Optimized design for a hybrid magnetic bearing for the artificial heart *

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***Abstract* – In this study, an optimization design method is developed to design the magnetic circuit of the diagonal flow pump for the maglev artificial heart. An optimization design method of the magnetic circuit is developed with genetic algorithms. A reluctance model by using an equivalent circuit method is used to model the magnetic bearing. Using the proposed method, we were able to optimize a magnetic bearing with an attractive force of 24.2 (N), which is larger than the desired attractive force. The magnetic bearing also has a power consumption of 1.5 (W), which is less than the expected power consumption. In addition, the size of the magnetic bearing is small enough to use for the maglev artificial heart. The developed optimization method with genetic algorithms and the reluctance model by using an equivalent circuit method is a useful design tool for magnetic bearings.**

***Index Terms* – diagonal flow pump, magnetic bearing, optimization, genetic algorithms, artificial heart**

I. INTRODUCTION

Mechanical parts such as sealing parts and mechanical bearings in the motor determine the lifetime of the artificial hearts. The magnetic bearing technique is useful for eliminating the mechanical parts in artificial hearts in order to achieve long lifetime and high durability [1]-[6]. Recently, turbo pumps, which are smaller pumps, have been applied as blood pumps in the artificial heart.

There are three kinds of turbo pumps: centrifugal pumps, the diagonal flow pumps, and the axial flow pump. The centrifugal pump needs a larger impeller to pump the fluid by centrifugal force. The axial flow pump uses the lifting force to pump the fluid, and so the impeller size is smaller for higher rotational speeds. The axial flow pump can reduce the pump size to below that of the centrifugal pump. However, it is hard to produce the higher-pressure head, whereas the centrifugal pump can produce the higher-pressure head. The size of the pump becomes bigger than axial flow pump. The size of the diagonal flow pump is between that of the centrifugal pump and that of the axial flow pump. The diagonal flow pump has better performance on pressure head than the axial pump and is smaller than the centrifugal pump.

We have been developing the magnetically suspended artificial heart with a diagonal flow pump. The artificial heart should be small enough to implant, and a magnetic bearing with of minimum size and high performance should be designed. Thus, optimization of the design parameters that can be miniaturized while maintaining high performance is required.

In the present study, an optimization design method is developed in order to design the magnetic circuit of the diagonal flow pump for the maglev artificial heart.

II. METHODS

A. *Maglev artificial heart*

The basic structure of a maglev artificial heart with a diagonal flow pump is shown in Fig.1. The pump consists of a hybrid magnetic bearing system, a rotor that encloses the impellers and a motor. The rotor is suspended in the axial direction using a hybrid magnetic bearing system. The axial position and the tilt motion of the levitated rotor are controlled actively, i.e., the movement in the radial direction is restricted by the passive stability. The motor stator to rotate the rotor is placed in the outlet port.

The hybrid magnetic bearing system consists of four permanent magnets and four electric magnets. On each electric magnet, two electromagnetic coils are wound in series.

The levitation mechanism of the hybrid magnetic bearing system is shown in Fig.2. This figure shows one quarter of the magnetic bearing system and the rotor. The bias magnetic flux produced by the permanent magnet is shown by the dotted lines in Fig.2. When the levitated rotor moves to the left, the upper two electromagnetic coils produce clockwise magnetic flux and the lower two coils produce counterclockwise magnetic flux, shown as solid lines in Fig.2. Thus, the magnetic flux of the left side is decreased and the magnetic flux of the right side is increased. As a result, the rotor position is maintained in the centre.

B. *Magnetic bearing model*

The reluctance model by using an equivalent circuit method is used to model the magnetic bearing [7]. Fig. 3 shows the equivalent electrical circuit for our hybrid magnetic bearing system.

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In Fig.3, V_e and V_p represent the magnetomotive forces produced by the electromagnetic coil and the permanent magnet, respectively, R represents the reluctance of the pole and the air gap, and kR represents the reluctance of the permanent magnet. In this model, the reluctance of the magnetic core is neglected.

The magnetic flux at the one side of the air gap is increased by the controlled magnetic flux, and that at the other side of is decreased.

