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# Topology optimization of magnetic actuator based on the ON/OFF method and reluctance network modeling

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**RÉSUMÉ** – Les actionneurs magnétiques sont largement utilisés dans l'industrie. Pour concevoir de tels actionneurs, un modèle est nécessaire pour prédire ses performances électromécaniques. Habituellement, trois approches sont couramment utilisées : l'analyse analytique, l'analyse par éléments finis (FEA) et l'analyse par réseau de réluctances (RNA). Dans cet article, l'approche RNA est utilisée, car il possède un bon compromis entre rapidité d'évaluation et précision des résultats. La validité de ce modèle est vérifiée en le comparant à l'approche FEA. La méthode ON/OFF est utilisée comme stratégie d'optimisation de la topologie. Cet article détaille la mise en œuvre de cette optimisation.

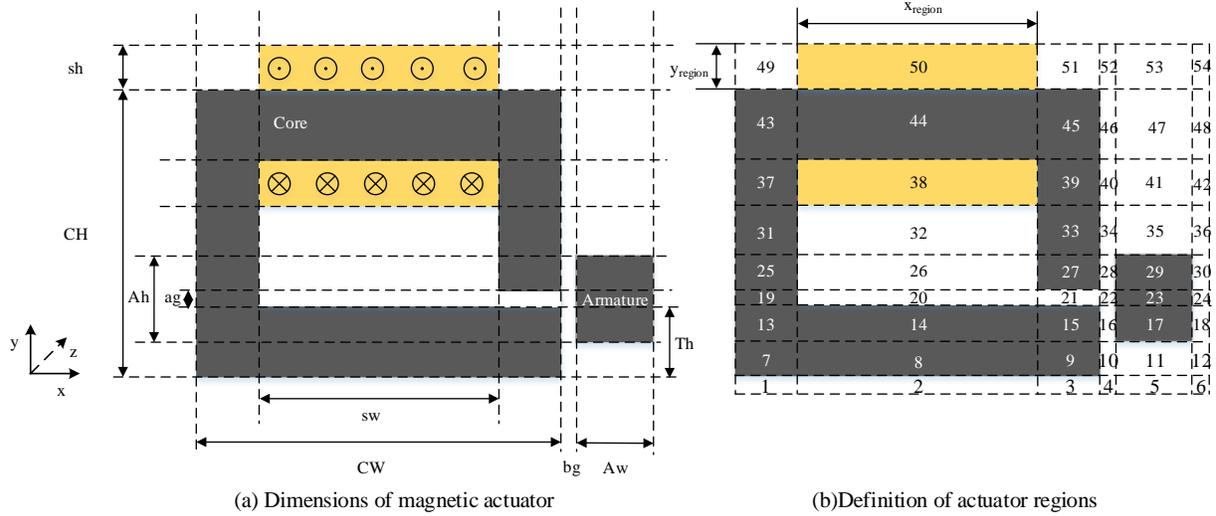
**ABSTRACT** – Magnetic actuators are widely used in industry. To design such actuators, a model is needed to predict its electromechanical performance. Usually, three approaches are commonly used: analytical analysis, finite element analysis (FEA) and reluctance network analysis (RNA). In this paper, the RNA approach is used, as it has a good compromise between speed of evaluation and accuracy of results. The validity of this model is verified by comparing it with the FEA approach. The ON/OFF method is used as a topology optimization strategy. This article details the implementation of this optimization.

