Calculation of transient electromagnetic forces in an axisymmetrical electromagnet with conductive solid parts

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CALCULATION OF TRANSIENT ELECTROMAGNETIC FORCES IN AN AXISYMMETRICAL ELECTROMAGNET WITH CONDUCTIVE SOLID PARTS

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ABSTRACT

The paper describes the analysis and the calculation of transient response of a voltage fed electromagnet. This calculation is based on the simultaneous solution of the magnetic field equations and the electrical circuit equations. In the modelling of the magnetic fields, eddy currents in solid conductive parts and saturation of magnetic parts are taken into account. This modelling uses Finite Element Method for the calculation of magnetic fields and forces with special quadrilateral elements. Experimental and simulation results for an axisymmetrical electromagnet are presented and compared.

INTRODUCTION

The transient response of voltage supplied electromagnetic structures with solid conductive parts has been an object of important works last years [1],[2],[3]. The numerical analysis must be made by the simultaneous solution of the magnetic field equations and the electrical circuit equations. If, for the current response, the obtained results now give satisfaction, the calculation of forces in the moving parts, which are closely dependent on the discretization grid, is still the theme of investigation. This paper brings some contribution to the solution of this problem by using a special discretization, based on cut quadrilateral Finite Elements, inside the regions where great accuracy is required.

ADOPTED METHODOLOGY

The magnetic field in an electromagnetic device is governed by the electromagnetic diffusion equation. If the magnetic potential vector **A** is employed we can write:

$$\mathbf{curl}((1/\mu)\mathbf{curl}\mathbf{A})=-\sigma d\mathbf{A}/dt+\mathbf{J}_{ext} \qquad (1)$$

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where μ is the magnetic permeability, which is the function of **A** to take into account saturation effects, σ is the electrical conductivity and J_{ext} is the supply windings current density.

When the device is voltage fed, the current density J_{ext} is unknown. In order to relate the applied voltage to the field equation (1) we can use the electric circuit equation:

$$V=RI+LdI/dt+dN\Phi/dt \qquad (2)$$

where V is the applied voltage, I is the winding current which may be related to the current density J_{ext}, NΦ is the windings flux linkage which is calculated from the field equations. R is the winding electric resistance. The winding leakage inductance L may be added if it is not taken into account in the field equation.

The electric circuit equations (2) and the electromagnetic field equations (1) are solved simultaneously by Finite Element and time-stepping technique. The β-algorithm [4] is used to calculate dA/dt and dI/dt. Saturation in the magnetic parts are taken into account by means of the Newton-Raphson method.

In order to solve the magnetic equations (1) we use triangular first order Finite Element method. Nevertheless in the regions needing a refined mesh the spacial discretization may give triangular elements oriented in the same way (Figure 1a). Such orientation affects the precision of the results.The way to avoid this problem is to work with the quadrilateral element of Figure 1b cut as illustrated [5].

At the end of each time step, the magnetic field vector is known in the device, and the force in the moving parts can be calculated. The well known Maxwell Stress Tensor is used:

$$F=\int_S [(-\mu_0/2)H^2 dS+\mu_0(H.dS)H] \qquad (3)$$

where S is an integration surface passing in the air and surrounding the volume where **F** is searched, **dS** is a vector in the normal direction to S and **H** is the magnetic field vector.

