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Optimal design of the magnetic microactuator using the genetic algorithm

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Abstract

This paper presents the optimal design of the magnetic microactuator using the genetic algorithm. The magnetic microactuator is composed of an enclosed core and a permalloy plate to form a closed magnetic circuit. The present design allows the area of the magnetic poles to be optimally enlarged and achieve a maximum force generation. To obtain the optimal geometry and maximum force, the genetic algorithm (GA) which is a robust, stochastic search method modeled on the concept of natural section and evolution is proposed. To increase the search efficiency of the GA, strategies like population-elitist scheme, fitness scaling, and operator probability adaptations are used. The simulation results indicated that a dramatically improvement in generating magnetic force, that has the potential to enhance the actuating aspect in MEMS applications.

Keywords: MEMS; Magnetic microactuator; Magnetic circuit; Optimal design; Genetic algorithm

1. Introduction

Magnetic microactuators have attracted much attention in the area of microelectromechanical systems (MEMS). One of the reasons is that microactuation based on electromagnetism has the advantages of generating large force and displacement with low driving voltage. To increase the efficiency of the microactuators in generating the magnetic force, a closed magnetic circuit that reduces the leakage flux from the micromachined electromagnet is essential in the present development. Among the existing designs of the closed magnetic circuits, three planar types of microactuators are developed: spiral type [1–3], solenoid type [4], and meander type [5]. These designs have high inductance for generating large magnetic forces and thus have great potential in practical applications. However, the magnetic force will vary with given designed dimensions of the microactuator due to the change of the reluctance and flux density. Accordingly, it is necessary to optimize the design of the microactuator to generate the maximum magnetic force.

In this paper, the genetic algorithm (GA) is proposed to optimize the magnetic microactuator design. In order to increase the search efficiency of the GA, strategies like population-elitist scheme, fitness scaling, and operator probability

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adaptations are utilized. And, the parameters of the GA are investigated to increase its effectiveness in achieving the optimal design of the micro-actuator.

2. Magnetic microactuator design

Fig. 1 shows a typical magnetic microactuator, including an electromagnet and a movable permalloy plate [3]. The micromachined electromagnet consists of two layers of coils, two layers of magnetic core, and three layers of insulator, as shown in Fig. 2. It is enclosed by the magnetic core and there is a ring-like hole on the top layer of the magnetic core. The permalloy plate is supported by a flexible polyimide structure, as shown in Fig. 3. When the current is applied to the coils, the magnetic flux flows along the magnetic circuit formed by the enclosed core, permalloy plate, and air gap. Thus, the permalloy plate will move downward when attracted by the magnetic force. This microactuator has advantages such as it allows a large variation in lengths of the permalloy plate and magnetic poles. Note that, a small area of permalloy plate can reduce the mass of the moving part to obtain higher frequency and provide a larger rotating range for the torsion component, such as a micromirror. Besides, the area of the poles can be optimally enlarged to increase the efficiency in generating the magnetic force.

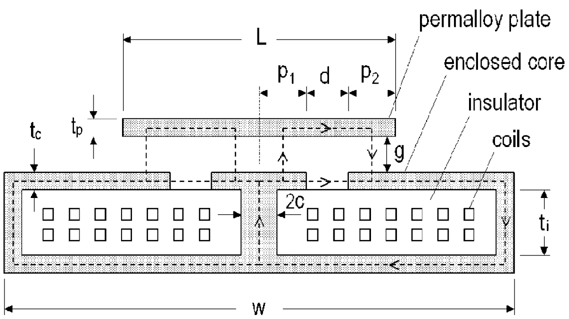

Fig. 1. A typical magnetic microactuator.

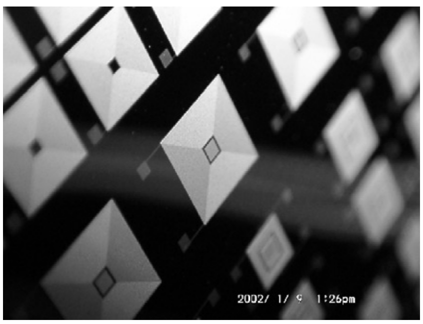

Fig. 2. Photograph of the electromagnet.

