c)\geqslant F(X_p) \end{cases}. \tag{7}$$

The step length α is annealed by enlarging or reducing it by a factor of 0.85 according to the number of mutations for the previous ten generations, i.e.,

$$\alpha=\begin{cases} \alpha 0.85 & \text{if number of mutations}>2N \\ \alpha/0.85 & \text{otherwise} \end{cases}. \tag{8}$$

IV. NUMERICAL EXAMPLE

The design target is to obtain the constant torque coefficients at the various positions of the rotor coil. The objective function to be minimized, hence, is defined as

$$F=\int_{\theta=-15°}^{\theta=15°}[T(\theta)-T_0]^2 d\theta \sim \sum_{k=1}^{N_T}(T_k-T_0)^2, \tag{9}$$

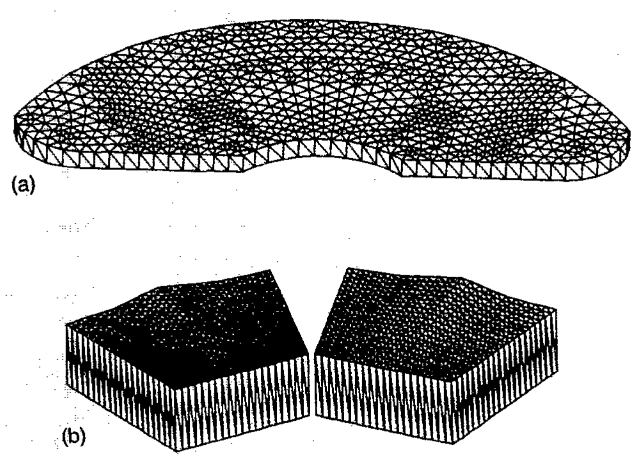

FIG. 4. Boundary element discretizations for yoke (a) and magnets (b).

TABLE I. Optimized design variables.

Case studies	Initial	Optimized	Generations
(h1,h3)	(28,30)	(28.90,29.398)	20
relative error	6.3%	0.62%	
(h1,h2,h3)	(28,29,30)	(28.16,28.68,29.31)	23
relative error	6.3%	0.54%	
(h1,h2,h3)	(28,28,28)	(28.19,28.70,29.31)	21
relative error	2.7%	0.54%	

where T_k and T_0 are the computed and target values of torque at kth coil position, respectively, and the torque generated can be expressed in vector form as

$$T(\theta)=\oint_l r\times[i\times B(\theta)]dl, \tag{10}$$

where i is the current in the coil and l is the current loop.

The upper shape of the magnet is represented as four straight lines and the three design variables (h1,h2,h3) are taken to modify the shape of the magnet as shown in Fig. 3.

In order to compute the magnetic induction in the air gap by using the boundary element method, the yoke and the permanent magnet are discretized into 6200 and 3520 linear triangular elements, respectively, as shown in Fig. 4.

The final optimized design variables are shown in Table I where the maximum relative error, E_r, is defined as

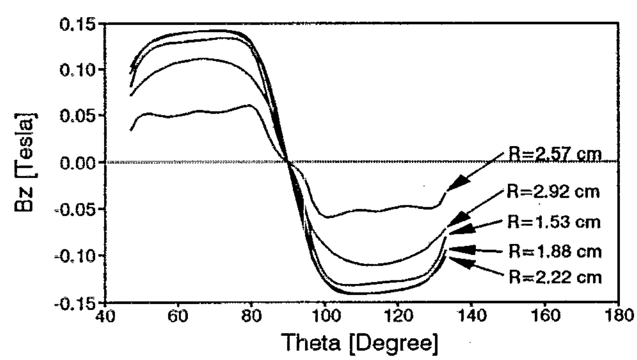

FIG. 5. Distribution of the magnetic induction in the air gap (z=7.94 mm).

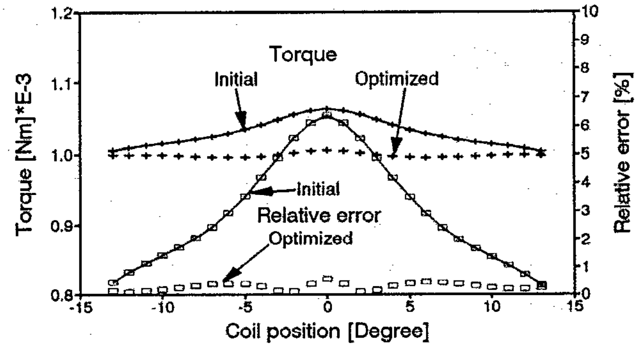

FIG. 6. Distribution of the torque coefficients.

$$E_r=\max_{1\leq k\leq N_T}\left(\frac{|T_k-T_0|}{T_0}\times 100\right)[\%]. \tag{11}$$

From Table I, it is found that more elaborate design is achieved with three design variables than with two design variables. In the case of two design variables, the mean value of h1 and h3 is taken for h2. Furthermore, final results are considered as a global optimum because different initial shapes converged into nearly the same shape. Figure 5 shows the distribution of the magnetic induction in the air gap at the final optimized shape. The torque coefficients are compared in Fig. 6 at the initial and final optimized shapes where the maximum relative error at the optimized shape is only 0.4[%].

V. CONCLUSION

An effective optimum design method is developed for the design of VCM by combining the three-dimensional boundary element method and the (1+1) evolution strategy. The method converges to a global optimum point from different initial points. It is found, through the numerical example, that the optimum shape of the magnet can be easily found within a reasonable number of iterations and more elaborate design can be achieved by increasing the number of design variables.

[1] C. Dong, IEEE Trans. Magn. **MAG-19**, 1689 (1983).
[2] J. Arthur Wagner, IEEE Trans. Magn. **MAG-18**, 1770 (1982).
[3] T. Nakata, Trans. IEE Jpn. **105B**, 483 (1985).
[4] I. D. Mayergoyz, J. D'Angelo, and C. Crowely, J. Appl. Phys. **57**, 3832 (1985).
[5] A. Gottvald, IEEE Trans. Magn. **MAG-28**, 1537 (1992).