Topology Modification을 이용한 Thomson coil Actuator의 형상 최적화

리웨이[*], 정영우[**],고창섭[*]
충북대학교[*], LS산전[**]

Shape Optimization of a Thomson coil Actuator of Arc Eliminator Using Topology Modification

Wei Li[*], Young-Woo Jeong[**],Chang-Seop Koh[*]
Chungbuk National University[*], LSIS, Co. Ltd[**]

Abstract – The shape optimization of a Thomson coil actuator used in an arc eliminator is done for fast response by adopting topology modification method. The performance of the actuator is analyzed by using an equivalent circuit method. Both shape optimization and performance analysis are accomplished based on the segmentation of plate. The effectiveness of the proposed method is proved by the comparison of results before and after the shape optimization.

1. Introduction

An open arc due to a severe fault in switchgear can result in a series of damage if the arcing time is long, such as high temperature, high pressure, and poisonous gases. Therefore, to feed the requirement of high service reliability and safety for personnel, a device named arc eliminator is developed for extinguishing the arc by bypassing the power current from the distribution line to a ground with a very high speed action in terms of just a few milliseconds. For this reason, Thomson coil actuator, which is remarkable for its high speed, is being more and more employed as the driving unit of the arc eliminator [1]. The Thomson coil actuator is mainly composed of, as shown in Fig. 1, an exciting coil and a moving plate having ground connection. In order to get a quick ground connection when the switch S is on, the parameters, such as capacitance and its initial charging voltage, exciting coil configuration, might be optimally decided. When selection of the parameters is limited for economic reason(the peak current is very often limited for a cheap switching device), however, the shape optimization of the conducting plate is a good alternative for quick response.

In this paper, the conducting plate of a Thomson coil actuator for an arc eliminator is shape optimized using ON/OFF method based on the contribution of each segment to objective function [2].

2. Shape Optimization

2.1 Performance Analysis

The system is analyzed by using a numerically efficient calculation method that we have developed based on equivalent circuit method. To figure out the eddy current distribution, the plate is divided into a series of segments in radial and axial directions according to the field continuity condition, Each individual segment physically corresponds to one conducting ring with the circuit parameters of resistance and inductance as shown in Fig. 2(a), and the eddy current, in each segment, is assumed to be uniform. In this way the whole system is transformed into equivalent circuits as shown in Fig. 2(b). The circuit equations, magnetic flux equations and motional equation are obtained, if the plate is divided into N segments, as follows:

$$q/c+I_sR_s+d\lambda_s/dt=0 \tag{1}$$

$$I_iR_i+d\lambda_i/dt=0 \quad i=1,2,\ldots,N \tag{2}$$

$$\frac{d\lambda_s}{dt}=L_{ss}\frac{dI_s}{dt}+\sum_{j=1}^{N}L_{sj}\frac{dI_j}{dt}+\sum_{j=1}^{N}I_j\frac{\partial L_{sj}}{\partial z}\frac{dz}{dt} \tag{3-a}$$

$$\frac{d\lambda_i}{dt}=L_{is}\frac{dI_s}{dt}+I_s\frac{\partial L_{is}}{\partial z}\frac{dz}{dt}+\sum_{j=1}^{N}L_{ij}\frac{dI_j}{dt},\ i=1,2,\ldots,N \tag{3-b}$$

$$(M+M_a)\frac{d^2z}{dt^2}=F_e-F_g-F_f \tag{4}$$

where the subscripts s and i stand for the exciting coil and i-th segment of the plate, respectively, λ is the linkage flux, F_e, F_g, and F_f are the electromagnetic, gravitational and friction forces, M and M_a are masses of the plate and mechanical appendage, respectively, and other symbols have their usual meaning. The electromagnetic force, F_e, acting on the conducting plate is computed as follows:

$$F_e=\sum_{i=1}^{N}f_i=-\sum_{i=1}^{N}I_sI_i\frac{\partial L_{si}}{\partial z}\ [N] \tag{5}$$

2.2 Shape Optimization using ON/OFF Method

The optimization target, in this paper, is the displacement of the conducting plate after 3.5 milliseconds from switching on. When the conducting plate is divided into N small segments, each segment will contribute to acceleration of the plate by developing electromagnetic force on its eddy current and, at the same time, to deceleration by its own gravitational force.

