Analysis of Eddy-Current Brakes（ECB）for High Speed Railway Using Meshless Method

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***Abstract*—In this paper we point out the analysis ECB should not apply FEM because the velocity term appears and the numerical solutions contain spurious oscillations. Then the authors introduce the Meshless method, the formulation and application examples. An experimental prototype is founded to get the verification results and the results of the examples indicate the validity method.**

***Index Terms*— ECB; High speed railway; Meshless method.**

I. INTRODUCTION

Nowadays, high speed rail transportation is seeing a rapid development. More attention has been paid to the safety of vehicle, in which the braking system plays an very important role. The eddy current brake (ECB) is promising a vast application due to its obvious advantages: abrasion-free, making no noise, energy-saving, and thus money saving. Massive studies have been concentrated on this new type braking technique. Currently, ECB system as Fig.1 has been applied in high speed train and vehicles, as well as the stepless speed regulation of cranes.

ECB structurally can be divided into disk type as Fig.1 and linear type. In this paper, we analysis disk type ECB structure which include moving conductors where there is eddy current and non-eddy current area where there is excitation current. When magnetic fields in moving conductors are computed, eddy currents (J_e) due to the movement of conductor are

$$J_e=\sigma(\nabla\phi+\frac{\partial \boldsymbol{A}}{\partial t}-\boldsymbol{V}\times\nabla\times\boldsymbol{A}) \tag{1}$$

For the $\boldsymbol{A}$-ϕ method, the governing equations are

$$\nabla\times\frac{1}{\mu}\nabla\times\boldsymbol{A}+\sigma(\nabla\phi+\frac{\partial \boldsymbol{A}}{\partial t}-\boldsymbol{V}\times\nabla\times\boldsymbol{A})=J_s \tag{2a}$$

$$\nabla\cdot\sigma(\nabla\phi+\frac{\partial \boldsymbol{A}}{\partial t}-\boldsymbol{V}\times\nabla\times\boldsymbol{A})=0 \tag{2b}$$

Where $\boldsymbol{A}$ and ϕ are the magnetic vector potential and the electrical scalar potential, respectively. μ and σ are the permeability and the conductivity, respectively, and $\boldsymbol{V}$ is the velocity of the media relative to the source. J_s is the excitation current. There is no excitation current in moving conductors of ECB system, so that $J_s=0$.

Equation (2) is mathematically a Convection–Diffusion equation. When it is solved by using the ordinary Galerkin finite element method, especially with a high speed of conductors and high relative permeability of the moving parts, the numerical solutions should contain spurious oscillations, on account of a large Peclet number which is more than one unity.[1]-[4] . The element Peclet number is defined as

$$P_e=\boldsymbol{V}\sigma\mu h/2 \tag{3}$$

Where h is the length of the element in the direction of the velocity. In order to eliminate the spurious oscillations, the mesh must be refined to insure $P_e<1$. Therefore, when the speed is high, the mesh must be more precision. This almost increases the requirement of both the computer memory and the CPU time greatly, and sometimes makes the method unpractical. In this work, we will use meshless method to analysis ECB. It is known that meshless method has been used in numerical calculation of electromagnetic fields in recent decade years. The radial basis function (RBF) collocation method is one of meshless methods [5]-[9] which use a set of nodes instead of traditional mesh elements in computational domain, so that it has more flexibility, fast convergence and no mesh generator.

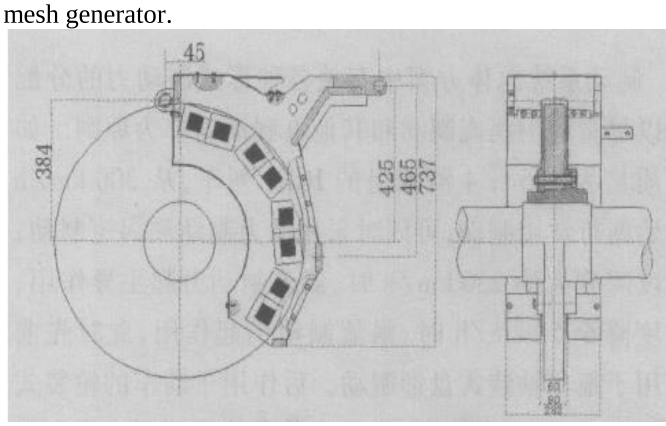

Fig.1.Disk type ECB structure on the high-speed train

II. RBF COLLOCATION METHOD TO ANALYSIS ECB

In order to make ECB system easy analysis, we use the source superposition principle in the medium of linear magnetization curve, so that the magnetic field would be considered to be an addition of two fields generated by the excitation current and the eddy current. The magnetic field produced by excitation current is easy to compute, so we simplify the model as a moving conductor in static magnetic field, and the static magnetic field will be competed separately. The magnetic vector potential $\boldsymbol{A}$ is below

