Optimum Design of Electromagnetic Solenoid by Using Artificial Bee Colony (ABC) Algorithm

Wataru Kitagawa, Takaharu Takeshita

Abstract -- Recently, as electrical machinery design is some techniques of using electromagnetic numerical analysis with optimization methods. Usually, meta-heuristics is used in order for calculating the global optimal solution (strict solution) to have forced. A typical thing has the GA and IA which are classified into the evolutionistic calculation technique. Moreover, as swarm intelligence algorithm, PSO and the ACO and so on. In this paper, the performance was compared and verified the Artificial Bee Colony algorithm (ABC) of the multi-point search algorithm which obtained the idea to action of the honeybee.

Index Terms-- Artificial Bee Colony (ABC) Algorithm, Optimization, Finite Element Method, Electrical Machinery

I. INTRODUCTION

RECENTLY, as electrical machinery design is some techniques of using electromagnetic numerical analysis with optimization methods. Usually, meta-heuristics [1] is used in order for calculating the global optimal solution (strict solution) to have forced. A typical thing has the Genetic Algorithm (GA) [2],[3] and Immune Algorithm (IA) [4] which are classified into the evolutionistic calculation technique. Moreover, as swarm intelligence algorithm, Particle Swarm Optimization (PSO) [5] and the Ant Colony Optimization (ACO) [5] and so on. In this paper, the performance is compared with GA and verified the Artificial Bee Colony algorithm (ABC) [6]-[8] of the multi-point search algorithm which obtained the idea to action of the honeybee. Verification analysis models are two models. One is Axial symmetry electromagnetic solenoid. This model use compare with the capability of GA and ABC. Another one is pole type electromagnetic solenoid. This model use check of capability for ABC algorithm.

II. ARTIFICIAL BEE COLONY (ABC) ALGORITHM

A bee colony can be thought of as a swarm whose individual agents are bees. Each bee at the low-level component works through a swarm at the global level of component to form a system. Thus, the system global behavior is determined from it is individual's local behavior where the different interactions and coordination among individuals lead to an organized teamwork system. This system is characterized by the interacting collective behavior through labor division, distributed simultaneous task performance, specialized individuals, and self-organization. The exchange of information among bees leads to the formation of a tuned collective knowledge. A colony of honey bees consists of a queen, many drones (males) and thousands of workers (non-reproductive females). The queen's job is to lay eggs and to start new colonies. The sole function of the drones is to mate with the queen and during the fall they are ejected from the colony. The worker bees build honeycomb, and the young, clean the colony, feed the queen and drones, guard the colony, and collect food [9].

In the ABC algorithm, the colony of artificial bees contains three groups of bees: employed bees, onlookers and scouts. A bee waiting on the dance area for making decision to choose a food source is called an onlooker and a bee going to the food source visited by it previously is named an employed bee. A bee carrying out random search is called a scout. In the ABC algorithm, first half of the colony consists of employed artificial bees and the second half constitutes the onlookers. For every food source, there is only one employed bee. In other words, the number of employed bees is equal to the number of food sources around the hive. The employed bee whose food source is exhausted by the employed and onlooker bees becomes a scout. In the ABC algorithm, each cycle of the search consists of three steps: sending the employed bees onto the food sources and then measuring their nectar amounts; selecting of the food sources by the onlookers after sharing the information of employed bees and determining the nectar amount of the foods; determining the scout bees and then sending them onto possible food sources. At the initialization stage, a set of food source positions are randomly selected by the bees and their nectar amounts are determined. Then, these bees come into the hive and share the nectar information of the sources with the bees waiting on the dance area within the hive. At the second stage, after sharing the information, every employed bee goes to the food source area visited by her at the previous cycle since that food source exists in her memory, and then chooses a new food source by means of visual information in the neighborhood of the present one. At the third stage, an onlooker prefers a food source area depending on the nectar information distributed by the employed bees on the dance area.

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As the nectar amount of a food source increases, the probability with which that food source is chosen by an onlooker increases, too. Hence, the dance of employed bees carrying higher nectar recruits the onlookers for the food source areas with higher nectar amount. After arriving at the selected area, she chooses a new food source in the neighborhood of the one in the memory depending on visual information. Visual information is based on the comparison of food source positions. When the nectar of a food source is abandoned by the bees, a new food source is randomly determined by a scout bee and replaced with the abandoned one. In our model, at each cycle at most one scout goes outside for searching a new food source and the number of employed and onlooker bees were equal [7]. Thus, each bees type and steps is below.