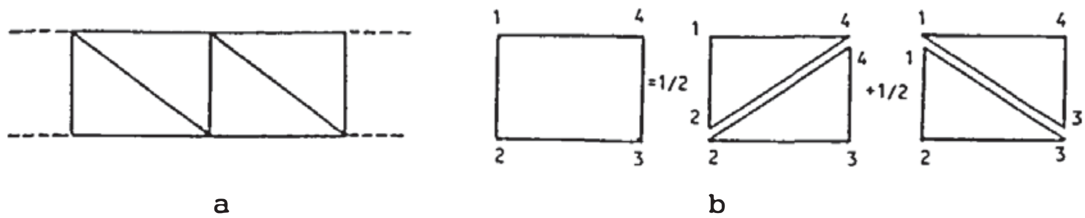


Figure 1-Quadrilateral element cutting method

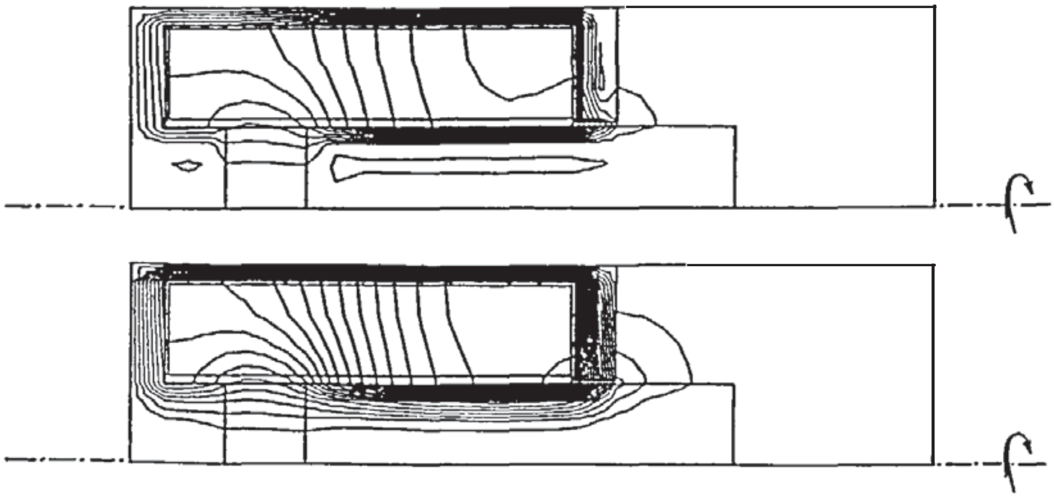
RESULTS

The above presented method has been applied to the analysis of an axisymmetrical electromagnet.

Figure 3 shows the simulation results when the electromagnet is supplied by a 24 Volts d.c. step.

Figure 4 gives the corresponding experimental results. The force on the plunger was measured by means of a strain gauge sensor.

There is a good agreement between the calculated and measured results.



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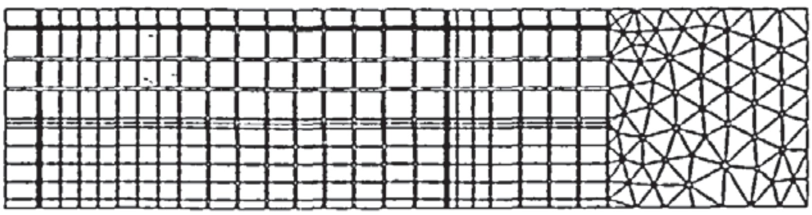

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Figure 2 - a) Equipotential lines at two simulation times (25 ms and 0.3 s)
b) The adopted Finite Element grid.

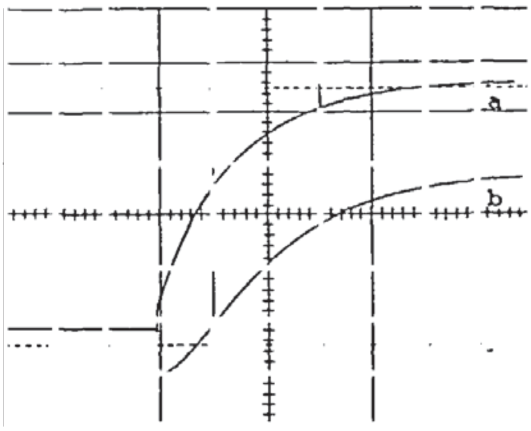

Figure 3-Simulation Results
a)Current vs time
b)Force vs time
Current 0.5 A/div.
Force 20 N/div.
Time 50 ms/div.

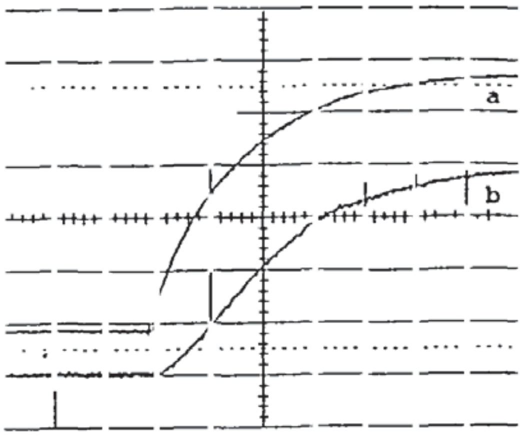

Figure 4-Experimental Results
a)Current vs time
b)Force vs time
Current 0.5 A/div.
Force 20 N/div.
Time 50 ms/div.

CONCLUSION

The method allowing the transient current and force calculation on a voltage supplied axisymmetrical electromagnet has been presented. The Finite Elements grid based on quadrilateral elements has been adopted. The experimental and calculated results which have been compared, show the validity of the method. This discretisation method is general and can be used to study other electromagnetic devices, particularly those involving thin air-gaps.

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