**Mots-clés** – Optimisation de la topologie, Analyse du réseau de réluctance, Méthode ON/OFF, Force d'actionnement

## 1. Introduction

There is a large family for magnetic actuators. Its working principle is based on the forces acting at distance. The electrical input energy is converted to magnetic energy which creates the mechanical actuating force. Some typical applications include robots, tractors, loudspeakers, and fuel injectors [1]. There are two ways to achieve the design of an actuator: parametric, a process that varies the dimensions, and non-parametric, a process that distributes the material. Compared with conventional parametric optimization problem, the topology optimization has more freedom in determining the device shape, which can make it possible to significantly increase the result obtained. Among all the optimization strategies, such as: genetic algorithms (GA) with ON/OFF sensitivity [2], Constraint Maximum-Weight Connected Graph theorem (CMWG) [3], Level Set Method (LSM) [4] and Multi-Objective Ant Colony Optimization (MOACO) [5], the ON/OFF method is the most efficient and simplest one [6]. However, its limitation is also evident, that the computational cost is important. In this paper, Reluctance Network Analysis (RNA) method is used for modeling the system, because this model has a good compromise between the model evaluation time and its accuracy. To verify the validity of the model, Finite Element Analysis (FEA) is chosen as reference. Then, the ON/OFF optimization strategy is applied, associated with a reluctance network, in order to optimize the performance of the actuator.

## 2. Case study



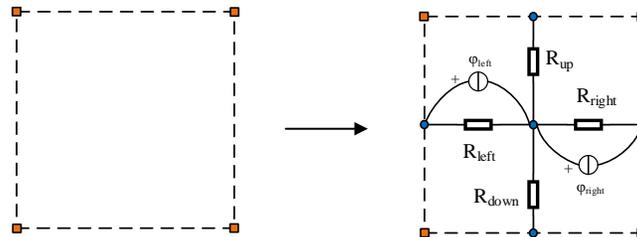
**Figure 1: The initial structure of magnetic actuator**

Herein, we used the magnetic actuator depicted in the figure 1(a) as an example to apply the topology optimization. The system mainly consists of three parts, the coil, the core and the armature. The wire is wound around the core and forms a coil with 420 turns, and there is 1 A current flowing through it. The material of core and armature is iron and its relative permeability is set to 1000 and 2000 respectively. We kept a same set of structure parameters with reference [7], and these are listed in the table 1. To note that, the air gap between the armature and the core ( $bg$ ) is not defined by that reference. Here, we choose a value of 1 mm for  $bg$ .

**Table 1 Dimensions of magnetic actuator**

| Parameter | Value | Unit | Parameter | Value | Unit |
|-----------|-------|------|-----------|-------|------|
| CW        | 60    | (mm) | sw        | 42    | (mm) |
| CH        | 30    | (mm) | sh        | 5     | (mm) |
| Th        | 8     | (mm) | Aw        | 12    | (mm) |
| ag        | 2     | (mm) | Ah        | 10    | (mm) |
| bg        | 1     | (mm) |           |       |      |

## 3. RNA model



**Figure 2: The mesh element and its associated magnetic equivalent circuit**

The physical electromagnetic domain is decomposed into element via a mesh. In our case, each element, can be represented by a magnetic equivalent circuit consisting of lumped reluctances and flux sources with a structure similar (Figure 2). This structure can be represented by four reluctances ( $R_{left}$ ,  $R_{right}$ ,  $R_{up}$ ,  $R_{down}$ ) and two flux sources ( $\phi_{left}$ ,  $\phi_{right}$ ). Every reluctance is expressed by formula (1) or (2), while the flux sources are expressed by the formula (3).

The reluctance values depend on the discretization of the region to be studied (Figure 1b) and actuator dimensions in Figure 1a and Table 1. The coefficient N is chosen to respect Ampère's theorem in each loop of the circuit.

$$R_{horizontal} = R_{left} = R_{right} = \frac{1}{\mu_0} \frac{1}{\mu_{r_{region}}} \frac{1}{depth} \frac{\Delta x_{region}/2}{\Delta y_{region}} \quad (1)$$

$$R_{vertical} = R_{down} = R_{up} = \frac{1}{\mu_0} \frac{1}{\mu_{r_{region}}} \frac{1}{depth} \frac{\Delta y_{region}/2}{\Delta x_{region}} \quad (2)$$

$$\varphi_{horizontal} = \varphi_{left} = \varphi_{right} = \frac{N I}{R_{horizontal}} \quad (3)$$

Where  $\mu_0$  is the vacuum permeability,  $\mu_r$  is the relative permeability of the physical material.