A. Employed bee (Honeybee 1)

The honeybee 1 presupposes that search within the limits has food source (feeding area), and is related with the food source. And the honeybee 1 searches the food source where evaluation is still higher near the associated food source. In other words, the one honeybee 1 corresponds to one food source, and the number of food sources and the number of the honeybees 1 are equal.

B. Onlookers (Honeybee 2)

The honeybee 2 searches the higher food source the neighborhood food sources of evaluation relatively comparing with the honeybee 1 searched.

C. Scout (Honeybee 3)

In search of the honeybee 1 and the honeybee 2, when the food source where updating was not made between a certain set-up number of times of search exists, the honeybee 1 which searched the food source moves a search place, and begins search in other food source as. Thus, Scout is equivalent to the “mutation” in the GA.

In the search range of 1-dimension, the schematic view of ABC algorithm is shown in Fig. 1. The black point in Fig. 1 shows the honeybee 1, and it distributes this honeybee 1 on a function to calculate for a solution. The larger fitness is good shape (solution) on this function, and food source is on this function. Therefore, the honeybee 1 searches to the food source selected at random. Next, after the honeybee 1 searches, the honeybee 2 searches the good neighborhood of a food source of adaptive value from each information on the honeybee 1.

The honeybee 1 which is not made into the search candidate point by the honeybee 2 turns into the honeybee 3 which searches other food sources, when the state continues.

Fig. 2 shows the schematic view of the ABC algorithm of the case in the search range of 2-dimensional plane. The honeybee 1 evaluates like the outline in Fig. 1 in each food source of 2-dimensional plane. From the synthetic information on the honeybee 1, the honeybee 2 searches the neighborhood of the high food source of relative evaluation. If the low food source of evaluation does not have updating within the set-up period, the honeybee 1 will turn into the honeybee 3 and will search another food source.

The flow chart of an ABC algorithm is shown in Fig. 3.
Step 1: Initialize each parameter. Furthermore, the total $S_0$ of a searching point is determined. Moreover, the number of times of the maximum iteration (Maximum Iteration Count: MNC) is determined.

Step 2: Generate the honeybee 1 with a random number and search a food source. Next, the updating candidate point is generated from all the searching points based on the search information on the honeybee 1. Then it is considered as $x_y$ ($i=1, \ldots, S_N$) and an updating candidate point is set to $v_y$ ($i=1, \ldots, S_N$), it is shown in (1)

$$v_y = x_y + u(x_y - x_y)$$

where $u$ is random number for [-1,1], $j=1,\ldots,d$: $d$ is dimension number and $k=1,\ldots,S_N$

Step 3: The fitness value of each updating candidate point acquired by the formula (1) is calculated. Relative probability is searched for using the fitness value as (2)

$$P_i = \frac{fit_i}{\sum_{n=1}^{S_N} fit_i}$$

where fit is fitness value.

One searching point is chosen from the relative probability by roulette selection in the (2). The honeybee 2 correspond to this selected searching point, and an updating candidate point is generated like Step 2.

Step 4: The honeybee 1 of the searching point which did not turn into an updating candidate point within a certain predetermined number turns into the honeybee 3, and moves to another food source according to a random number. This step of 2-4 is continued, and when an iteration count exceeds MNC, it ends.

### III. FITNESS FUNCTION

In this paper, Maxwell's stress method [10] is used as the technique of calculating the thrust used as fitness value in an ABC algorithm from the magnetic field analysis result by the finite element method. The stress supposes that a magnetic action will also be depended on distortion of a magnetic field based on Maxwell's idea of being transmitted by distortion of space. According to this idea, If the inside is made into the domain 1 and the exterior is made into the domain 2 when the arbitrary closed surfaces $S$ are in a magnetic field, as for the stress in which the domain 2 acts on the domain 1, will certainly be passed $S$. Thus, if stress of acting per unit volume of the domain 1 is set to $f$ and stress per unit area of $S$ is set to $p$, the power $F$ of acting on the domain 1 whole will serve as the following formula.

