ACCURATE DESIGN OF EDDY CURRENT BRAKE BY FEM

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Abstract : *This paper presents the accurate design of eddy current brake based on 2-D Galerkin-FEM and Upwind-FEM. For the large peclet number, the performances of eddy current brake can be accurately analyzed with respect to the velocity by using 2-D Galerkin-FEM. The equivalent magnet stack width of eddy current brake and the nonlinear analysis is used to increase the analysis accuracy. The validity of the analysis results is verified by comparing to the experimental ones.*

Key words: *Eddy current brake, Convective-diffusion equation, Galerkin-FEM, Upwind-FEM.*

1. Introduction

The speed of the passenger trains has been increased by the development of design and control technology. With the increase of speed, the deceleration of the train must be guarantee for the passenger's security.

There are some types of brake in the high speed train: disk brake, eddy current brake and regenerative brake. In these brake systems, eddy current brake uses the principle that moving conducting material in the magnetic field generates the retardation force [1].

In the design of eddy current brake, the prediction of the performance based on accurate analysis method is very important [2]-[3]. The performance of eddy current brake can be predicted by analyzing traveling magnetic field problem. When the problem is analyzed by Galerkin FEM, it is well known that unnecessary oscillation will be expected for the large cell Peclet number ($P_e=\mu\sigma vh$, in which v is the velocity, σ is the conductivity, μ is the permeability and h is the elemental length in the direction of motion).

A possible way to overcome the oscillation is Upwind-FEM suggested by Zienkiewicz [4] and Christie [5] in 1-D problem. However, in case of performance calculation such as force calculation in the airgap, the difference between the results from Galerkin-FEM and Upwind-FEM is insignificant.

In this paper, the performances of eddy current brake have been calculated with the key parameter such as speed by using Galerkin-FEM and Upwind-FEM. The equivalent magnet stack width is calculated by field variable with vector potential in order to compensate the flux fringing effect due to the difference between the stack widths of eddy current brake and rail [7]. The conductivity of the rail is compensated to consider the transverse edge effect in the rail [6]. Non-linear analysis is performed by using direct convergence method, a simple iterative technique that proceeds by successively solving linear system of equations ($B=\mu H$) starting with an estimated value. The validity of the analysis results by Galerkin-FEM and Upwind-FEM is achieved by comparing the experimental results.

2. Problem Formulation and Analysis Models

A. Problem Formulation

The governing equation for 2D finite element analysis in traveling magnetic field problem, is expressed as follows;

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A}{\partial y}\right)=-J_o+\sigma\left(\upsilon_x\frac{\partial A}{\partial x}\right) \qquad (1)$$

where, A is the z-directional magnetic vector potential, J_o is the exciting current density, σ is the conductivity, μ is the permeability and υ_x is the x-directional velocity of the DC-magnet.

After applying the weighted residual method with tetragonal element, equation (2) is derived by

$$\int_{S_e}\sum_{1}^{4}\left(\frac{1}{\mu}\frac{\partial L_i}{\partial x}\frac{\partial N_j}{\partial x}+\frac{1}{\mu}\frac{\partial L_i}{\partial y}\frac{\partial N_j}{\partial y}\right)A_j\,ds$$
$$+\sigma v_x\int_{S_e}\sum_{1}^{4}\left(L_i\frac{\partial N_j}{\partial x}\right)A_j\,ds+J_o\int_{S_e}L_i\,ds=0 \qquad (2)$$

The linear interpolation function N_i and upwind interpolation function L_i for tetragonal element are given by

$$N_i = \frac{1}{4}(1+\xi_i\xi)(1+\eta_i\eta) \tag{3}$$

$$L_i = \frac{1}{4}(1+\xi_i\xi-\alpha\xi_i f(\xi))(1+\eta_i\eta) \tag{4}$$

where,

$$f(\xi) = 3(1-\xi^2)/4 \tag{5}$$

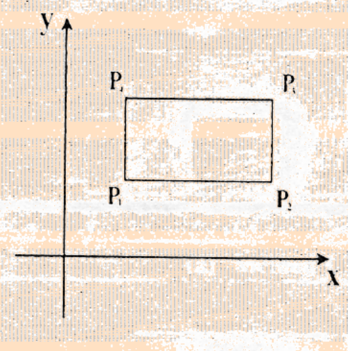
Equation (3), (4) and (5) are obtained by using the normalized rectangle in the local coordinates system of Fig. 1(b). In (6), the parameter α is upwinding factor and it was given by Heinrich [3].

