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Characteristic Simulation of PM-Type Magnetic Circuit Breaker

Han-Seok Park† · Hong-Sub Jung* · Kyung-il Woo*

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Abstract : This paper presents the characteristic simulation of PM-type magnetic circuit breaker with the 2D finite element magnetic field solution including non-linearity of the material and an eddy current. Change of dynamic characteristic of the actuator is quantified from the finite element analysis. The results obtained from a commercial finite element analysis software are compared with those calculated from the developed finite element analysis software. A new modified model to decrease the eddy current is proposed. The characteristics of the two models are compared.

Key words : Eddy current, finite element analysis, non linearity, PM-type magnetic circuit breaker

1. Introduction

The purpose of using circuit breakers is to protect the electric power systems from the various fault currents. The conventional circuit breakers are composed of springs, gears, and so forth. However, they have a defect that requires periodic repairs and part replacement after a great number of operation times. The new PM-type magnetic circuit breakers can overcome this shortcoming, and can improve the reliability of overall performance, and their advantages have recently drawn great attention [1]. The various and sophisticated analysis method considering the effect of magnetic saturation and eddy current is needed in the design stage of linear actuators [2]-[3]. In particular, the analysis should compute the eddy current density induced in the non-laminated core of the mover, because the eddy current can cause a time delay in the flux build-up and the force production, and this will eventually bring about a bad effect on the quick response of the mover by milliseconds.

This paper describes the characteristic simulation of the PM-type magnetic circuit breaker considering the eddy current induced in the non-laminated mover, and further attempts to propose a

† Corresponding Author(Div. of Electrical & Control Instrument Engineering Pukyong National University, Busan Korea), E-mail : phanseok@pknu.ac.kr, Tel : 051)620-1436

* Div. of Electrical & Control Instrument Engineering Pukyong National University, Busan Korea

design modification. The electromagnetic field, the external electric circuit, and the motional equation of the plunger are coupled for the dynamic solutions. The results such as force, current and speed obtained from a commercial finite element analysis software are compared with those calculated from the developed finite element analysis software. The static forces by the permanent magnet of the manufactured actuator and developed software are compared. A method to improve the electric and mechanical characteristics of the plunger is investigated. Finally a new laminated mover model is suggested to reduce the eddy current effect. The characteristics comparison between the non-laminated model and the laminated model is reported.

2. Characteristic Simulation

2.1 Analysis Model

Linear actuators can be classified into moving coil type, moving magnet type, and moving core type. The analysis model of this paper is the moving core type with permanent magnet, as shown in Fig. 1. The stator is usually laminated. However, the plunger is made of a solid core in order to enhance the mechanical strength. The motion of the plunger is controlled by the alternate excitation of the coils. When there is no excitation of the coils, the position of the plunger is strictly held by the detent force by the permanent magnet. If the current flows through the coil A, the plunger is attracted upward by the excited magnetic flux. Table 1 shows the specification of the PM-type magnetic circuit breaker.

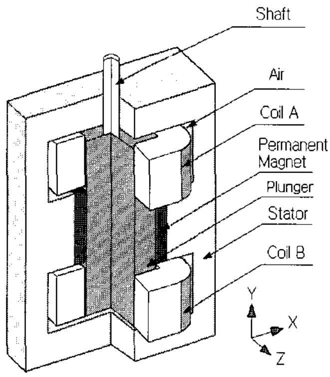


Fig. 1 The designed model of the PM-type magnetic circuit breaker

Table 1 Specification of Designed Model

Input voltage	125[V]
Residual Flux density of PM	1.25[T]
Width of plunger	139[mm]
Height of plunger	50[mm]
Moving distance of plunger	20[mm]
Turn of winding	240

2.2 Finite Element Analysis

The governing equation of the analysis region of the circuit breaker is expressed as

$$\frac{1}{\mu}\frac{\partial^2 A}{\partial x^2}+\frac{1}{\mu}\frac{\partial^2 A}{\partial y^2}=-J_0+\sigma\frac{\partial A}{\partial t}-\frac{1}{\mu}\left(\frac{\partial M_y}{\partial x}-\frac{\partial M_x}{\partial y}\right) \quad (1)$$

where, A is magnetic vector potential at every nodes in the z-direction and M_x, M_y are the remanent magnetization in the x- and y- direction, respectively and σ is the corrected conductivity of the mover considering the transverse edge effect.