$$F = \int_V f \, dv = \int_S p \cdot dS$$

On the other hand, supposing it is expressed with divergence of unknown vector $T(x)$ with the $x$ direction ingredient $f_x$ of $f$,

$$f_x = \text{div}T(x) = \frac{\partial}{\partial x}T_{xx} + \frac{\partial}{\partial y}T_{xy} + \frac{\partial}{\partial z}T_{xz}$$

Suppose similarly that it is expressed with divergence of $T(y)$ and $T(z)$ about $f_y$ and $f_z$. (4) If $x$ ingredient of both the neighborhoods of a formula is taken,

$$\frac{\partial}{\partial x}p_x \cdot dS = \int_S f_x \cdot dS = \int_V \text{div}T(x) \cdot dv = \int_S T_x \cdot dS$$

where, if $n$ is made into outward normal vector of $S$,

$$p_x = T_x \cdot n$$

Moreover, it can express similarly about $p_y$ and $p_z$. That is, it can express with following tensor.

$$p = (T) \cdot n, \quad (T) = \begin{pmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{pmatrix}$$

$(T)$ is in a two-dimensional place, when it is stress tensor of Maxwell of a magnetic field and the tension (the inside of a vacuum 0) of Helmholtz is disregarded,

$$\begin{pmatrix} \frac{1}{\mu} \left( B_y^2 - B_z^2 \right) \\ -\frac{1}{\mu} B_y \times \frac{1}{\mu} \left( B_z^2 - B_y^2 \right) \end{pmatrix}$$

where, $\mu$ is amplitude permeability. Therefore, the power $p$ per unit cross-sectional area of $S$ serves as the following formula.

$$p_x = \frac{1}{2\mu} \left( B_y^2 - B_z^2 \right) \cdot n_x + \frac{1}{\mu} B_y \cdot n_y$$

$$p_y = \frac{1}{\mu} B_y B_x \cdot n_x + \frac{1}{2\mu} \left( B_z^2 - B_y^2 \right) \cdot n_y$$

However, $n_x$ and $n_y$ are the unit normal vectors of the closed surface $S$. Fitness value is a thrust of a $x$ direction ingredient in this paper.

### IV. ANALYSIS MODEL

The outline of electromagnetism solenoid which is the model which performed the optimal design is stated to Fig. 4. This model consists of a stator, a mover, a coil, and a magnet. Moreover, the part for analysis of solenoid is axial symmetric structure. The number of turns of a coil is 970Turn, and exciting current is 0.4A. The magnetic material uses electromagnetism soft iron and NEOMAX-40 for the permanent magnet. With the electromagnetic force which occurs by giving the exciting current 0.4A to a central coil, Mover is drawn to stator, adsorbs and operates as a switch. In this paper, fitness of this algorithm which gap length is 0.3mm between mover and stator
Fig. 4. Axial symmetry electromagnetic solenoid

Fig. 5. Design parameter of axial symmetry electromagnetic solenoid

Fig. 6. Pole type electromagnetic solenoid

Fig. 7. Design parameter of pole type electromagnetic solenoid

Fig. 5 is shown the design parameter. The design parameter are four parts for convex part of stator. These parts are jointed mover parts, therefore effective of magnetic force change by modifying of design.

Furthermore, as the analysis model for verification, pole type electromagnetic solenoid is used. Fig. 6. is shown basic design of pole type electromagnetic solenoid. This model is symmetry of up and down. It consists of a stator, a mover, a coil, and a magnet. The electromagnetic material of the mover and stator are used soft iron. And Br of magnet is 1.0T, Hc is 748kA/m for ferrite type magnet on the initial model.

As for a principle of operation, the convex portion on the magnet by the side of stator serves as the S pole with the relation of the magnetic N pole and the S pole. And by adding exciting current through a coil in the direction of perpendicular this side of Fig. 5, the left convex part by the side of mover serves as the S pole, a right convex part becomes the N pole, and stator and mover adsorb. Moreover, by adding exciting current to a coil in the direction of the perpendicular back of Fig. 5, the pole of mover interchanges and mover and stator oppose. The solenoid operates as a switch by this operation.

Fig. 7. is shown the design parameter. The convex portions of stator and mover changed only height, without changing the width. In addition to it, it set up to make the height of a magneto portion change only in the negative direction.