$$\alpha = \coth(\frac{P_e}{2}) - \frac{2}{Pe} \tag{6}$$

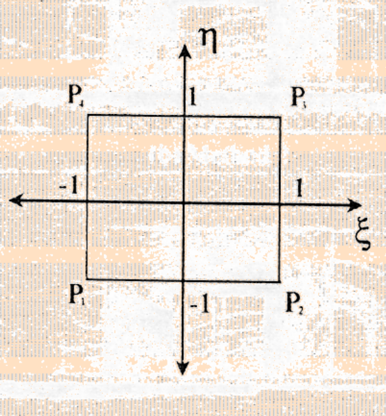
where,

$$P_e = \sigma\mu v_x h \tag{7}$$

The parameter P_e is called the cell peclet number, the parameter h is the element size in x-direction. It is well known that solutions oscillate between the adjacent nodes in the case that the cell peclet number is over two.



(a) Cartesian coordinate



(b) Local coordinate
Fig. 1. Coordinate transformation

B. Analysis Model

Fig. 2 shows the eddy current brake for the analysis. The magneto-motive-force (MMF) is 12000 AT. Dirichlet boundary conditions are chosen on four boundary sides. The DC-magnet moves at constant speed along the x-direction. This model is analyzed by three methods including Upwind-FEM. Non-linear analysis is used to increase the analysis accuracy and the analysis results are compared to the experiment results. The initial estimated value of permeability is $1000\times4\pi\times10^{-7}$ (H/m), materials S40C and ST37 are used for B-H curve data of the core and the rail of the nonlinear analysis respectively.

In the 2D analysis model considering the eddy current, all currents exist in the z direction only. Consequently, the conductivity of the rail is compensated to consider the transverse edge effect in the rail. The compensated conductivity is 1.61×10^6 (mho/m).

- Method 1: Galerkin-FEM with triangle element
- Method 2: Galerkin-FEM with quadrilateral element
- Method 3: Upwind-FEM with quadrilateral element

B. Equivalent Magnetic Stack Width

In the eddy current brake system, 3D analysis is necessary for the accurate analysis results because of the fringing effect due to the different stack widths between the eddy current brake and the rail. However, 2D analysis is much easier and faster than 3D analysis in modeling and computation time. Consequently, the equivalent magnetic stack width is calculated by field variable with vector potential in order to compensate the flux fringing effect and obtain more accurate 2D analysis results. The flux Φ per stack width and stored energy W_m in the airgap are express respectively as follows:

$$\Phi = S \cdot B \tag{8}$$

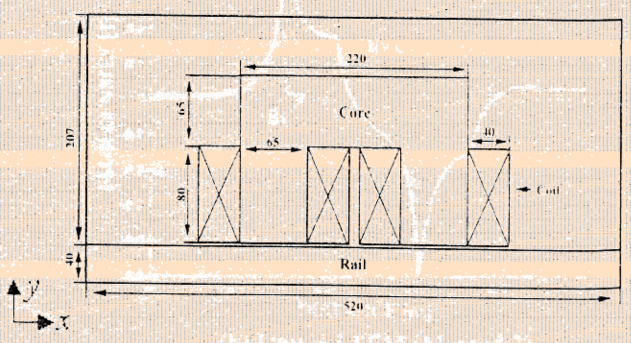


Fig. 2. Analysis Model

$$W_m = \int_V \left(\int_B \vec{H} \cdot d\vec{B} \right) dV \tag{9}$$

where, S is the magnet area, B is the flux density of magnet. V is the whole element of the analysis model.