The magnetic flux ϕ_{pull} (Wb) at the air gap at flux increased as follows:

$$\phi_{pull} = (2V_e + V_p)/2R \quad (1)$$

In addition, the magnetic flux at the air gap at flux decreased side, ϕ_{push} (Wb), is as follows:

$$\phi_{push} = (2V_e - V_p)/2R \qquad (2)$$

The attractive force F_{pull} (N) in the axial direction produced at the side of increased magnetic flux is then derived as follows:

$$F_{pull} = \frac{4V_e^{\,2} + 4V_e V_p + V_p^{\,2}}{2R^2 \mu_0 A_g} \qquad (3)$$

where μ_0 (H/m) is the vacuum permeability, $4\pi \times 10^{-7}$ (H/m), and A_g (m^2) is the cross sectional area of the electromagnetic circuit between the pole of the stator and the rotor.

The attractive force in the axial direction F_{push} (N) produced at the other side is as follows:

$$F_{push} = \frac{4V_e^{\,2} - 4V_e V_p + V_p^{\,2}}{2R^2 \mu_0 A_g} \qquad (4)$$

Thus, the attractive force F (N) actually acting on the rotor is as follows:

$$F = F_{pull} - F_{push} = \frac{4V_e V_p}{\mu_0 R^2 A_g} \qquad (5)$$

Under the assumption that the operating point can be determined simply from knowledge of the geometry of the magnetic circuit and the properties of the magnet, the magnetic field intensity in the permanent magnet H_m is represented as follows:

$$H_m = \frac{B_r}{\left(\frac{B_r}{H_c} + \mu_0 \frac{A_g l_m}{A_m g}\right)} \qquad (6)$$

where B_r (T) is the remnant magnetization, H_c (A/m) is the coercivity, A_m (m^2) is the cross sectional area of the core (i.e., the permanent magnet), g (m) is the length of the air gap between the pole of the stator and the rotor, and l_m (m) is the length of the permanent magnet.

From Eq. (6) and other parameters such as N (turns), which represents the number of turns in each electromagnetic coil, and I (A), which represents the control current to excite the electromagnetic coil, Eq. (5) is rewritten as follows:

$$F = \frac{4\mu_0 N I A_g l_m B_r}{g^2 \left(\frac{Br}{Hc} + \frac{\mu_0 A_g l_m}{2A_m g}\right)} \quad . \qquad (7)$$

C. Optimization methods

An optimized design method of the magnetic circuit is developed with genetic algorithms (GAs), which are optimization methods based on the evolution of living organisms.

The following terms and definitions will be used to describe the GAs.

Population: The set of parameters for magnetic bearing (Solution).

Generation: The subset of the population that is under consideration at a given point in time.

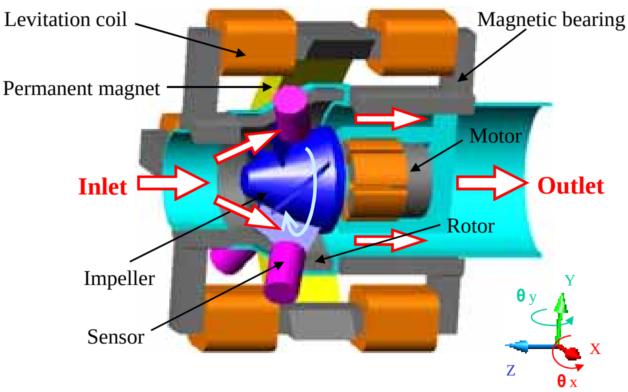

Fig.1 Basic structure of the hybrid magnetic bearing

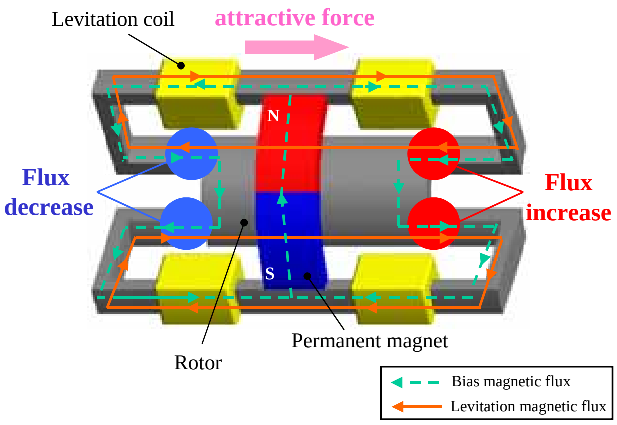

Fig.2 Levitation mechanism

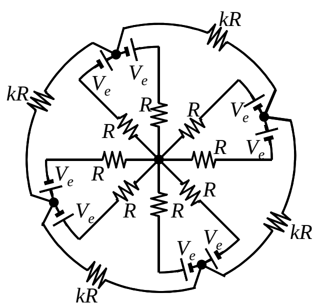

Fig.3 Equivalent electric circuit of the hybrid magnetic bearing

Individual: A single member of the population; in our case, a single set of parameters for magnetic bearing. The individual has a genetic code that represents the parameters.