V. ANALYSIS PARAMETER

Table I is shown GA parameter for comparative method and ABC parameter. GA parameter details are follow. GA does not search for one searching point in search space at a time in order, but uses two or more searching points simultaneously. And the searching point is a virtual living thing with a gene. Fitness with environment is calculated to an each individual, respectively. \( x \) is used as the gene of an individual on the example of the search problem shown in Fig. 1, and \( f(x) \) is fitness value with environment.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>ABC</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individuals</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Employed bees</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Number of onlookers</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Scout / Mutation (%)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Cross over</td>
<td>-</td>
<td>15</td>
</tr>
</tbody>
</table>

An individual with low adaptive value is screened, and is extinguished, and the high individual which an adaptation degree has is proliferated. The individual of the posterity whom the gene which inherited parents' character has is generated, and a change-of-generation simulation is performed. Operation which arises also in reproduction of an actual living thing and which is called crossover and mutation of a gene is performed. And finally, the very high
fitness of individual value $x$ which in other words gives maximum $f(x)$ are calculated. That is, the parameter of GA must set up individual number, crossover rates, and mutation rates. The number of individuals in GA presupposes that it is equivalent to what added the honeybee 1 and the honeybee 2 in the ABC algorithm. That is, it is considered as 40 individuals and the honeybee 2 is made into the half. Moreover, both mutation rates of the honeybee 3 and GA are set up to 3%. This performs comparison of GA and an ABC algorithm. CPU is Intel Core i7 X980 (3.33 GHz) and memory is 24.0 GB and OS is Windows7 Service Pack 1 and 64bit system for the PC. In addition, parallel computing is not used, it is analyzing by the stand-alone.

VI. ANALYSIS RESULTS

The relation between the fitness and the generation number by GA in the analysis which used axial symmetry solenoid, the relation of fitness value, and the relation between the number of times of iteration and fitness by an ABC algorithm are shown in Fig. 8. The ABC algorithm results is calculate to 37.0N as the maximum fitness value, and it is better than the result of GA. The results of GA is 36.8N.

The calculation time is about 88min. for ABC algorithm and about 80min. for GA. According to this results, setting parameters of GA and ABC are affected. Thus, If number of individuals are large, the calculation time is longer both of GA and ABC. And in case of GA, mutation and crossover rate are affected to calculation time. Fig. 9. is shown the solution of axial symmetry electromagnetic solenoid by GA. And Fig. 10. is shown the solution of axial symmetry electromagnetic solenoid by ABC. According to the results of GA and ABC, the concave portion is difference in the mover. That is the difference the results between GA and ABC. The flux distribution is about equal.
Fig. 11 is shown the pole type electromagnetic solenoid relationship of iteration and fitness. The axial symmetry electromagnetic solenoid has four design parameter. Thus, GA can be solve the optimal solution. But this pole type electromagnetic solenoid has eight design parameter. Therefore, searching point is $10^8$. ABC can be solve optimal solution because it has advantage to large dimension analysis. And authors try the calculation by GA, it was not get the any solutions. As the results, the fitness is 9.31N by ABC solution, and calculation time is about 734min.

And, Fig. 12 is shown initial flux distribution of pole type electromagnetic solenoid and Fig. 13 is shown optimal flux distribution of it. The convexity portion of optimal shape is shorter, and its left side portion is lower than initial shape. Thus, these modified portion guard to leak inductance, and it is up to improve the thrust.

Fig. 14 is shown the size of optimum design of pole type electromagnetic solenoid. The magnet size is not changed, but other six parameter is modified shape better than shape in Fig. 6.

VII. CONCLUSIONS

In this paper, the performance was compared with GA and verified the Artificial Bee Colony algorithm (ABC) of the multi-point search algorithm which obtained the idea to action of the honeybee. Conclusions are follow.

(1) The performance was compared ABC and GA by using axial symmetry electromagnetic solenoid. The result of fitness by ABC is better than GA. But, calculation time is about equal.

(2) The capability was verified by using pole type electromagnetic solenoid. The optimal shape was acquired and the calculation time is about 734min.

As a future examination, comparison examination is performed with other meta-heuristics algorithms, and it must verify further which algorithm is effective in the optimal design of electromagnetic machinery.

VIII. REFERENCES