Using the Galerkin's method with weighting function N_j, we can obtain (2) for all elements.

$$[[S]-[C]]\begin{bmatrix}[A]\\ [I]\end{bmatrix}+\frac{\partial}{\partial t}[[T]-[0]]\begin{bmatrix}[A]\\ [I]\end{bmatrix}=[G] \quad (2)$$

where unknown variables are vector potential at nodes and current. In (2), $[S]$ is a coefficient matrix related to node positions and permeability, $[C]$ and $[T]$ are coefficient matrices for coil current density and eddy current density respectively, and $[G]$ is a driving matrix corresponding to equivalent magnetization current density. Equation (2) is combines with circuit equation so that

$$\frac{d}{dt}[\Psi]+[L_o]\frac{d}{dt}[I]+[R][I]=[V] \quad (3)$$

where

$[V]$: voltage vector,

$[I]$: current vector,

$[R]$: resistance vector,

$[L_o]$: end winding leakage inductance vector

$[\Psi]$: magnetic flux linkage vector.

The motion of the mover is determined by

$$F=M\frac{dv}{dt}+F_L \quad (4)$$

where, F and F_L are the force calculated from the finite element analysis and load thrust. M(6.6kg)and ν are the mass and the linear speed of the plunger, respectively.

2.3 Translating Motion Technique

Fig. 2 shows the meshes of the 2D analysis model. We set the analysis model into horizontal position, and analyze only the half model utilizing the symmetry of the analyzing domain. In Fig. 2, the plunger is assumed to move to the right direction. The meshes in the deforming regions (part A and part B) are distorted to model the movement of the plunger. In order to keep the initial shapes of the elements, the translating motion technique is used[5]. Fig. 3 illustrates the local remeshing of the

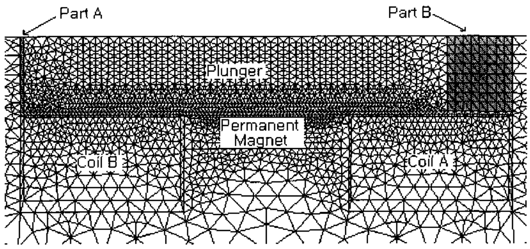
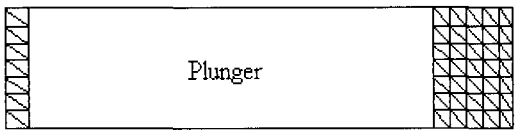


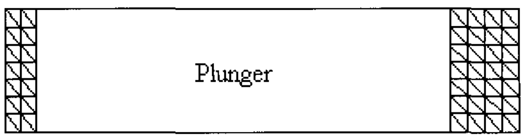
Fig. 2 Mesh shape

Moving direction →

(a) Initial condition



(b) The displacement is smaller than the half size of the element



(c) The displacement is greater than the half size of the element

Fig. 3 Remeshing of the deforming regions during the solving process

element in the deforming regions. For each displacement of the plunger, the translating motion feature is automatically remeshed during the each time stepping process. Nodes of the moving part and deforming regions are moved first.

If the displacement is smaller than the half size of the elements in the part B, the nodes of the moving part and the deforming regions are changed by the amount of displacement as shown in Fig. 3(b). If the displacement is greater than the half size of the elements in part B, the nodes of the deforming regions are made as shown in Fig. 3(c).

2.4 Calculation of Force

To calculate the force acting on the plunger the Maxwell stress tensor can be used as (5).

$$t_n=\frac{1}{2\mu_0}(B_n^2-B_s^2),\quad t_s=\frac{B_nB_s}{\mu_0} \tag{5}$$

where B_n, B_s are the normal and tangential components of the air gap flux density, respectively.