The equivalent stack width of the eddy current brake can be calculated as equation (10) [5]

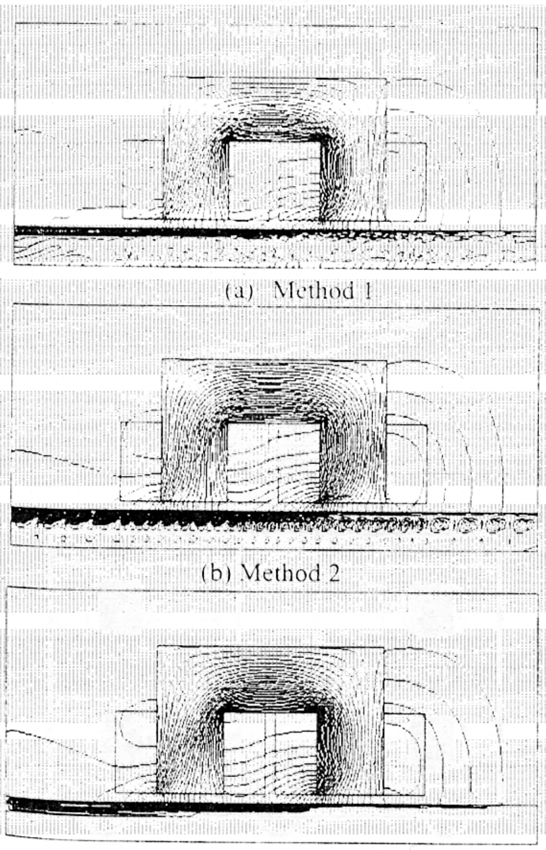
$$W_{eff} = (g\,\Phi^2)/(2 W_m\, l_p \mu_0) \tag{10}$$

where g is the mechanical airgap length and l_p is the pole length.

2. Analysis Results and Discussion

A. Flux Distribution

Fig. 3 (a), (b) and (c) show the flux distribution of the analysis model calculated by method 1, method 2 and method 3 respectively. The distortion of flux appear in the rail part in case of triangle element applying method 1 and quadrilateral element applying method 2, but these loops disappear in case of tetragonal element applying method 3.



(a) Method 1

(b) Method 2

(c) Method 3

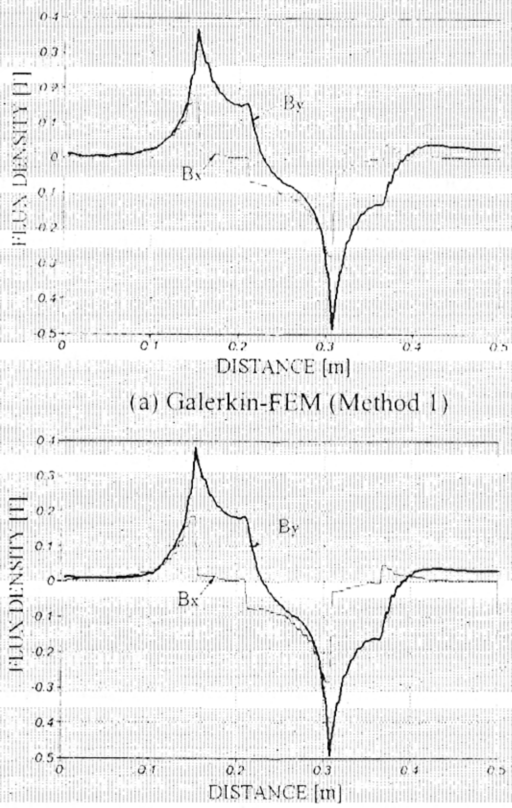
Fig. 3. Flux distribution of the analysis model

Fig. 4 (a) and (b) show the flux density distributions in the center of the airgap at the velocity of 300 (km/h) in the eddy current brake by method 1 and method 3 respectively. The difference of flux density distributions in the airgap between the results by method 1, Galerkin-FEM and method 3, Upwind-FEM are insignificant for the large peclet number.

B. Force Performance

Fig. 5 (a) and (b) show the magnetic forces of eddy current brake according to the variation of the velocity by Upwind-FEM and Galerkin-FEM. The magnetic forces can be calculated by Maxwell Stress Tensor method. It is observed that the Upwind-FEM and Galerkin-FEM give good agreement with the experimental data in Fig. 5.