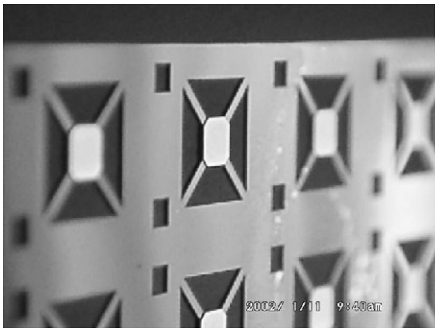

Fig. 3. Photograph of the permalloy plate support by a flexible polyimide structure.

Table 1
The ranges of the geometrical parameters (μm)

L	g	p_1	p_2	c	t_p	t_c	t_i
800	20	0–400	0–400	0–400	5–50	5–30	40–60

The geometrical parameters of the microactuator are specified in Fig. 1 and their ranges are listed in Table 1. Also, the line pitch is 20 μm, coil number is 40, and the relative permeability of the permally plate and magnetic core is 1000. The objective of the optimal design is to find the optimal values of the geometrical parameters to generate a maximum force given the fixed plate length L, gap g, line pitch, and coil number. Fig. 4 shows the design procedure. First, the effects of geometrical parameters on magnetic force generation are analyzed by conducting a series of finite-element simulations. Then, those geometrical parameters, which have the critical effect in optimization, are found as the design variables. Next, the GA is applied to find the optimal values of the design variables and the maximum magnetic

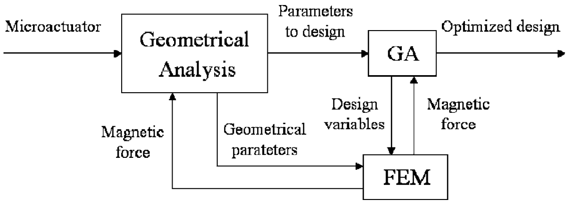

Fig. 4. Block diagram of the magnetic microactuator design.

force. Before we perform the optimization, we first build an accurate computational model to compute the magnetic force of the microactuator, described below.

3. Model for magnetic force computation

The magnetic force can be easily computed by using the equivalent reluctance method [3]. However, the microactuator fabricated by the surface fabrication technology is thin. The reluctance of the magnetic core and isolation layer then become comparable to that of the air-gap, thus they cannot be neglected [6]. In such a case, the effects on the reluctance result in the leakage flux in the surrounding and inner microactuator. Therefore, the simplified equivalent reluctance model may not be accurate enough and a more complicated reluctance model is demanded. However, to build such a model is difficult because the equivalent magnetic circuit is not easy to identify. And, solving the electromagnetic equations directly may be more appropriate in analyzing the microactuator, described below.

The magnetic vector potential representation of the Maxwell equations in the magnetostatic case can be formulated as

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \vec{A} \right) = \vec{J}_0, \tag{1}$$

where $\vec{A}$ is the magnetic vector potential, μ is the permeability, and $vecJ_0$ the input density of current. The flux density $\vec{B}$ can be expressed in terms of the vector potential $\vec{A}$ as follows:

$$\vec{B} = \nabla \times \vec{A}. \tag{2}$$

The magnetic co-energy W' can be calculated by integrating the constitutive equation of flux density B and magnetic field intensity H, described in Eq. (3):

$$W' = \int_V \int B \, \mathrm{d}H \, \mathrm{d}V. \tag{3}$$

Using the virtual work principle, the expression for the magnetic force is

$$F_m = \frac{\partial W'}{\partial s}, \tag{4}$$

where s is the virtual displacement of the moving part.

With the electromagnetic equations for magnetic force computation above, the finite-element method (FEM) that is popular for evaluating the performance of the electromagnetic devices is used to solve the problem. The results in Refs. [3,7] have shown that the FEM approximation has the merit in its high accuracy for magnetic force calculation. Thus, we also use the finite-element software ANSYS 5.4 to analyze the microactuator model, which is assumed to be with the axial symmetry and built by the two-dimensional (2D) axial symmetry element PLANE53. The air surrounding is an infinite extended boundary, so the 2D infinite boundary element is incorporated to the boundary of the model. The magnetic material of the permalloy plate and magnetic core is assumed to be operated in the unsaturated range, and the relative permeability is set to be a constant. To find the magnetic force acting on the permalloy plate, the magnetic virtual displacement loading is used in the ANSYS simulations. For our initial design of the microactuator, the values of the geometrical parameters are p_1 200 μm for pole length, p_2 100 μm for pole length, c 100 μm for core radius, t_p 10 μm for plate thickness, t_c 10 μm for core thickness, and t_i 50 μm for insulator thickness. The magnetic force is 512.2 μN with the current of 0.08 A.