Fitness: The value by which the individual is evaluated.

GAs are iterative procedures to maintain a population of individuals that are candidate solutions to a specific problem [8][9]. Fig. 4 shows a flowchart of the optimization iteration procedures. The GA starts with a large population, in which each individual has a randomly generated genetic code. In the present study, the population was set to 200. At each generation the individuals in the current population are rated according to their effectiveness as solutions by decoding their genetic code. A new population of candidate solutions is formed using specific genetic operators. This evolution process is repeated until the best individual, which has a reasonably optimal solution, is obtained.

The three primary genetic operators are selection, crossover, and mutation.

Selection: There are two types of selection process. The generational selection process replaces the entire population with a new population. In contrast, the other type of reproduction process replaces only a part of population. We used an elitist reproduction process, in which individuals that have a high fitness remain in the next generation. In addition, we set the percentage of the population that remains in the next generation as 1%. Whichever type of selection is used, individuals with higher fitness usually have a greater chance of contributing to the next generation. There are several methods to select parents, such as 'proportional' and 'ranking'. We used the ranking selection method, in which the probability of selection as parents is related to an individual's rating.

Crossover: A crossover operator manipulates a pair of individuals (called parents) to produce a new individual by exchanging segments from the parent's genetic code. The crossover process is, in effect, a method for sharing information between two successful individuals. There are several crossover methods, including one-point crossover, two-point crossover, multi-point crossover and uniform-crossover. We used the uniform-crossover process, which is good for solving general problem.

Mutation: To modify one or more of the genetic code of an existing individual, the mutation process creates new individuals. This operation increases the variability of the population. In this study, the mutation rate was set to 20% of the gene in the 20% of the population.

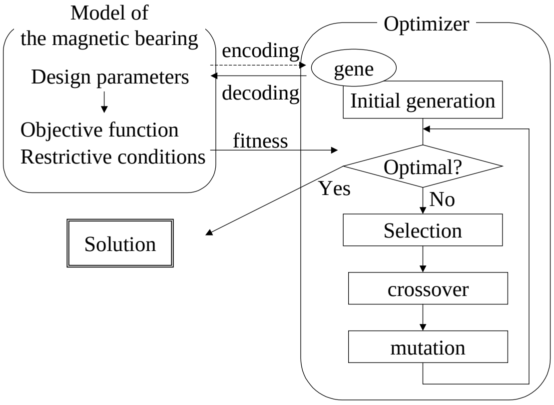

Fig.4 Optimization procedure

To represent the magnetic bearing, the seven variables shown in Table 1 were selected to construct the genetic code. The variables are converted linearly to real numbers from 0 to 1 to encode each variable into the genetic code.

The fitness of an individual is calculated based on the attractive force acting on the rotor with (7). In addition, the following restrictive conditions are used to evaluate individuals.

1. The magnetic flux in a stator core made by a soft magnetic iron is less than 1.5 (T).
2. The power consumption for the magnetic levitation is less than 2 (W).
3. The total length of the magnetic bearing is less than 50 (mm).
4. The maximum diameter of the magnetic bearing is less than 60 (mm).
5. The length of the permanent magnet should be less than the length in which the permanent magnet can be assembled between the stators.
6. The gap area is smaller than the size in which the stators can be assembled without a point of contact between adjacent poles.

The fitness is set to a low value when the individual cannot accomplish the restrictive conditions, because the solution must accomplish these restrictive conditions.

The termination condition of the GA operation is that the attractive force in the axial direction produced by the magnetic bearing is greater than 24.2 (N), because the thrust force in the axial direction acting on the rotor is calculated as 24.2 (N).