Therefore, the whole system can be represented by an equivalent network. We apply nodal analysis to every node of the circuit (4). This equation for the whole system can be expressed by a matrix form like (5). By solving the matrix system, the values of magnetic potential in each node is obtained  $\{\varepsilon\}$ . Other information such as magnetic potential difference (6) and magnetic flux (7) can also be deduced.

$$\frac{\varepsilon_{left} - \varepsilon_{center}}{R_{left}} + \frac{\varepsilon_{right} - \varepsilon_{center}}{R_{right}} + \frac{\varepsilon_{up} - \varepsilon_{center}}{R_{up}} + \frac{\varepsilon_{down} - \varepsilon_{center}}{R_{down}} = \varphi_{left} - \varphi_{right} \quad (4)$$

$$[M_{inc_{\Lambda}}]^T \text{diag}(\{\Lambda\}) [M_{inc_{\Lambda}}] \{\varepsilon\} = [M_{inc_{\varphi}}]^T \{\varphi_s\} \quad (5)$$

$$\{\Delta\varepsilon\} = [M_{inc_{\Lambda}}] \{\varepsilon\} \quad (6)$$

$$\{\varphi_{\Lambda}\} = \{\Lambda\} \{\Delta\varepsilon\} - \{\varphi_s\} \quad (7)$$

With:

|                         |  |      |
|-------------------------|--|------|
| $[M_{inc_{\Lambda}}]$   | Incidence Matrix of Permeances                 | (..) |
| $[M_{inc_{\varphi}}]$   | Incidence Matrix of Flux Sources               | (..) |
| $\{\Lambda\}$           | Vector of Permeances Values                    | (H)  |
| $\{\varphi_s\}$         | Vector of Flux Sources Values                  | (Wb) |
| $\{\varphi_{\Lambda}\}$ | Vector of Flux Permeances Values               | (Wb) |
| $\{\varepsilon\}$       | Vector of Magnetic Potential Values            | (A)  |
| $\{\Delta\varepsilon\}$ | Vector of Difference Magnetic Potential Values | (A)  |

To calculate the magnetic force a magnetic actuator, Maxwell stress tensor method is used for calculation and its formula is shown in (8).

$$\vec{F} = \sum_{cell_F=1}^{N_{contour}} \frac{1}{2} ( \vec{H}_{cell_F} (\vec{B}_{cell_F} \cdot \vec{n}_{cell_F}) + \vec{B}_{cell_F} (\vec{H}_{cell_F} \cdot \vec{n}_{cell_F}) - (\vec{H}_{cell_F} \cdot \vec{B}_{cell_F}) \vec{n}_{cell_F} ) \quad (8)$$

Where  $\vec{H}$  is the magnetic field,  $\vec{B}$  is the flux density and  $\vec{n}$  denotes the normal direction to the surface at the point of interest. This formula describes the differential force on unit area, thus the magnetic force is got by integrating the magnetic stress over surface [9].