4. Geometrical parameter analysis

To design the microactuator, six geometrical parameters, pole lengths p_1, p_2, radius c, plate thickness t_p, magnetic core thickness t_c, and insulator thickness h need to be determined.

However, it is difficult to find the optimal parameters with all of the six parameters as the design variables in optimization. Thus, in order to perform the optimization, we analyze the effects of the geometrical parameters, take out those not so critical, and use the remaining critical ones as the design variables.

In our analysis, we observe that the pole area plays an important role in generating the magnetic force. The relation between pole length p_1 and magnetic force is obtained through a series of the FEM simulations by varying pole length p_1 with the fixed plate length L and pole length p_2, as shown in Fig. 5. It can be seen that the peak force occurs when pole length p_1 is about 250 μm. The effect of different pole lengths p_1 on the magnetic flux is also investigated and the result is shown in Fig. 6. In Figs. 6a–b, the magnetic flux increases as pole length p_1 increases. As shown in Fig. 6c, if pole length p_1 keeps increasing, the magnetic flux also increases but there is a partial leakage flux along with a branch magnetic circuit caused by the ring-like hole. When pole length p_1 increased and connected with p_2, less magnetic flux passes through the plate and most of the magnetic flux remains inside the electromagnet, shown in Fig. 6d. Thus, a peak-shaped curve of the magnetic force versus pole length p_1 is obtained. Similar results are also observed for pole length p_2 on magnetic force generation.

Second, we observe the effect of radius c of the magnetic core in the central position on magnetic

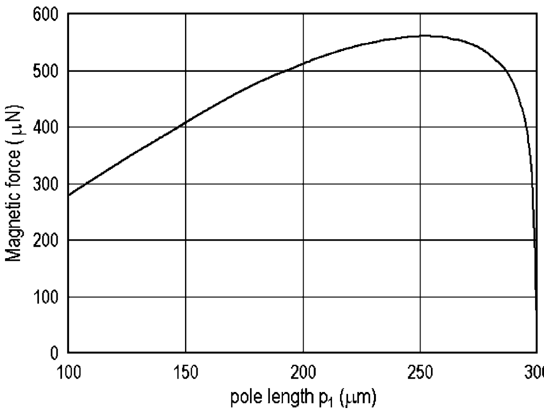

Fig. 5. Relation between pole length p_1 and the generated magnetic force.

(a)
(b)
(c)
(d)

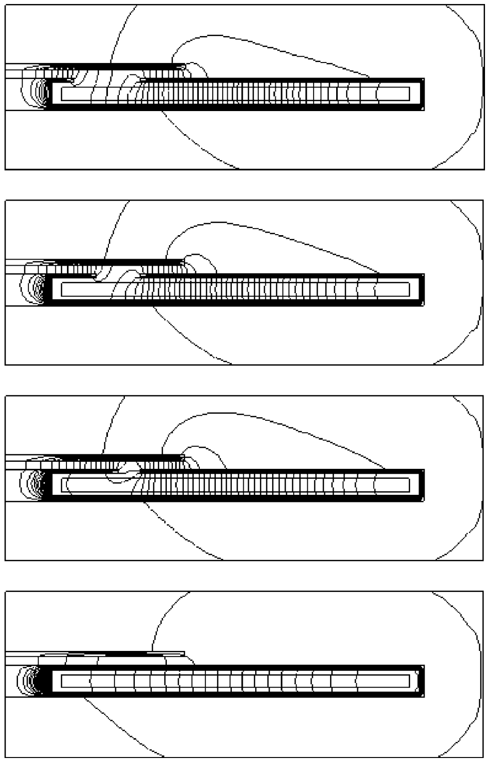

Fig. 6. Magnetic fluxes at different pole lengths p_1: $p_1 = 150\,\mu m$, (b) $p_1 = 200\,\mu m$, (c) $p_1 = 250\,\mu m$, and (d) $p_1 = 300\,\mu m$.