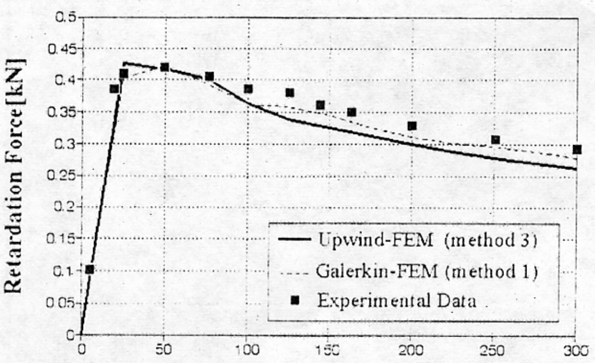
Fig. 6 and table I show the experimental equipment and the specification of the eddy current brake system respectively. The equipment is designed to the rotary type for the high velocity. This equipment is composed of flywheel, load cell and electromagnet roughly. Diameter of flywheel is 885[mm] and it turned by four 10hp motors. Three load cells are used to measure attraction and retardation force.



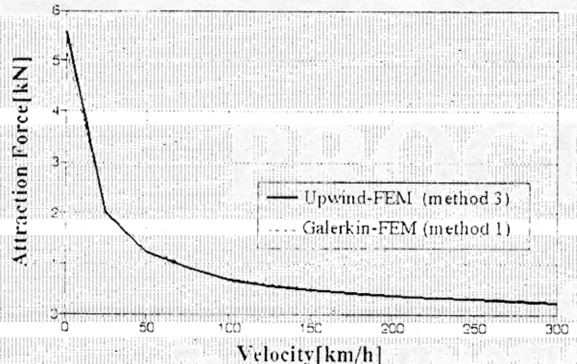
(a) Galerkin-FEM (Method 1)

(b) Upwind-FEM (Method 3)

Fig. 4. Flux density distributions in the center of airgap of the eddy current brake

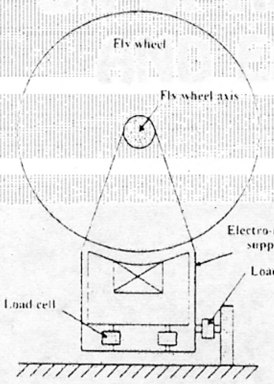


(a) Retadation force



(b) Attraction force

Fig. 5. Force performance according to the velocity



(a) Lateral view

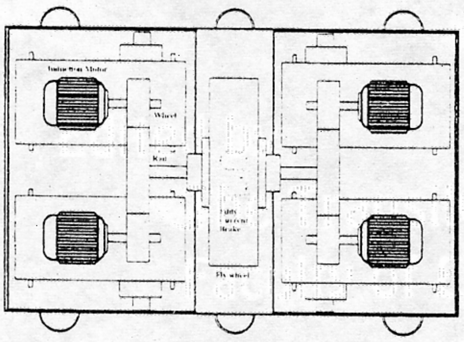

(b) Floor view

Fig. 6. Experimental equipment

TABLE I
Specification of the eddy current brake system

Variables	Values
Electromagnet-pole width	0.065 [m]
Electromagnet length	0.12 [m]
Slot height	0.07 [m]
Slot width	0.09 [m]
Airgap length	0.01 [m]
Magneto-Motive Force	12,000 [AT]
Current density	4.5 [A/mm^2]
Coil resistance	5.5 [Ω]
Coil cross-section	1[mm^2]
Rated voltage	50 [v]
Inductance	1.5 [H]

4. Conclusion

In this paper, the performances of eddy current brake have been accurately analyzed with respect to the velocity by using Upwind-FEM and Galerkin-FEM. In order to obtain the accurate design parameters, equivalent magnetic stack width, compensated conductivity and nonlinear analysis are applied. As the results, for the large peclet number, the performances of eddy current brake can be accurately analyzed by using 2-D Galerkin-FEM.

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