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Shape Optimization of a Thomson Coil Actuator for Fast Response Using Topology Modification

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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 displacement of the plate in a fixed calculation time is taken as the objective function. The objective function and contribution factor are calculated by using an adaptive equivalent circuit method which has been proved accurate and efficient. Both shape optimization and performance analysis are accomplished based on the segmentation of plate. Through the refinement of the sensitive segments a precise optimal plate shape can be obtained. The effectiveness of the proposed method is proved by the comparison of results before and after the shape optimization.

Keywords: Adaptive equivalent circuit method, Shape optimization, Thomson coil actuator, ON/OFF method

1. Introduction

An arc eliminator is a fault throwing device used in switchgear, to protect the system and personnel from damage caused by an arc, by bypassing the power current to a ground with high speed in terms of just a few milliseconds. Owing to the fast function, the arc eliminator can provide arc extinction and mitigate effects by the prolonged arc with poisonous and contaminating gas flow. For this reason, Thomson coil actuator is being more and more employed as the driving unit of the arc eliminator for its remarkable high speed compared with a conventional electromagnetic actuator utilizing electromagnetic attractive force [1].

The Thomson coil actuator is mainly composed of, as shown in Fig. 1, an exciting coil supplied by capacitor bank and a nonmagnetic conducting plate having ground connection. Normally, the normal current will flow along the transmission path, as labeled in Fig. 1, and the plate stays at the opening position. At this moment, the fixed contact and the moving contact are separated. If an open arc due to a severe fault in the switchgear is detected by the arc monitoring system, then a trip signal will be sent to close switch S, due to which a pulse current will be generated in the exciting coil. The electromagnetic repulsive force generated between the exciting coil and plate will drive the plate together with the moving contact away to the close position, at which the conducing path of fault current is constructed by the connection of fixed contact and moving contact. Therefore, the fault current will be bypassed to the ground through the conducting path. As the arcing time is very short, it will not cause any high pressure or any thermal damage at all.

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.

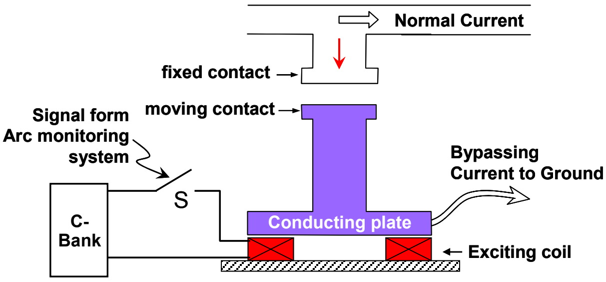

Fig. 1. The simplified mechanism of the Thomson coil type actuator.

Because, in the Thomson coil actuator, the distance between the moving and fixed contacts is fixed, a quick response means a short traveling time. However, in the calculation, time criterion is much more convenient than displacement criterion. Therefore, in this paper, the final displacement of the conducting plate within a fixed time is taken as the objective function and maximized. The conducting plate of a Thomson coil actuator is shape optimized using ON/OFF method based on the contribution of each segment to the objective function. The objective function of the obtained shape is calculated by using an

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adaptive equivalent circuit method which has been proved accurate and efficient.

2. Performance Analysis

2.1 Equivalent circuit method

The electromagnetic force of the Thomson coil actuator is generated by the interaction between the magnetic field by the exciting current and eddy current induced in the conducting plate. The precise approximation of the eddy currents in the plate, therefore, is essential for accurate performance analysis. In this paper, the conducting plate is divided into a series of segments, as shown in Fig. 2(a), and the eddy current, in each segment, is assumed to be uniform. As the structure is axial symmetric, each segment, then, physically corresponds to a conductive ring with its circuit parameters of resistance and inductance as shown in Fig. 2(a). In this way the whole system is transformed into the equivalent circuits as shown in Fig. 2(b). The equations of the exciting circuit and segments circuits are obtained, if the plate is divided into N segments, as follows [2]:

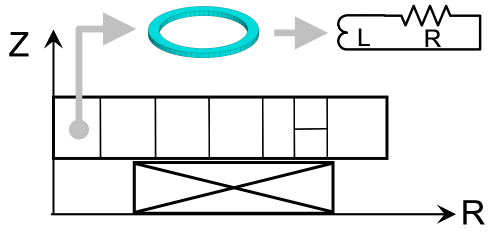
$$Q/C + I_s R_s + d\lambda_s/dt = 0 \tag{1}$$

$$I_i R_i + d\lambda_i/dt = 0 \quad i = 1, 2, \cdots, N \tag{2}$$

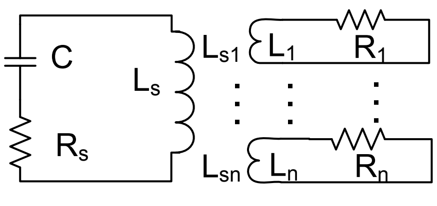
$$\frac{d\lambda_s}{dt} = L_{ss}\frac{dI_s}{dt} + \sum_{j=1}^{N} L_{sj}\frac{dI_j}{dt} + \sum_{j=1}^{N} I_j \frac{\partial L_{sj}}{\partial z}\frac{dz}{dt} \tag{3a}$$

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

where Q and C stand for the charge and capacitance. R_s, I_s and λ_s are resistance, exciting current and flux linkage of the exciting circuit. R_i, I_i and λ_i are resistance, eddy current and flux linkage of the i-th segment circuit. L_{ss} is the self inductance of the exciting coil. L_{si} or L_{sj} is the mutual inductance between the exciting circuit and i-th circuit or the j-th circuit. L_{ij} is the mutual inductance between the i-th and j-th circuits. As there is no magnetic material in the system, the inductance only depends on the geometry dimension. As the self inductance will not change with the relative position between the exciting coils and the moving plate, the derivative of the self inductance to the position is zero. Furthermore, all the segments move together as a whole plate, the derivative of mutual inductance between two segments is also zero. In this paper, the inductance is calculated by using a method based on Bartky's transformation [4].



(a) segmentation of plate



(b) equivalent circuit

Fig. 2. Equivalent circuit model of the system.

The energy W and electromagnetic force F_e can be calculated as follow:

$$W = \frac{1}{2}\sum_{i=s,1}^{N}\sum_{j=s,1}^{N} L_{ij} I_i I_j \tag{4}$$

$$F_e = -\frac{\partial W}{\partial z} = \sum_{i=1}^{N} f_i = -\sum_{i=1}^{N} I_s I_i \frac{\partial L_{si}}{\partial z} \tag{5}$$

It can be seen that if all the current values are solved and the derivative of mutual inductance are calculated, the force can be obtained easily.

The motional equations of the moving plate can be expressed as follow:

$$(M + M_a)\frac{d^2 z}{dt^2} = \left(F_e - F_g - F_f\right) \tag{6}$$

$$\dot{z} = v \tag{7}$$

where 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. z and v represent the displacement and speed respectively.

The dynamic state equations of the system can be obtained by combining (1)-(3) and (6)-(7) as follows:

$$L_{ss}\dot{I}_s + \sum_{j=1}^{N} L_{sj}\dot{I}_j = -\frac{Q}{C} - I_s R_s - v\sum_{j=1}^{N} I_j \frac{\partial L_{sj}}{\partial z} \tag{8a}$$

$$L_{si}\dot{I}_s + \sum_{j=1}^{N} L_{ij}\dot{I}_j = -I_i R_i - v I_s \frac{\partial L_{si}}{\partial z}, \quad i = 1, 2, \cdots, N \tag{8b}$$

$$\dot{z} = v \tag{8c}$$

$$\dot{v} = \left(F_e - F_g - F_f\right)/(M + M_a) \tag{8d}$$

$$\dot{Q} = I_s \tag{8e}$$

where, F_e can be calculated from (5). The dynamic characteristics such as exciting current, force, speed and displacement, can be obtained by solving these ordinary differential equations with initial conditions using the Runge-Kutta-Fehlberg method.