force generation. Note that, radius c shall not be larger than pole length p_1 with the fabrication process [3,8]. Here we set radius c to vary from 50 to 200 μm. Fig. 7 shows that a peak magnetic force is obtained when radius c reaches about 115 μm. The reasons are in twofold. First, when radius c increases, the magnetic core reluctance decreases that helps to increase the magnetic force. Second, the positions of all coils move outward as radius c increases, which leads to magnetic force reduction. The phenomenon can be explained by observing force generation on different positions of the single coil, as shown in Fig. 8. The inner single coil generates much more magnetic force than the outer single coil, because the inner single coil has less leakage flux in the insulator than the outer single coil.

Finally, the thickness parameters of the micro-actuator are discussed. We found the larger the

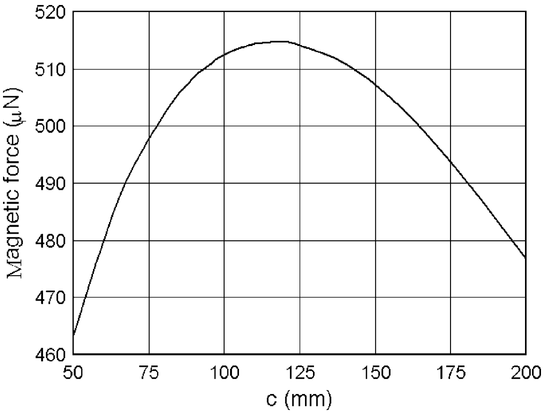

Fig. 7. Relation between core radius c and the generated magnetic force.

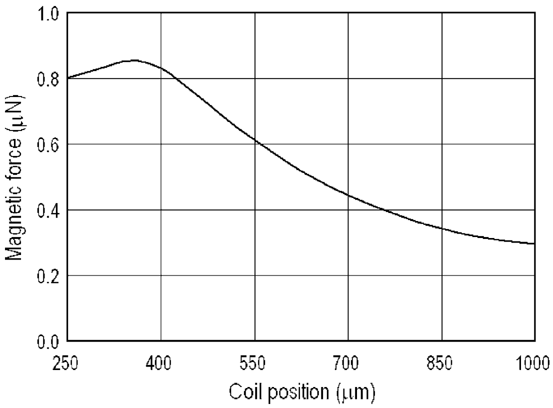

Fig. 8. The influence of the position of a single coil on magnetic force generation.

thickness parameter t_p is, the smaller the equivalent reluctance of the plate is. The same phenomenon is observed for magnetic core thickness t_c. And the larger the insulator thickness t_i is, the less the internal leakage flux is. Thus, the increase of these thickness parameters will increase the magnetic force monotonically. In other words, the maximum force is obtained with the maximum thickness parameters. Thus, these parameters need not to be considered when selecting design variables in optimization. However, the thickness is usually very thin due to the surface micromachining technology. To obtain a larger thickness, the LIGA (a German acronym for X-ray lithographie/lithography, galvanic/electroforming, and abformung/molding) technology may be helpful for fabricating a microstructure of about several dozens micron in thickness.

From the analysis above, the remaining parameters including pole lengths p_1, p_2, and radius c which exhibit the peak-shaped relationship are taken as the major design variables. Plate thickness t_p, magnetic core thickness t_c, and insulator thickness t_i are set with fixed values in finding the optimal values of pole lengths p_1, p_2, and radius c for maximum force generation. We then apply the GA, which is recognized as an effective tool in optimization, to search for the optimal values of these design variables.

5. Genetic algorithm

The GA, originally developed by Holland, is a computational optimization paradigm modeled on the concept of biological evolution [9,10]. The GA manipulates a population of potential solutions to an optimization problem. The quality of possible solutions is evaluated by a fitness function. The solutions with relative high quality are used to create new generations that inherit the features providing the solutions of high quality from the original generation. Note that, the GA can solve the nonlinear problem with a large search space and do not use any derivative or complex mathematical information during the searching process.

Basically, GAs are modeled on the "survival of the fittest" principle of the natural evolution. The initial population is randomly generated and contains individuals represented by feature-encoding chromosomes. A new population is generated by three operators: reproduction, crossover, and mutation. The reproduction operator stochastically selects individuals to become parents with the probability according to the fitness value. A scheme called roulette wheel selection is one of the commonly used reproduction mechanism [9]. The crossover operator randomly swaps a portion of chromosomes between two chosen parents to produce offspring chromosomes. The mutation operator randomly flips a bit in chromosomes.