## 4. Validation of RNA model

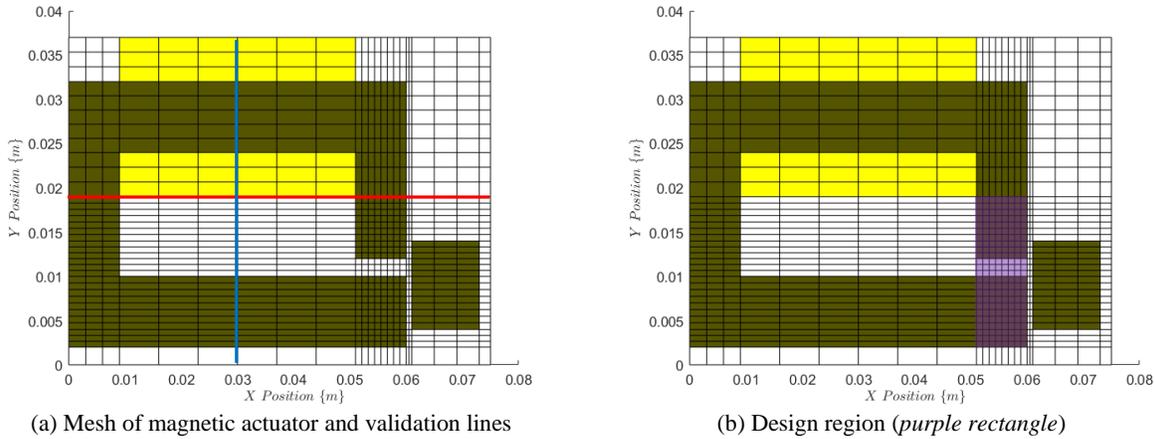


Figure 3 : (a) Mesh of magnetic actuator and validations lines (b) The chosen design region

The system is meshed (Figure 3) and modeled using RNA method. To verify the validity of the model, RNA approach compared to FEA approach. The key parameters obtained by modeling with these two methods are compared, such as the normal flux density ( $B_n$ ) distribution and the actuating force before optimization. The figure 4 describes the variation of flux density along the red and blue line separately with RNA and FEA. The result shows that the flux density obtained by RNA method keeps good agreement with FEA method in red and blue line.

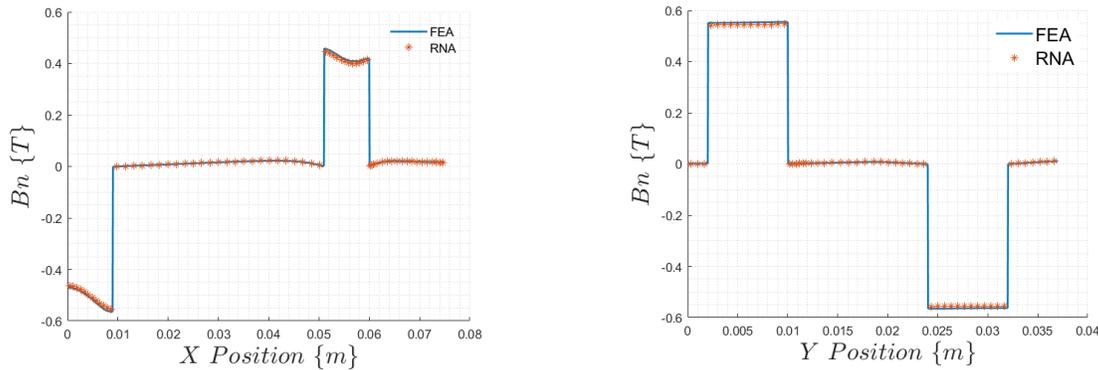


Figure 4: Comparisons of normal direction flux density

The comparison of actuating force before topology optimization is given in Table 2. The system is divided into the same level of elements, around 9750 elements. The actuating force evaluated is 1.24 N and 1.32 N, the difference is 6% which is within the acceptable range. Therefore, we can conclude that the reluctance network model has nearly the same precision with FEA model and it can be used for topology optimization.