2.2 Verification of calculation accuracy and efficiency

An adaptive refinement algorithm that based on field continuity condition is applied to the division of plate, which ensures the calculation accuracy [3]. The accuracy and efficiency of the adaptive equivalent circuit method is tested by solving a prototype of Thomson coil actuator. This problem is also solved by using Maxwell axis-symmetric 2D software with a mesh of about 40,000 second order triangular elements with adaptive time step control. The calculated displacements are shown in Fig. 3. It can be seen that the calculated displacement of the proposed method matches very well with the FEM calculation result. However, both the numerical results show some errors compared to the measured one. This is mainly because the friction that exists in the experiment cannot fully be considered in the calculation. By FEM calculation, the computing time is about 10 hours. While with the proposed method, the computation time is less than 8 minutes even with 95 segments. In this paper, the adaptive equivalent circuit method is adopted not only for its fast calculation of objective function, but also for the evaluation of contribution factors of all the segments.

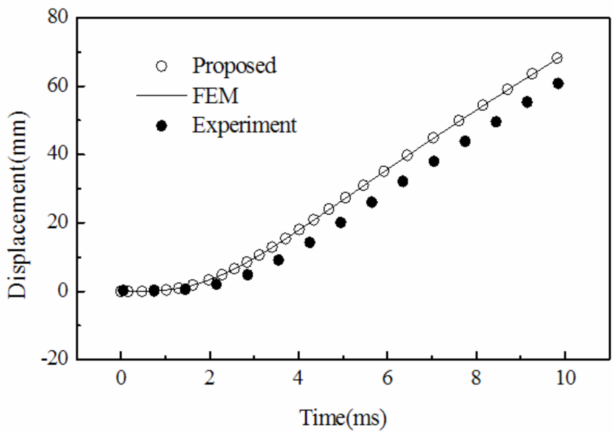


Fig. 3. Verification of calculation results.

3. Shape Optimization using ON/OFF Method

3.1 ON/OFF method

The optimization target, in this paper, is the displacement of the conducting plate after 3.5 milliseconds from switching on. Fig. 4 shows the initial shape and optimization region of the plate. The dashed line represents the mechanical constraint. The material of the plate is aluminum. To apply the ON/OFF method, the optimization region is subdivided into many segments, as shown in Fig. 5. The material in each segment is allowed to have only one state, that of air or aluminum. If the material is aluminum, then this state is called as "ON", and if the material is air, then this state is called as "OFF". At each calculation loop, the material distribution is updated so that the designed result can be obtained [5].

3.2 Calculation of contribution factors

To determine the material distribution of all segments by judging "ON" or "OFF" state of each segment, the contribution factor of each segment to the objective function is calculated by using the adaptive equivalent circuit method. As the moving contact and guidance contribute a little to the objective function, we ignore these two parts by just considering the additional mass M_a when doing the performance analysis. 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.

The acceleration of the whole plate is calculated from (6), and can be rewritten as follows:

$$a = \left[F_e - (M + M_a)g - F_f\right] \big/ \left(M + M_a\right) \qquad (9)$$

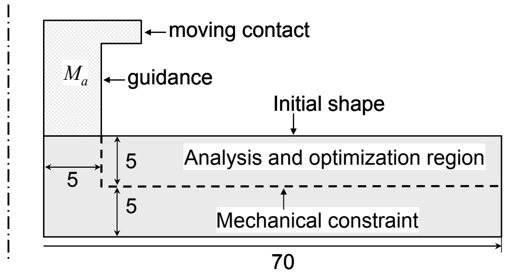


Fig. 4. Initial structure of plate and moving contact.

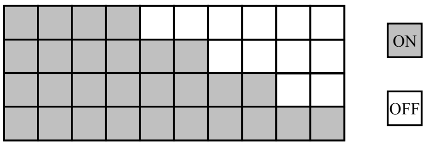


Fig. 5. ON/OFF method.

where g is the acceleration of gravity. When the i-th segment is removed from the plate which means the material state of the i-the segment is "OFF", the acceleration of the plate will be expressed as follows:

$$(a)_i = \left[(F_e)_i - \left((M)_i + M_a\right)g - F_f\right] \big/ \left((M)_i + M_a\right) \qquad (10)$$