III. RESULTS

Fifty trials of optimizations were carried out. Fig. 5 shows the characteristics of the best individual obtained by each trial. The best fitness, which is the biggest attractive force, was 27.0 (N), and the results of fifty trials varied

TABLE I
Range of the variables for the magnetic bearing

Height of stator poles: a	0 – 0.015 [m]
Width of stator poles: b	0 – 0.015 [m]
Cross sectional area of the permanent magnet: A_m	0 – 0.002 [m²]
Length of the permanent magnet: l_m	0 – 0.05 [m]
Number of turns of the electromagnetic coils: N	0 – 300 [turn]
Length of where the electromagnetic coils is wound: l_c	0 – 0.03 [m]
Current into the the electromagnetic coils: I	0 – 2 [A]

between 27.0 (N) and 24.2 (N). The minimum power consumption was 1.52 (W), and the maximum power consumption was 2.0 (W). The sum of the length and maximum diameter of the magnetic bearing were varied between 104 (mm) and 109.9 (mm). The result shows that there is a tradeoff relationship between larger attractive force and smaller power consumption.

Fig. 6 shows an example of the history of the highest fitness in the population. The fitness was improved from it in the initial generation as the generations were advanced. And an optimized solution was obtained from the 106^{th} generation, in this case. The shortest generation to obtain a solution was the 25^{th} generation, and the computational time was less than 1(s). The longest generation to obtain a solution was the 971301^{st} generation, and the computational time was approximately 37 (min).

We chose the design parameters to indicate the minimum power consumption from these fifty solutions. The length of the stator core is 3.1 (mm). The cross sectional area of the permanent magnet is 48.6 (mm^2). The length of the permanent magnet is 9.9 (mm). The number of turns of the coil is 155 (turns). The current into the magnetic coils is 0.41 (A). The total length of the magnetic bearing L (mm) is 48.4 (mm). The maximum diameter of the magnetic bearing D (mm) is 60.0 (mm). Fig. 7 shows the optimized magnetic bearing. Fig. 8 shows a photograph of the magnetic bearing system. The maglev artificial heart with the optimal designed magnetic bearing is currently being manufactured.

IV. Discussion

Optimization of a magnetic bearing design for an artificial heart is a multi-objective optimization problem. The proposed method solved this problem by setting multi restrictive conditions by using GAs. The reason why we used GAs for design optimaization is as follows. GAs are random, yet directed, search algorithms. They are superior to 'gradient descent' techniques because the search is not biased toward local optimal solutions. On the other hand, they are also superior to random sampling algorithms due to their ability to direct the search toward relatively prospective regions in the search space. The main advantage of GAs is that they do not require any knowledge of the function derivatives or restrictions on the continuity of the first derivative. In the present study, GAs were treated primarily as a robust optimization technique, for which only overall evaluations of candidate solutions are only need.

However, the fitness became extremely low if an individual had not satisfied all restrictive conditions and sometime this method may have difficulty to escape from a local optimal solution. Therefore, higher mutation rate was used to avoid the local solution convergence in the optimisation process.

The size of the designed magnetic bearing was suitable for an implantable artificial heart. The power consumption of the designed magnetic bearing is assumed to be less than 1.5 (W), which is sufficient for implantation. The magnetic bearing model that is used in this study was a very simple model that neglects a leakage flux at the air