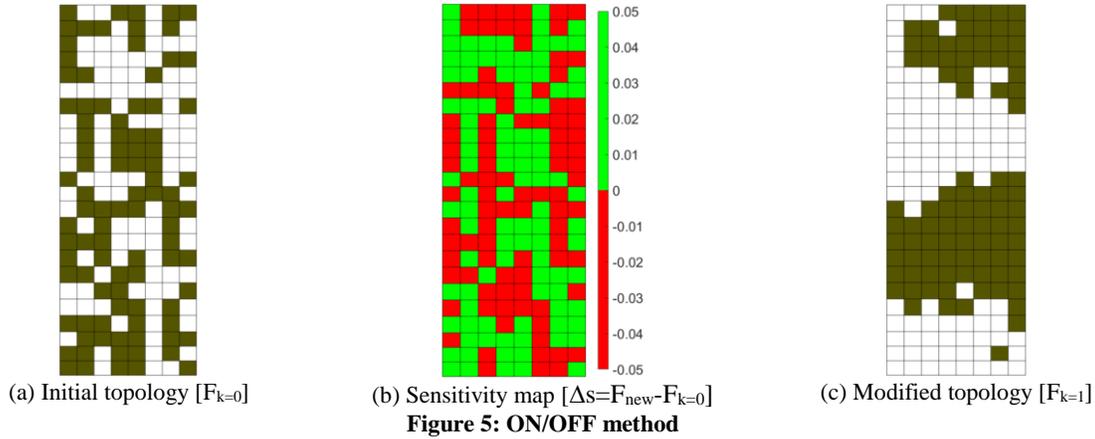
Table 2. Comparison of actuating force in the x direction with the structure of Figure 1a and Table 1.

|            | RNA   | FEA   | Unit   |
|------------|-------|-------|--------|
| Force_x    | -1.24 | -1.32 | ( N )  |
| Elements   | 9696  | 9750  | ( .. ) |
| Nodes      | 29285 | 5019  | ( .. ) |
| Difference | 6 %   |       | ( .. ) |

## 5. ON/OFF method (Sensitivity computation)

As its name says, each element in the design region has two states. The solid state (ON state) represents the element with material and the void state (OFF state) represents the element without material (Figure 5a). In order to determine

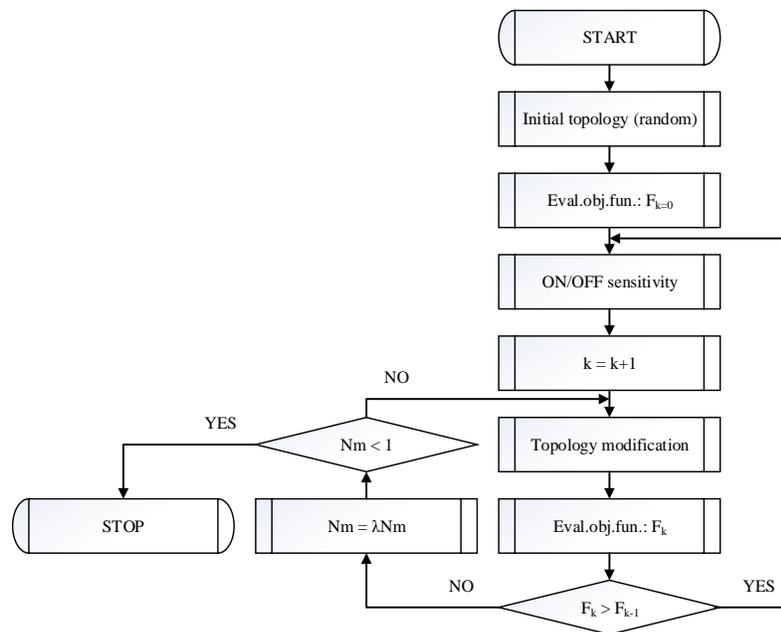
the material distribution in the design region (Figure 3b), the sensitivity of each element in the design region should be evaluated. A sensitivity map corresponding to the design region is created (Figure 5b). Then, according to this map, all the elements that need to change of its state during the next iteration can be determined (figure 5c).



First, the force of the initial configuration of actuator is calculated  $F_{k=0}$  (figure 5a). To calculate the sensitivity of each element, the state of one element in the design region is changed (from 0 to 1 or from 1 to 0). Then, the new force  $F_{new}$  of its new topology is evaluated for each change. For each element, the difference between  $F_{k=0}$  and  $F_{new}$  is regarded as the sensitivity  $\Delta s$  of that element. As a result, a sensitivity map is obtained (figure 5b). Check the sign and value of  $\Delta s$ , where the positive value means that the performance is improved by changing its state. It means that we should keep that change for the next iteration. Then, a new value of force is computed  $F_{k=1}$ .