To calculate the force the integrating loop is chosen like Fig. 4. The force equations of each loop are given by (6)

$$\begin{aligned} F_{loop1} &= \int_{loop1} \frac{1}{2\mu_0}\left(B_n^{(e)^2} - B_s^{(e)^2}\right) hdl \\ F_{loop2} &= \int_{loop2} \frac{B_n^{(e)} B_s^{(e)}}{\mu_0} hdl \\ F_{loop3} &= \int_{loop3} \frac{1}{2\mu_0}\left(B_n^{(e)^2} - B_s^{(e)^2}\right) hdl \end{aligned} \tag{6}$$

where h is the stack length of the analysis model and $B_n^{(e)}$, $B_s^{(e)}$ are the normal and tangential components of the flux density of the element placed along the integrating loop, respectively. The total force acting on the mover is obtained from (7).

$$F_{total}=2(F_{loop\,1}+F_{loop\,2}-F_{loop\,3}) \tag{7}$$

In (7), multiplication of 2 is to compensate the half model analysis.

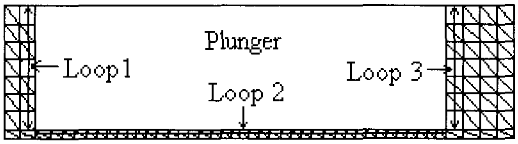


Fig. 4 Integrating loop to calculate the force

3. Simulation Result and Discussion

To find out the validity of the programmed software we compared the analysis results with those obtained from the commercial software. We set the conductivity of the plunger as 10^6[mho/m]. Fig. 5 shows the force characteristics. The force acting on the plunger is negative initial value due to the permanent magnet. Fig. 6 shows the current characteristic. The peak current flowing in the coil is about 90[A]. The current increases after reaching the top area because there is not back e.m.f. The nonlinear iteration is used to consider the magnetic saturation. The difference of the current values may be due to the nonlinear iteration error. Fig. 7 shows the speed characteristic by the force characteristic. The maximum speed of the plunger is about 4.3[m/s]. Fig. 8 shows the manufactured model of the magnetic circuit breaker and experimental set. The static force by the permanent magnet is measured. Table 2 shows the static force obtained from the experiment and simulation.

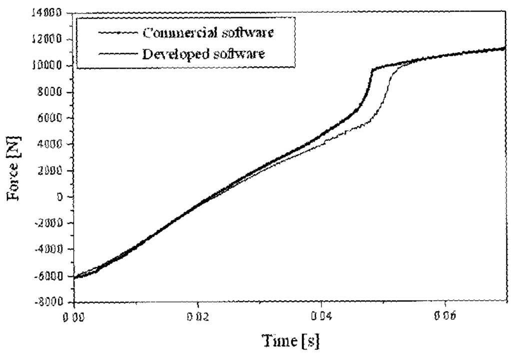


Fig. 5 Force characteristic

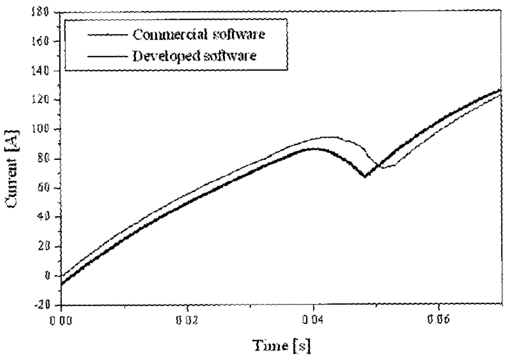


Fig. 6 Current characteristic

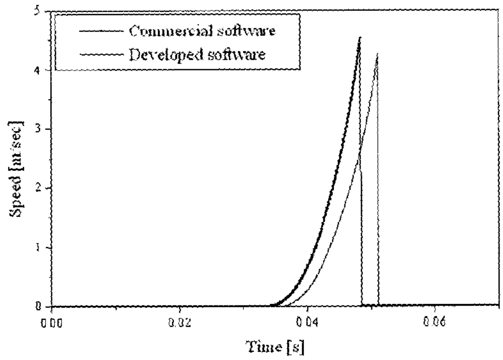


Fig. 7 Speed characteristic

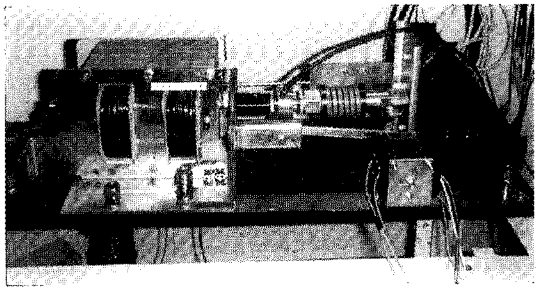


Fig. 8 Manufactured model and experimental set

Table 2 Static Force Characteristic

Method	Static Force
Simulation	6200[N]
Experiment	6900[N]