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:

$$c_i = \int_{t_i}^{t_f}\left(a-(a)_i\right)dt = \frac{m_i}{(M)_i + M_a}\int_{t_i}^{t_f}\left(a_i - a\right)dt \qquad (11)$$

$$a_i = \left(f_i - m_i g\right)/m_i \qquad (12)$$

where m_i is the mass of the i-th segment, a_i is the imaginary acceleration of the i-th segment calculated as (12), f_i is the electromagnetic force generated by the i-th segment which can be calculated from (5). Therefore, in each time step, a_i and a can be calculated. The total effect of the contribution factor c_i in the whole calculation time can be evaluated by doing integration in time domain as shown in (11). Therefore, the contribution factors for all segments can be obtained. The displacement of the plate, finally, can be increased by removing the segments which have small contribution factor from the plate. Due to the skin effect, the segment that is near to the bottom surface of the plate gives bigger contribution factor, therefore, the removing of segments will begin from the upper side of the plate.

3.3 Optimization procedure

During the optimization process, on the one hand we hope that only the segments with bigger contribution factors remain, however, on the other hand, as the moving component also includes the moving contact and guidance which contribute a little to the electromagnetic force while have a relative big mass, there should be enough number of useful segments that can afford this part of mass. Therefore, there must exist a best shape of the plate corresponding to which the system can give the best performance.

The flowchart of the shape optimization algorithm using ON/OFF method is shown in Fig. 6. The overall procedure is summarized as follows:

Step 1: Decision of the initial segmentation
The adaptive refinement is done to guarantee the calculation accuracy of the objective function, and the size of segments is given bigger initially for fast calculation.

Step 2: Calculate objective function and contribution factor
The objective function $S^{(k)}$, contribution factors of all segments are computed by using the adaptive equivalent circuit method.

Step 3: Modification of topology
Segments with small contribution factor are removed. At this stage some segments cannot be removed due to a mechanical constraint.

Step 4 and 5: Accept the modified topology or otherwise
The objective function $S^{(k+1)}$ is calculated. If the modified topology gives a better performance (i.e. bigger displacement), the new topology is accepted, set the ($k+1$)-th loop as the original parameters and go to *Step* 3 for next iteration.

Step 6, 7 and 8: Refinement of the segments
If the modified topology gives worse performance in *Step* 5, set (k-1)-th loop as the original parameters. The optimum shape exists between the (k-1)-th loop and ($k+1$)-th loop. The removed segments between the (k-1)-th loop and ($k+1$)-th loop are treated as sensitive segments. If the sizes of sensitive segments are small enough, the k-th loop is considered as the optimal shape, else refine them and go to *Step* 2 for more precise topology modification.

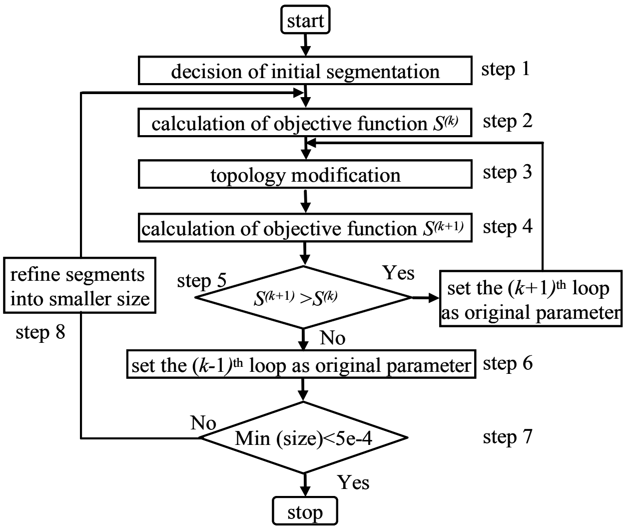


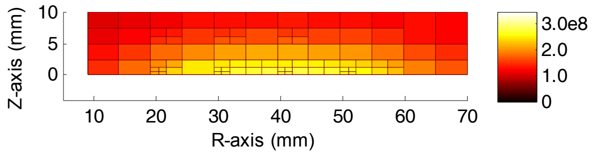
Fig. 6. Initial structure of plate and moving contact.