## 6. Process of topologic optimization

The detailed of topologic optimization is depicted in Figure 6. The  $F$  is the objective function, here it is the magnetic force and  $k$  represents the number of iterations.  $N_m$  is the number of elements that are to be changed of its state after sensitivity computation.



**Figure 6: Flow chart of the topological optimization**

Firstly, an initial topology in the design region is created randomly, and based on this topology, the actuating force is determined  $F_{k=0}$ . This force is chosen as reference to compute the sensitivity of each element. According to the sensitivity map created, the material in the design region is updated. After that modification, the actuating force is evaluated once again. Compare with these two forces, and continue with the loop if the force after topology modification is improved. To help with the convergence of the optimization, we introduced annealing factor  $\lambda (=0.9)$  [8]. Reduce the number of elements to be changed and evaluate the force again until the number  $N_m$  equals to 0.

## 7. Result of topologic optimization

Table 3. The topology optimization scheme

|                              |                       |                                       |           |
|------------------------------|-----------------------|---------------------------------------|-----------|
| <b>Objective function</b>    | Max (Force)           | <b>Cells Number of the system</b>     | 828       |
| <b>Optimization variable</b> | Relative Permeability | <b>Cells of disgn region</b>          | 192       |
| <b>Optimization strategy</b> | ON/OFF Method         | <b>Number of simulations</b>          | 2317      |
| <b>Annealing Factor</b>      | 0.9                   | <b>Computation Time</b>               | 126 (s)   |
| <b>Modeling Method</b>       | Reluctance Network    | <b>Computation Time / Simulations</b> | 0.054 (s) |

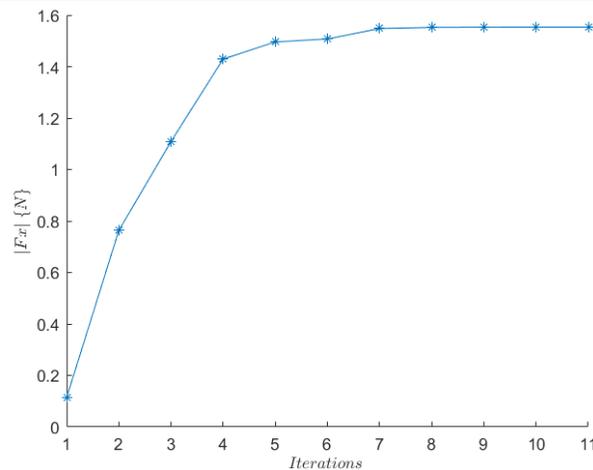


Figure 7: Force versus iteration (new structure)

The proposed methodology is adopted in topology optimization and the final result is shown in Figure 8 (a). after optimization, the value of actuating force reaches to 1.5533 (N) which is improved than initial one. The Figure 8 (b) is the flux density distribution obtained by RNA. Different color represents the different value of B, and the arrow gives its direction and magnitude.