Crossover and mutation operate with probabilities. The algorithm stops when the optimum is found or the maximum number of generations is reached.

However, the GA suffers the drawbacks including premature convergence, low search efficiency, and difficulty for parameter setting in the GA. To deal with these drawbacks, we propose the following modifications.

5.1. *Fitness scaling*

It is important to regulate the number of offsprings that an individual can have to maintain diversity in the population. Linear fitness scaling can help for the regulation. The relation between the raw fitness f and the scaled fitness f' is expressed as

$$f' = af + b, \tag{5}$$

where the coefficients a and b are chosen to satisfy the following conditions. First, the averages of f and f' are the same. Second, the maximum of f' is S times of the minimum of f'. $S = 1.5$–3, as empirical value, are used and they work well in the present GA.

5.2. *Population elitist with rank selection reproduction*

A population elitist with rank selection reproduction scheme is used and realized in three steps [10]. First, the individuals with fitness functions' values lower than the lowest one in the previous generation will be eliminated from the population. Second, the relatively good individuals from the previous generation will be put back to make up the deficiency. Third, the roulette wheel reproduction and population-elitist method are performed. By applying this scheme, not only the elimination of good individuals is avoided but also the search is speeded up by taking out bad individuals.

5.3. *Adaptation of operator probabilities*

According to the Schema theory [10], the crossover and mutation probabilities indeed affect the search efficiency. Crossover exchanges the possible partial solutions of different individuals and mutation helps to maintain diversity. If premature convergence or excessive diversity occurs, the search becomes inefficient. This can be resolved if the parameters are automatically set and varied in different search procedures. Typically, the crossover probability ranges from 0.4 to 0.9 (per genotype) and the mutation probability from 0 to 0.2 (per bit). When premature convergence is observed, the crossover probability is decreased by 0.05, and mutation probability is increased by 0.005. When excessive diversity occurs, the crossover probability is increased by 0.05 while the mutation probability is decreased by 0.005. Note that we only set the initial probabilities and the GA will adapt itself to find the optimum.

Based on the discussion above, a modified GA genetic algorithm is developed described below.

Modified genetic algorithm:

Step 1: Initialize the GA parameters, including the number of generations, number of individuals, the bit string length of the chromosome, crossover rate, and mutation rate. And generate the initial population of chromosomes.

Step 2: Decode each chromosome for the geometrical parameters and compute each magnetic force by using the FEM.

Step 3: Execute the fitness scaling.

Step 4: Evaluate each chromosome by performing the population elitist with rank selection reproduction scheme.

Step 5: Perform the adaptation of the crossover and mutation probabilities.

Step 6: Create the new chromosomes by applying the operations of crossover and mutation.

Step 7: If the maximum number of generations is reached, go to step 2 for the next generation; otherwise, stop and output the optimal geometry and the maximum magnetic force.

To implement the proposed optimization scheme, a GA-based optimizer that contains a simulator driver to interface with the FEM is developed. The FEM is used to evaluate the generated electromagnetic force. In the GA

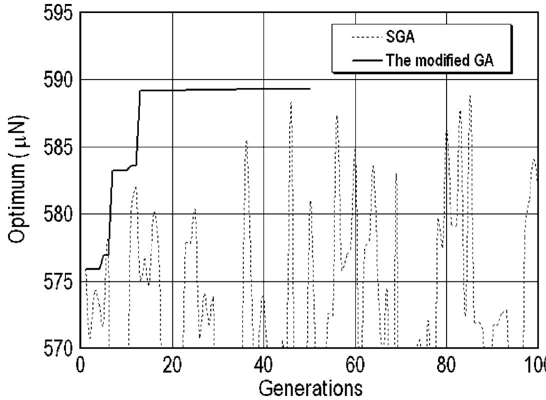

Fig. 9. Comparison of the evolution processes between the SGA and the modified GA.