4. Optimization Results and Discussion

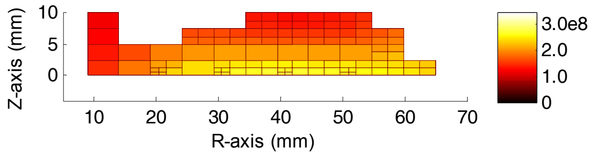
The conducting plate of the Thomson coil actuator is shape optimized by using the proposed algorithm. The circuit parameters of the exciting coil are given in Table 1. Fig. 7 shows the plate shape and eddy current density distribution corresponding to different iteration loop. The segmentation of the initial plate is done by using the adaptive refinement algorithm for a precise analysis result. It can be seen that during the optimization process the sensitive segments are refined three times for a precise optimization result. Finally, the optimized shape of the plate is obtained as shown in Fig. 7(e). Fig. 8 shows the variation of the final displacement and the plate mass with respect to iterations. After ten iterations, an optimum shape which gives 47.5mm displacement with 0.325 kg mass is obtained. At the 11-th iteration, the displacement decreases, and the size of sensitive segments is smaller than the given size, therefore, the shape optimization procedure is finished.

Table 1. Circuit parameters

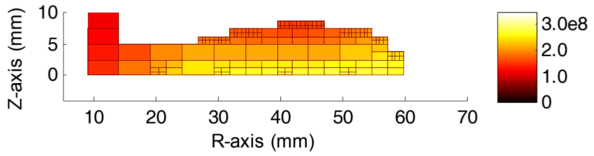
voltage (V)	capacitor (μF)	layers	turns/ layer	diameter (mm)
250	25000	19	2	2.6



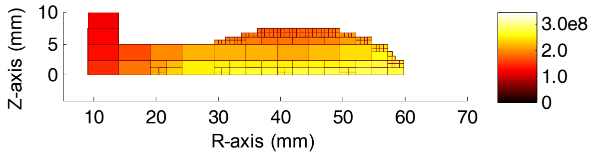
(a) initial shape



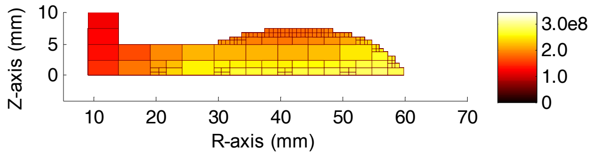
(b) the first refinement



(c) the second refinement



(d) the third refinement



(e) optimized shape

Fig. 7. Plate shape and eddy current density distribution (The unit of the eddy current density is Ampere per square meter).

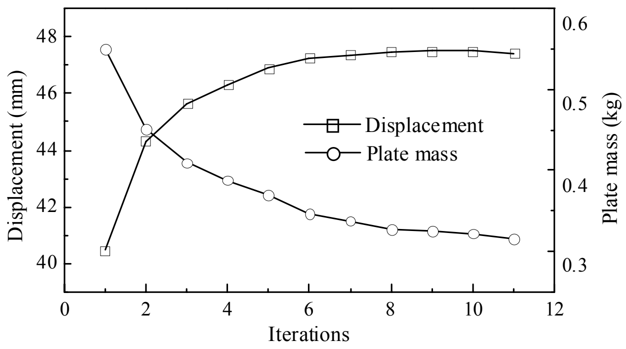


Fig. 8. Final displacement and mass at each iteration.

5. Conclusion

To shorten the action time of the Thomson coil actuator, the conducting plate is shape optimized by using ON/OFF method. The objective function is calculated by using adaptive equivalent circuit method which is proved accurate and efficient. Both shape optimization and performance analysis are accomplished based on the segmentation of plate. The contribution factors of all the segments are evaluated based on the calculation of real acceleration of the plate and imaginary acceleration of each segment. Due to the continuous distribution of eddy current and the influence of the additional mass, the optimal plate shape exists which gives the best performance. Through refinement of the sensitive segments, a precise optimal plate shape can be obtained. By using the proposed shape optimization algorithm, the final displacement of the plate is improved about 7 mm compared to the initial model.

Acknowledgements

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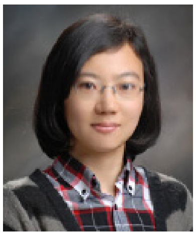

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