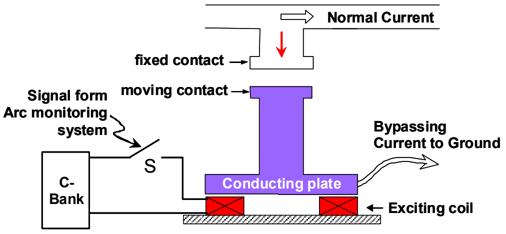
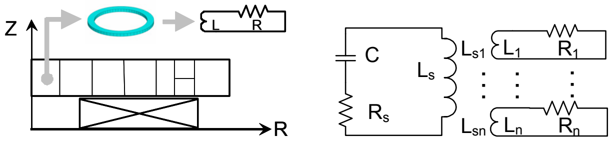


Fig. 1. Simplified mechanism of the Thomson coil type actuator.



(a) segmentation of plate (b) equivalent circuit

Fig. 2. Equivalent circuit model of the system.

The acceleration of the plate is calculated from (4), and can be rewritten as follows:

$$a=[F_e-(M+M_a)g-F_f]/(M+M_a) \tag{6}$$

where g is the acceleration of gravity. When the i-th segment is removed from the plate, the acceleration of the plate will be expressed as follows:

$$(a)_i=\{(F_e)_i-((M)_i+M_a)g-F_f\}/((M)_i+M_a) \tag{7}$$

where $(\cdot)_i$ is the quantity obtained without i-th segment. It is assumed, here, that elimination of the i-th segment does not change the friction force and eddy currents in other segments. The contribution factor of i-th segment to the acceleration of plate is finally estimated as follows:

$$c_i=\int_{t_i}^{t_f}(a-(a)_i)dt=m_i/(M+M_a-m_i)\int_{t_i}^{t_f}(a_i-a)dt \tag{8}$$

$$a_i=(f_i-m_ig)/m_i \tag{9}$$

where m_i is the mass of the i-th segment. The final displacement of the plate, finally, can be increased by removing the segments which have small contribution factor from the plate after computing the contribution factors for all segments.

The overall procedure of the shape optimization of the proposed algorithm is shown in Fig. 3 and summarized as follows:

Step 1. Decision of the initial segmentation

The number of segments should be enough to guarantee an accurate performance analysis.

Step 2. Performance analysis and calculation of contribution factors

The final displacement of the conducting plate, contribution factors of all segments are computed through performance analysis by using the equivalent circuit method.

Step 3. Modification of topology

According to the contribution factors the segments having small contribution factor are removed from the plate. At this stage some segments can not be removed due to a structural constraint.

Step 4. Accept or not the modified topology

With the modified topology, the performance will be analyzed again. If the modified topology gives a better performance (i.e. more displacement), the new topology is accepted as a new topology and go to *Step* 3 for next iteration.

Step 5. Refinement of the segments

If the modified topology gives worse performance than the previous topology in *Step* 4, it means the optimum shape exists between the previous and new topologies. If the sizes of all the segments to be removed are small enough, the previous topology is considered as an optimal shape. If some of the segments to be removed are not small enough, they will be divided into smaller segments, and go to *Step* 2 for more precise topology modification.

2.3 Results and Discussion

Fig. 4 shows the initial structure of the plate with the moving contact and structural constraints for enough mechanical strength. In the performance analysis the moving contact is ignored, and its mass is taken into account as the additional mass. The optimized shape of plate with eddy current density distribution is compared with the initial one as shown in Fig. 5. Fig. 6 shows the variation of the displacement and mass of the plate with respect to iterations. After 10 iterations, an optimum shape which gives 47.5mm displacement with 0.325kg mass is obtained.