$$\boldsymbol{A}=\boldsymbol{A}_s+\boldsymbol{A}_e \tag{4}$$

Where $\boldsymbol{A}_s$ and $\boldsymbol{A}_e$ is the two fields generated by the excitation current and the eddy current respectively. When $\boldsymbol{A}_s$ has been computed, we will simplify the model as a moving conductor, and the governing equations with $\boldsymbol{A}$-ϕ method are

$$\begin{cases} \frac{1}{\mu}\nabla\times\nabla\times\boldsymbol{A}_e+\sigma(\nabla\phi+\frac{\partial\boldsymbol{A}}{\partial t}-\boldsymbol{V}\times\nabla\times\boldsymbol{A})=0 & \text{in}\,\Omega \\ \sigma\nabla\cdot(\nabla\phi+\frac{\partial\boldsymbol{A}}{\partial t}-\boldsymbol{V}\times\nabla\times\boldsymbol{A})=0 & \text{in}\,\Omega \\ B(\boldsymbol{A}_e)=0 & \text{on}\,\partial\Omega \end{cases} \quad (5)$$

Where Ω is solving region and $\partial\Omega$ is the boundary of Ω. B means a boundary operator.

With $N_I+N_B=N$ collocation nodes respectively in Ω and on $\partial\Omega$, the magnetic vector potential $\boldsymbol{A}_e$ could be scattered by RBF formed as

$$\boldsymbol{A}_e=\sum_{j=1}^{N}a^e{}_jQ_j\left(\|x\text{-}x_i\|,\ c\right)^e=\boldsymbol{Q}_e{}^T\boldsymbol{a}^e \quad (6)$$

Where x is the coordinate of nodes in the solving domain. $Q_j\left(\|x\text{-}x_i\|,\ c\right)$ is the RBF centered at node x_i and $\boldsymbol{Q}_e{}^T$ is the vector form. c is a shape parameter. $\boldsymbol{a}$ is the unknown coefficient vector to be determined.

Using Crank-Nicolson time-matching scheme to deal with the time differential and construct iteration as below

$$\partial A/\partial t=(A^{k+1}-A^k)/\Delta t\,,\ A=0.5(A^{k+1}+A^k) \quad (7)$$

With the work we have done before, using RBF collocation method we can get the result of $\boldsymbol{A}_e$. Then, according to Ampere's force law, the torque imposed on the conductor by the magnetic field is

$$\begin{aligned} T&=\int f(x)\times r(x)dV \\ &=\int\left[J_e(x)\times\left(\nabla\times A(x)\right)\right]\times r(x)dV \end{aligned} \quad (8)$$

Where $f(x)$ is the force imposed on the note by the magnetic field, and $r(x)$ is the distance of the note to the center of moving conductive disc in ECB system. J_e could be computed in equation (1).

III. EXPERIMENTAL PROTOTYPE OF ECB

To get the verification results, an experimental prototype was founded as Fig.2 before. This equipment consists of three components which are moving conductive disc, motor and electromagnet.

The distance of air gap between conductive disc and electromagnet, and the excitation current of the electromagnet both could be adjustable in the equipment. The voltage of motor is set to 15V unchanged. Magnetic induction at the end face of electromagnet could be measured by hall sensor and the motor speed can be measured.

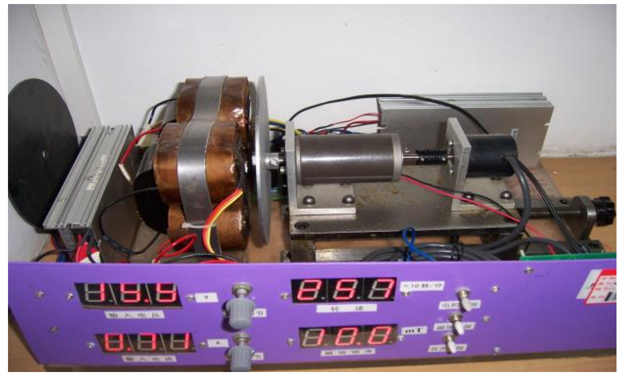

Fig.2. Experimental prototype of ECB system

With that we can get the torque of ECB system using law of conservation of energy of the steady state running motor at constant speed.

Fig.3 is the measurement results of the torque with magnetic induction in different distance of air gap. Bold black lines are the numerical results. The more detailed results of comparison and more work will appear in full paper.

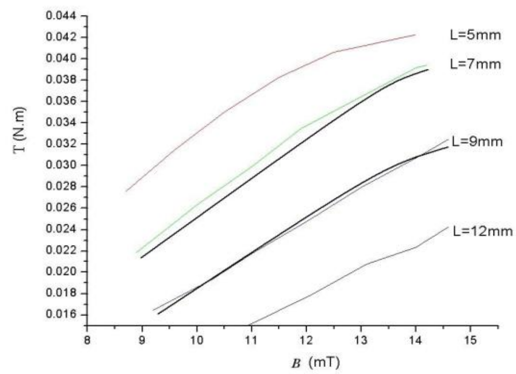

Fig.3. Results of the torque with B in different distance of air gap

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