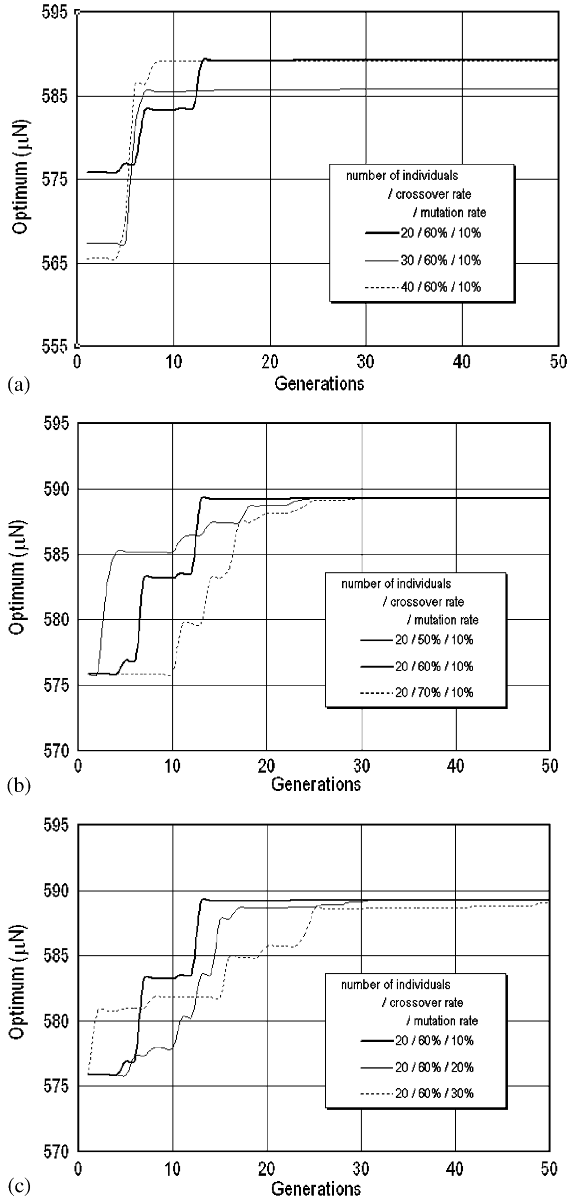

Fig. 10. The effects of the GA parameters on the evolution: (a) number of individuals, (b) crossover rate, and (c) mutation rate.

parameters, we set the number of generations to be 50, the number of individuals to 20 and the bit string length of the chromosome to 30. Fig. 9 shows the comparison of the evolution processes between the simple GA (SGA) and the modified GA. Here the modified GA includes the three proposed operators, while the SGA does not. We observe that the modified GA can converge much more quickly than the SGA.

During the simulations, we found the efficiency of the evolution is determined by the number of individuals, crossover rate, and mutation rate. Thus, we also search for better values for them by investigating the effects of these parameters on the evolution process. The results are shown in Fig. 10. Fig. 10a shows the effect of the number of individuals on the evolution process given the crossover rate 60% and mutation rate 10%, respectively. We observe that the number of individuals is better selected as 20. The effect of the crossover rate is shown in Fig. 10b and 60% is better selected given the number of individuals 20 and mutation rate 10%. Finally, the better mutation rate is selected as 10% given the number of individuals 20 and crossover rate 60%, as shown in Fig. 10c.

6. Results

With the proposed optimization scheme tuned up through the process above, we apply it to optimize the design of the microactuator. First, we design the microactuator with the fixed thickness given the fabrication conditions. The thickness values of the initial design are used. The plate thickness t_p, magnetic core thickness t_c, and insulator thickness t_i are 10, 10, 50 μm,

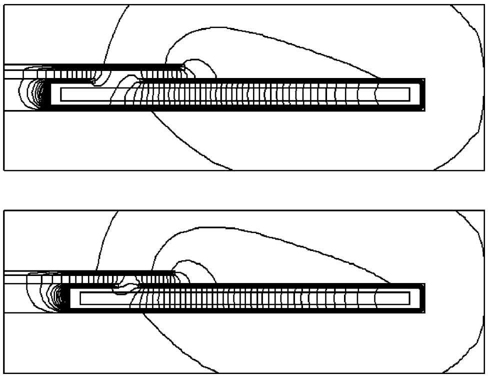

Fig. 11. Magnetic flux distribution for the initial and optimized geometry: (a) initial geometry and (b) optimal geometry.