3. Conclusion

In this paper, the shape optimization of a Thomson coil actuator is implemented by using a topology modification method based on the equivalent circuit analysis method. For a set of fixed circuit parameters, there exists a proper shape of plate which will give the best performance. The optimization results show the effectiveness of finding the proper shape using the developed method.

[Reference]

[1] T. Takeuchi, et al., "Electromagnetic analysis coupled with motion for high speed circuit breakers of eddy current repulsion using the tableau approach," *Electrical Engineering in Japan*, 152(4), pp. 8-16, 2005.

[2] N. Takahashi, S. Nakazaki, and D. Miyagi, "Examination of Optimal Design Method of Electromagnetic Shield Using ON/OFF Method", *IEEE Trans. on Magnetics*, 45(3): 1546-1549, 2009.

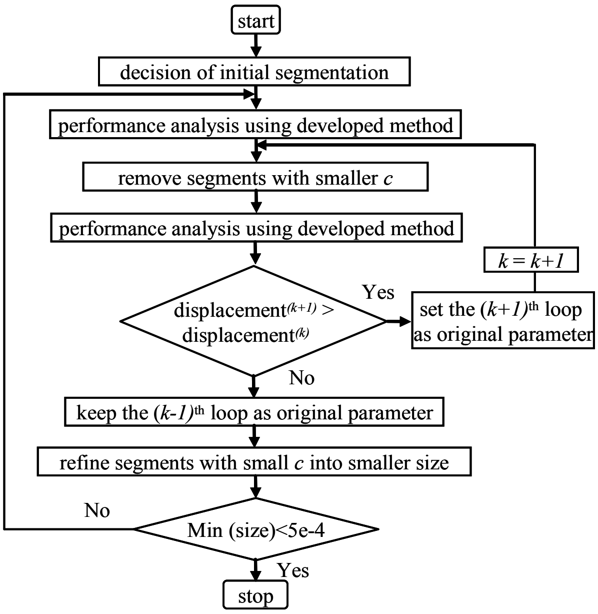


Fig. 3. The flow chart of the proposed optimization method.

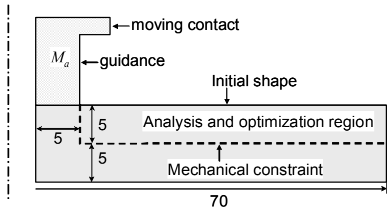
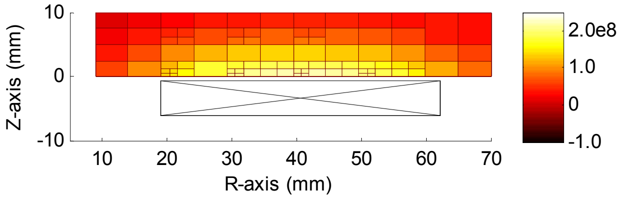
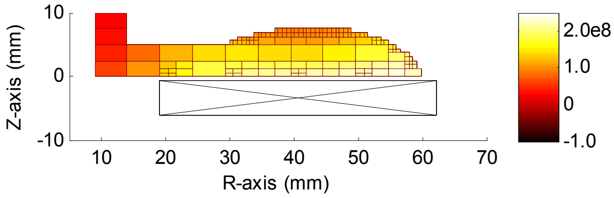


Fig. 4. Initial structure of plate and moving contact.



(a) initial shape.



(b) final shape.

Fig. 5. Plate shape and eddy current density distribution.

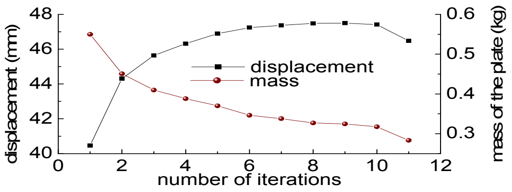


Fig. 6. Final displacement and mass at each iteration.