3D FEM Adjoin Formulations Combination for PM Material Modeling in High Temperatures

M. Beniakar, E. Tsampouris and A. Kladas
Faculty of Electrical and Computer Engineering; National Technical University of Athens
9 Iroon Polytechniou Street, 15780 Athens, Greece
Tel.: +30 210-772 3762, Fax.: +30 772 2336
E-mails: beniakar@central.ntua.gr, etsab@central.ntua.gr, kladasel@central.ntua.gr

Abstract — In this paper two different methodologies for permanent magnet material representation based on equivalent surface current densities and magnetic mass models are combined for high operating temperature analysis. The corresponding adjoin magnetic vector potential and magnetic scalar potential formulations have been developed under both two and three dimensional finite element configurations. SmCo and NdFeB magnetic materials were tested including extensive experimental validation. The temperature range of superiority of either material has been determined.

I. FORMULATION

Modeling of permanent magnet (PM) materials has aroused increased interest among researchers over the past decades due to the development of magnetic materials attaining 1.5 T remanence and improved stability at high temperatures enabling their implementation in electrical machines. Several models for PM materials have been developed in conjunction with finite element formulations [1-4]. In particular high temperature behavior of the magnets and their suitability for advanced motor drive systems with recent increased thermal stability of Neodymium-iron-boron alloys is under investigation [5].

The proposed methodology is adopting dual formulations based on vector and scalar magnetic potential in order to obtain accurate PM material representation. According to such analyses the PM material is modeled by using equivalent surface current densities (amperian model) or alternatively as step variations of the scalar magnetic potential on the magnet borders (magnetic mass model). Figure 1 illustrates the basic concept of the two aforementioned adjoin formulations developed.

The first formulation models PM materials through appropriate current sheets surrounding a fictitious material that has the same dimensions and incremental permeability involving zero coercive force (Fig. 1a). This modeling procedure is associated with magnetic vector potential formulation that can be expressed in case of a magnetostatic problem as follows:

$$\nabla \times \left(\frac{1}{\mu_o} \left(\nabla \times \bar{A} \right) \right) = -\bar{J}_{eq} \qquad (1)$$

In general, the constitutive relation for magnetic flux density in the magnet can be written:

$$\bar{B} = \mu_0 \left(\bar{H} + \bar{M} \right) \qquad (2)$$

where $\bar{A}$ is the magnetic vector potential, $\bar{M}$ is the magnetization, $\bar{B}$ is the magnetic flux density and μ_0 is the magnetic permeability of vacuum. In such a formulation the magnetization is represented through the equivalent surface current density surrounding the magnet involving total ampere-turns NI that can be evaluated as follows:

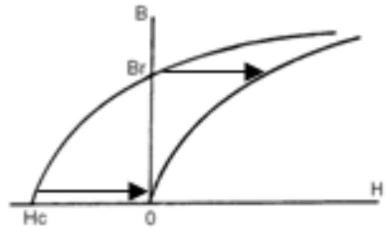
$$NI = H_c \cdot d \qquad (3)$$

where H_c is the permanent magnet coercive force and d the magnet width (Fig. 1b).

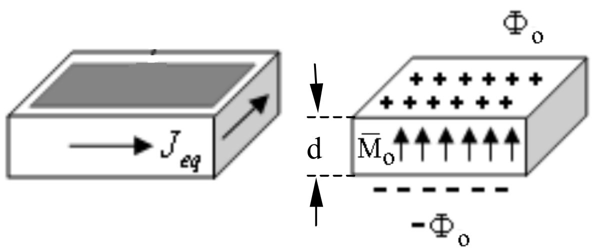
Alternatively, an adjoin formulation involving the magnetic scalar potential ϕ has been developed, where the magnetization $\bar{M}$ is represented through appropriate source linear potential ϕ_o inside the magnet corresponding to fictitious magnetic masses, as shown in Fig. 2c (equivalent to the way that electrostatic charges create an homogenous electric field). Since H is defined as the divergence of the magnetic scalar potential, the equation to be solved can be expressed as follows:

$$\nabla \cdot \left(\mu_o \nabla \phi \right) = \nabla \cdot \left(\mu_o \phi_o \right) \qquad (4)$$

where ϕ_o is the fictitious source magnetic scalar potential distribution.



(a)



(b) (c)

Fig. 1. Equivalent representations of the PM material
(a) amperian model (b) amperian model (c) magnetic mass model

II. EXPERIMENTAL SETUP

In order to validate the simulation results an experimental setup has been developed based on measurements of magnetic circuit attractive forces of SmCo and NdFeB magnets under various operating temperatures. This setup comprises a test chamber, an elementary magnetic circuit with variable air-gap, a temperature controller, a force sensor and a signal amplifier and filter (Fig. 2).

The test chamber is actually an insulated heating device, in which is placed the magnetic circuit incorporating the magnet. The heat in the test chamber is uniformly distributed by convenient heating resistances and the temperature is accurately measured by using a temperature sensor placed near the magnet. The temperature is controlled and kept constant through a temperature controller, based on appropriate PID feedback. The magnetic circuit is consisted of two main parts: a fixed one, attached on the floor of the test chamber, on which the magnet is placed, and a cylidrical moving part. The air-gap between the fixed part and the moving part of the magnetic circuit can be conveniently adjusted by a simple mechanism that is placed just above the test chamber, incorporating a force sensor. Therefore, the magnetic force can be measured for different air-gap lengths and operating temperatures illustrating the respective magnet demagnetizing characteristics. The experimental setup details are illustrated in Fig. 2.