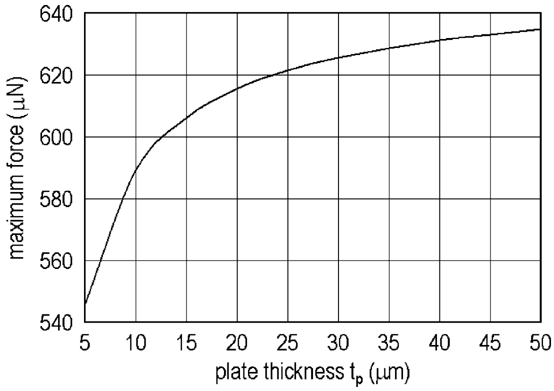

Fig 12. Effect of plate thickness on maximum magnetic force generation.

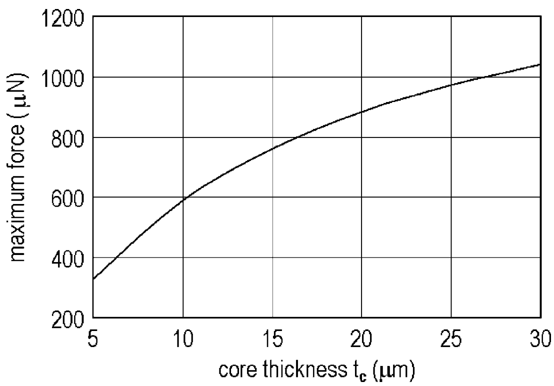

Fig 13. Effect of core thickness on maximum magnetic force generation.

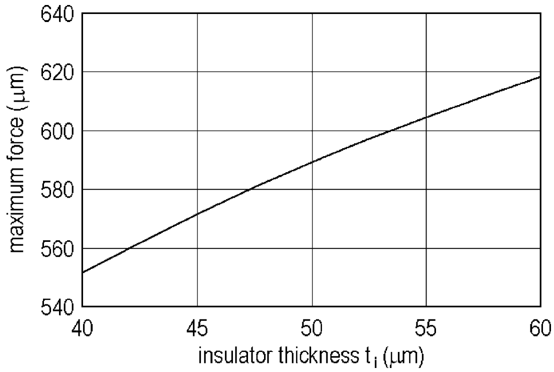

Fig 14. Effect of insulator thickness on maximum magnetic force generation.

respectively. The optimal design variables are found to be 290.8 μm for pole length p_1, 61.1 μm for pole length p_2, and 152.4 μm for radius c. Fig. 11 compares the magnetic flux distribution for the initial and optimized geometry. Magnetic flux flows much more through the permalloy plate after optimization. And the magnetic force is 589.2 μN for the optimized model, larger than 512.2 μN for the initial design. Note that, the improvement can be achieved by only designing the layout of mask.

Furthermore, we design the microactuator with the variable thickness when the fabrication conditions are tunable. To find the maximum magnetic force within the ranges of the geometrical parameters of the microactuator, we investigate the effects of the thickness parameters on magnetic force generation by performing a series of GA optimizations. The results for the plate thickness, core thickness, and insulator thickness are shown in Figs. 12–14, respectively. The maximum force increases as these thickness parameters increases, which coincides with the previous assumption by the reluctance theory. Among the three parameters, the core thickness has the most evident effect on maximum force generation. The maximum force approaches the largest value when the plate thickness increases. And the relation between the maximum force and insulator thickness is approximately linear. Thus, we set the plate thickness t_p, core thickness t_c, and insulator thickness t_i to be their maximum value simultaneously at 50, 30, and 60 μm, respectively. After the GA optimization, the maximum magnetic force is about 1160.9 μN, the largest among all of the models. And the corresponding optimal design variables are pole length p_1 270.7 μm, pole length p_2 96.1 μm, and core radius c 183.3 μm.

7. Conclusions

This paper has presented an optimization scheme based on the GA for the design of the microactuator. The effects of geometrical parameters in optimization have been analyzed. And the modified GA with better-selected parameters has been applied to search for the optimal values of the geometrical parameters. The results have showed remarkable improvement in magnetic force generation, making the magnetic microactuator ready for practical applications, such as optical switches, micromirrors, and microfluidics.

Acknowledgements

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