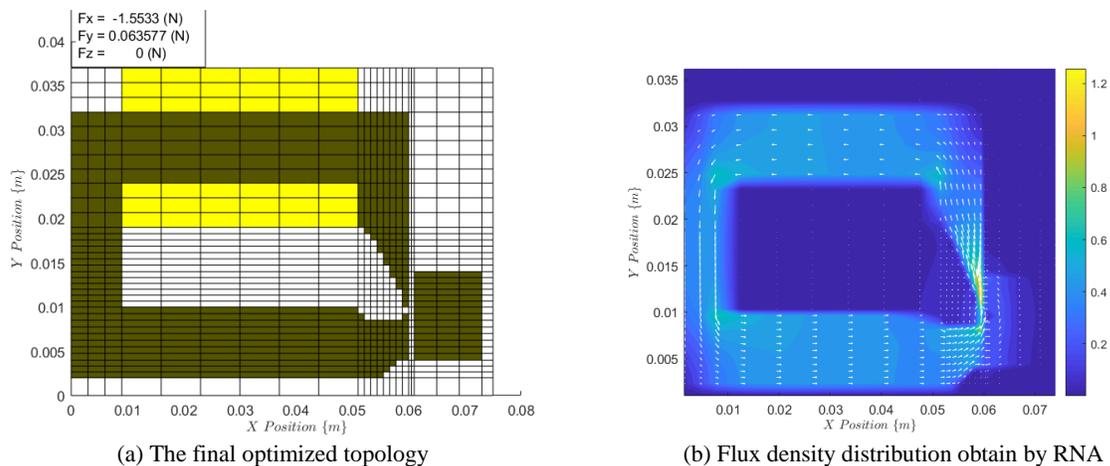


Figure 8 : Result of the topological design process

It is easy to find that most of the flux density is concentrated on the position closed to the armature, this may provide relatively large actuating force. As is depicted in Figure 7, the optimization process goes through 11 iterations (new structure). During the first iteration, the initial topology of the design region is created randomly, that is the reason it just gets a value of force about 0.11 N. Then, two iterations after, the objective force is increased greatly. Under the optimized topology, the actuating force obtained using ON/OFF method is 1.5533 N and its computation time is 126 s. The detailed information is listed in table 3.

## 5. Conclusion

In this paper, the RNA model of magnetic actuator is used for topology optimization. This model has advantage of high accuracy and fast calculating speed compared. The chosen optimization algorithm is ON/OFF method. The result shows that the optimized topology has higher force than before. The deficiency is that this final result depends on the initial random topology, that different initial topology may end with different actuating forces. Then, a Genetic Algorithm will be associated with the process, in order to ensure that the global optimum is found. Also, this optimized topology is not practical for fabrication, because the connecting part in the design region is too thin to break under high force. What's more, when the volume constraint is imposed on the design region, there would be some spots appearing. Therefore, in order to solve the both problems, a smoothing process should be introduced during the optimization process. Finally, We will take the nonlinear property of the magnetic circuit into consideration in the future research.

## References

- [1] John R. Brauer, "Magnetic actuators and sensors", Hoboken, NJ: Wiley, 2006.
- [2] J. Choi, J. Yoo, "Structural topology optimization of magnetic actuators using genetic algorithms and ON/OFF sensitivity", *IEEE Trans. Ind. Appl.*, Vol. 45, pp. 2276-2279, (2009).
- [3] M. Xia, S. Yang, S. Ho, "A New Topology Optimization Methodology Based on Constraint Maximum-Weight Connected Graph Theorem", *IEEE Trans. Ind. Appl.*, Vol. 54, (2018).
- [4] H. Shim, V. Ho, S. Wang, "Level set-based topology optimization for electromagnetic systems", *IEEE Trans. Ind. Appl.*, Vol. 45, pp. 1582-1585, (2009).
- [5] J. Zuliani, M. Cohen, L. Batista et al., "Multi-objective topology optimization with ant colony optimization and genetic algorithms", *IEEE Trans. Ind. Appl.*, Vol. 12, pp. 674-682, (2015).
- [6] J. D. Deaton and R. V. Grandhi, "A survey of structural and multidisciplinary continuum topology optimization: Post 2000", *Struct. Multidisciplinary Optim.*, Vol. 49, pp. 1-38, (2014).
- [7] S. Ho, S. Yang, Y. Bai, "A Fast Methodology for Topology Optimizations of Electromagnetic Devices", *IEEE Trans. Ind. Appl.*, Vol. 53, pp. 6-9, (2017).
- [8] Y. Okamoto, N. Takahashi, "A Novel Topology Optimization of Nonlinear Magnetic Circuit Using ON/OFF Method", *IEEJ Transactions on Fundamentals and Materials*, Vol. 125, pp. 549-553, (2005).
- [9] MEEKER, David. Finite element method magnetics. *FEMM*, 2010, vol. 4, no 32, p. 162