4. Proposed Model

The core of the plunger is generally made of solid steel, because the transformation of the plunger is usually accompanied with large mechanical impacts. The eddy current induced by the time varying flux in the plunger causes a time delay in the force production[6]. A new modified model with a lamination part in the plunger is proposed to reduce the eddy current effect as shown in Fig. 9. Fig. 10(a) and Fig. 10(b) show the comparison of force and current characteristics between non-laminated and laminated model obtained by the developed software. The force characteristic of laminated model is better than that of non-laminated model because of the reduction of eddy current density. The decrease of the exciting current through the coil in the laminated model is another advantage.

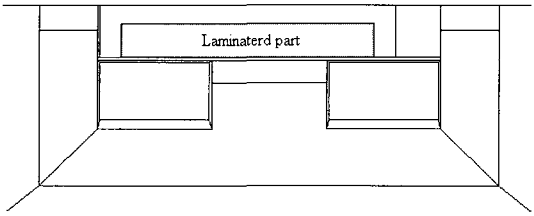
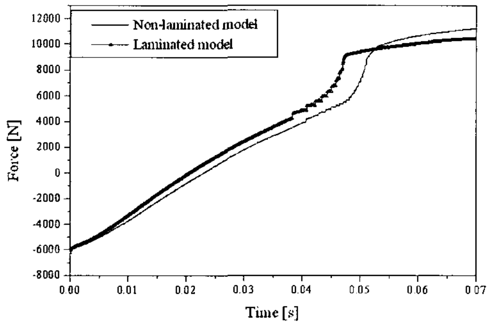
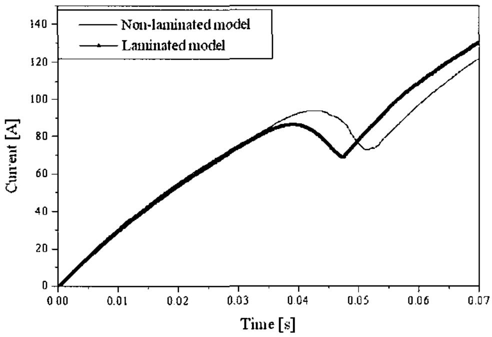


Fig. 9 New proposed model



(a) Force characteristic.



(b) Current characteristic

Fig. 10 Characteristic comparison non-laminated and laminated models.

5. Conclusion

This paper presents the characteristics simulation of the PM-type linear oscillatory actuator used as a magnetic circuit breaker considering the eddy current induced in the plunger. The solutions obtained from the developed software agree well with those from the commercial software and experimental results. To minimize the eddy current effect in the plunger, a new mover model with a lamination part is proposed and its characteristics are analyzed using the developed finite element code. From the characteristics comparison between the new laminated model and the initial solid model, the laminated model shows better electro-magnetic performance than the non-laminated model.

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Author Profile

Han-Seok Park

He received the B.S. and M.S. degrees in Electrical Engineering from Chung Ang University. He received the Ph.D. degree in Electrical Engineering from Korea Maritime University. He is currently a professor in the Division of Electrical, Control and Instrument Engineering of Pukyong National University. His research interest are energy conversion system and substitute energy system.

Hong-Sub Jung

He received B.S. degree in Electrical Engineering from Busan junior college of technology and M.S. degree in Electrical Engineering from Pukyong National University. He is currently in the Ph.D. course in Electrical Engineering from Pukyong National University. He is a manager of the port development team of korea container terminal authority.

Kyung-il Woo

He received the B.S, M.S., and Ph. D. degrees in Electrical Engineering from Hanyang University. He is currently a assistant professor in the Division of Electrical, Control and Instrument Engineering of Pukyong National University. His research interests are numerical analysis of electrical machines and control.