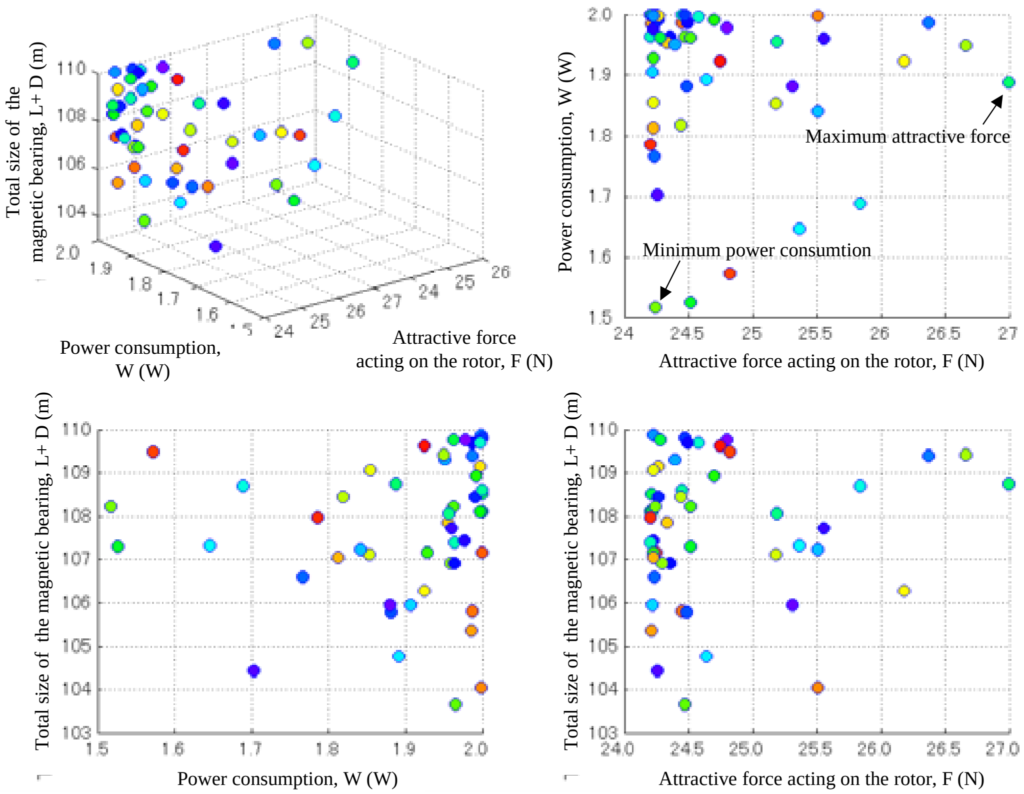

Fig.5 Results of the optimal design with the GA

gap and eddy-current losses in the core. It is possible the magnetic bearing will display different performance with the estimated values. We will report the performance of the optimization magnetic bearing and the pump in future studies.

V. CONCLUSION

We developed an optimization design method to design the magnetic circuit of the diagonal flow pump for the maglev artificial heart. The optimization design method was developed with genetic algorithms and a reluctance model by using an equivalent circuit method. A magnetic bearing, which can produce an attractive force of 24.2(N) and has a power consumption of 1.5(W), was designed by using the proposed method. The total length of the magnetic bearing was 48.4 (mm), and the maximum diameter of the magnetic bearing was 60.0 (mm). The optimized magnetic bearing was suitable for the construction of a diagonal flow pump for the maglev artificial heart.

The performance of the designed magnetic bearing and the pump will be reported in near future.

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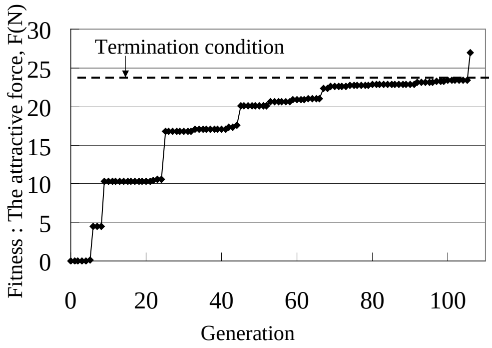

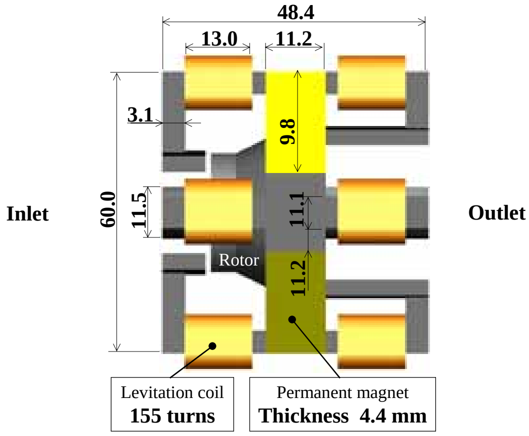

Fig.7 Optimization design of the magnetic bearing

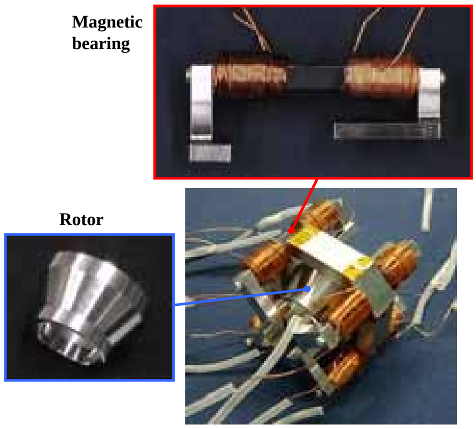

Fig.8 Photographs of the magnetic bearing system