III. RESULTS AND DISCUSSION

The proposed methodology involves combination of the two previously described adjoin modeling procedures for PM materials. This can adopt either 2D or 3D configuration, by using vector and scalar magnetic potentials, respectively. Such a combined analysis provides improved accuracy on the magnetic material representation by using reduced discretizations. Figures 3a and 3b illustrate the field distributions computed for SmCo magnet by using 2D (for small air gap-width) and 3D models (for large air-gap width), respectively. The simulated results concerning force variations with the air-gap width and temperature for SmCo and NdFeB magnetic materials are compared to the measured ones in Figs. 4 and 5, respectively. The thermal behavior and stability limits of the two materials were confirmed and their favored temperature ranges have been investigated. It was assessed that below 180 °C temperature NdFeB magnets exhibit better characteristics while SmCo ones are more effective for temperatures ranging from 180 °C to 350 °C.

IV. ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement AAT.2008.4.2.4-234119 CREAM within TEIP Consortium Member.

V. REFERENCES

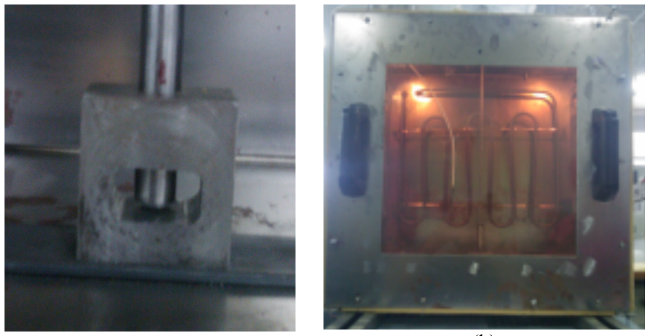
[1] F. Fouad, T. Nehl, and N.A Demerdash, "Permanent magnet modeling for use in vector potential finite element field analysis in electrical machinery", *IEEE Trans. on Magnetics*, vol.17, no. 6, pp. 3002-3004, 1981.

[2] P. Campbell, M. Chari and J. D'Angelo, "Three-dimensional finite element solution of permanent magnet machines", *IEEE Trans. on Magnetics*, vol.17, no. 6, pp. 2997 - 2999, 1981.

[3] D. Pavlik, V.K. Garg, J.R. Repp, and J. Weiss, "A finite element technique for calculating the magnet sizes and inductances of permanent magnet machines", *IEEE Trans. on Energy Conversion.*, vol. 3, no. 1, pp. 116-122, 1988.

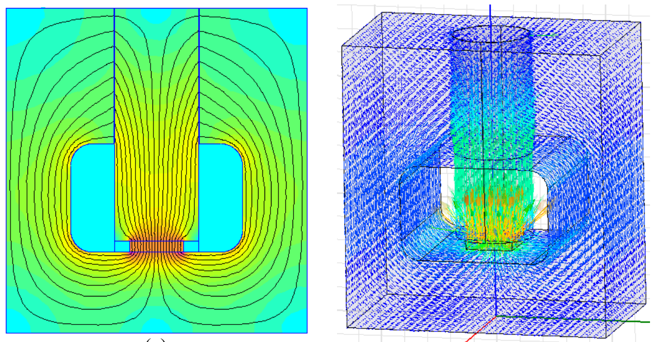
[4] M.A. Alhamadi, R. Wang and N.A. Demerdash, "Vector potential 3D-finite element modeling of magnetic fields in permanent magnet devices", *IEEE Trans. on Magnetics,* vol. 27, no. 6, pp. 5016-5018, 1991.

[5] A. Wang, H. Li, and C.T. Liu, "On the Material and Temperature Impacts of Interior Permanent Magnet Machine for Electric Vehicle Applications", *IEEE Trans. on Magnetics,* vol. 44, no. 11, pp. 4329-4332, 2008.



(a) (b)

Fig. 2. Photographs of the magnetic circuit (a) and the test chamber (b)



(a) (b)

Fig. 3. Magnetic field distribution calculated by the 2D model (a) and the 3D model (b) for SmCo alloy magnet case and temperature 25 °C.

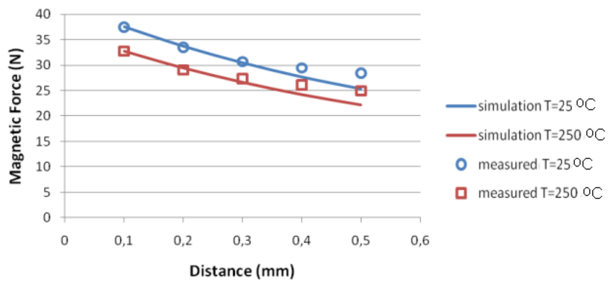


Fig. 4. Comparison of experimental and simulation results for two different operating temperatures for SmCo magnets

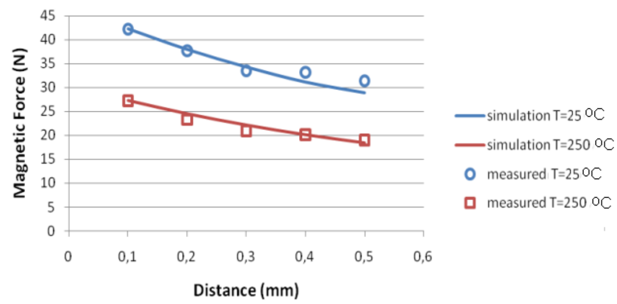


Fig. 5. Comparison of experimental and simulation results for two different operating temperatures for NdFeB magnets