Finite Element Analysis of a Synchronous Permanent Magnet Micromotor through Axisymmetric and Transverse Planar Simulations

Adrián C. Agüero, Fernando A. Actis
CIMM-Centro de Investigación de Materiales y Metrología, Av. Vélez Sársfield 1561- C.C. Central 884, 5000 Córdoba, Argentina

Viviane Cristine Silva, José Roberto Cardoso, Silvio I. Nabeta
LMAG/PEA Escola Politécnica da Universidade de São Paulo, Av. Prof. Luciano Gualberto, T. 3, n°158, 05508-900 São Paulo SP, Brazil

Abstract - **The aim of this work is to present and discuss an original way to analyze a synchronous permanent magnet micro-motor (SPMM) for design purposes. The analysis of the magnetic field distribution in the motor, whose geometry would require a 3D modeling, is instead carried out with the aid of two 2D finite-element (FE) simulations: one axisymmetric and one on the cross-section or transverse plane. To validate the suitability of the proposed method for torque computation, a 3D-field solution is also presented. Computed results of distribution of magnetic induction, as well as the torque developed by the motor in both 2D and 3D simulations, have shown good agreement with measurements in a prototype machine.**

Index terms - **Claw pole, synchronous permanent magnet micro-motor, finite element analysis of synchronous machines.**

I. INTRODUCTION

The SPMM is a low-cost device employed as a time reference, which provides rotating movement with low torque. Its main feature is its constant speed for a given supply frequency, independent of the load until it is in an overload state. In this condition, the motor loses synchronization with consequential speed reduction and oscillations. Typical applications include chart recorders, programming devices, valve drives, etc. Figure 1 illustrates the winding arrangement, stator claw poles and permanent magnet multi-pole ring rotor, which are magnetized along the radial direction [1-2].

Performance characteristics such as developed torque can be obtained with the aid of 2D and 3D FE analyses by assuming a magnetostatic behavior, since in both simulations one is interested in the steady state operation of the synchronous motor.

Although 2D representations of SPMMs provide less accurate results when compared to 3D modeling, they allow faster and lower-cost simulations [3].

II. 2D FE MODELS

The steady state operation of a SPMM has been simulated as a 2D magnetostatic phenomenon using a 2D FE package (FLUX2D) [4]. The domain studied consists of a 16-pole prototype synchronous motor with a permanent-magnet ring rotor (refer to Appendix for the SPMM dimensions and data). Figure 2 presents a schematic layout of the motor geometry in two views: axisymmetric and cross section, displayed by the geometric modeler of the FE package.

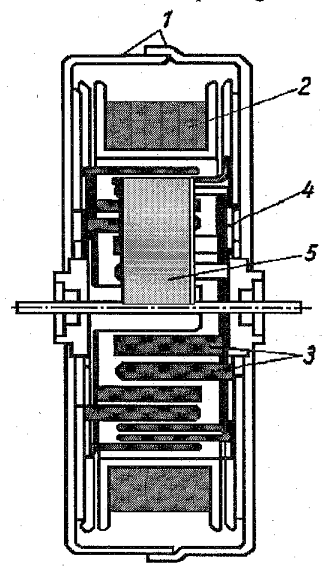

Fig. 1. Topology of the prototype SPMM: 1 - Stator housing, 2 - coil, 3 - claw poles, 4 -short-circuiting ring (copper), 5 - permanent-magnet rotor.

The prototype machine can be seen in Fig. 2 and has the following constructive features:
- the claw poles are made from electrical steel with a 1 mm thickness;
- the coil has 11000 turns and is made of copper wire with a 0.06 mm diameter;
- the magnet has a remanent induction of 0.2 T.

The first simulation assumes axial symmetry (Fig. 3a) and enables the determination of the normal component of the flux density distribution, B_n, on the portion of the claw surface facing the permanent magnet.

After solving the axisymmetric problem, the calculation of B_n was carried out along a path spanning from the top to the bottom of the permanent magnet (see dashed line in Fig. 3a). The plot of B_n along this path can be seen in Fig. 4. This curve will be used in the next step of the methodology: the 2D planar simulation.

To calculate the torque, a second 2D simulation assuming planar symmetry was carried out using the geometry shown in Fig. 3b, which represents a cross section of the prototype

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A. Agüero, fax: +54-51-699459; e-mail: aguero@com.uncor.edu; J. R. Cardoso, fax: +55-11-814 2092; e-mail: cardoso@pea.usp.br.
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machine, taken in the mid-height of the magnets. Along the external boundary (dashed line of Fig. 3a) a non-homogeneous Dirichlet boundary condition was imposed, i.e. a fixed magnetic vector potential (the state variable), which is numerically equal to the magnetic flux per meter crossing the cylindrical surface represented by the vertical dashed line of Fig. 3a.

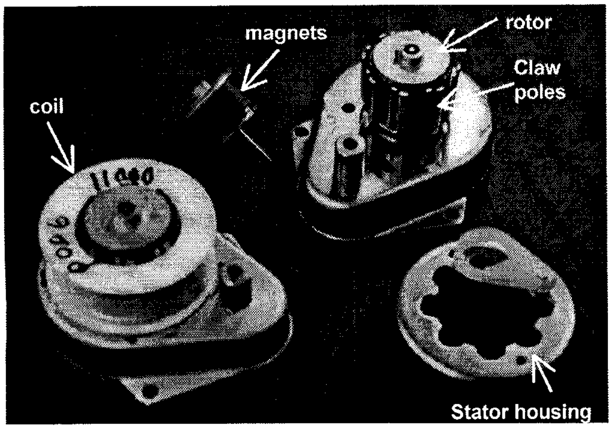

Fig. 2. The SPMM prototype.

This magnetic flux can be determined with the aid of the B_n curve of Fig. 4, plotted along the vertical dashed line in the axisymmetric simulation. The magnetic flux was calculated by taking the "mean value" of this curve, i.e. the value of B_n which gives a rectangular area equal to the area delimited by the curve in Fig. 4.

The second 2D simulation yielded the flux density distribution, which can be seen in Fig. 5 through contours of flux lines. The torque vs. load angle characteristic has also been determined in one pole pitch with the aid of this simulation. The result will be presented later on in this work.

III. 3D FE Model

The complicated shape of the claw poles usually needs a three-dimensional analysis. However, results from a 3D-FE modeling of the same prototype motor have presented a very close agreement with the proposed methodology, namely the two 2D simulations.

The 3D simulation presented in the sequence was carried out using a 3D finite element package, FLUX3D [5]. Fig. 6 shows the 3D FE mesh. Again, the phenomenon was assumed as a magnetostatic one, since the interest is the calculation of synchronous torque in steady state condition. Therefore, only one pole pitch needs to be modeled.

Figure 8 illustrates the distribution of the flux density vectors in a cut plane, parallel to the $x0y$ plane of global co-ordinate system, which cuts the z-axis at z = 15 mm (shown in Fig. 7). This case is equivalent to the second 2D FE model (cross section).

Figure 9b shows the flux density vectors in another cut plane, which is normal to plane $x0y$ (shown in Fig. 9a). This is equivalent to the axisymmetric 2D simulation.

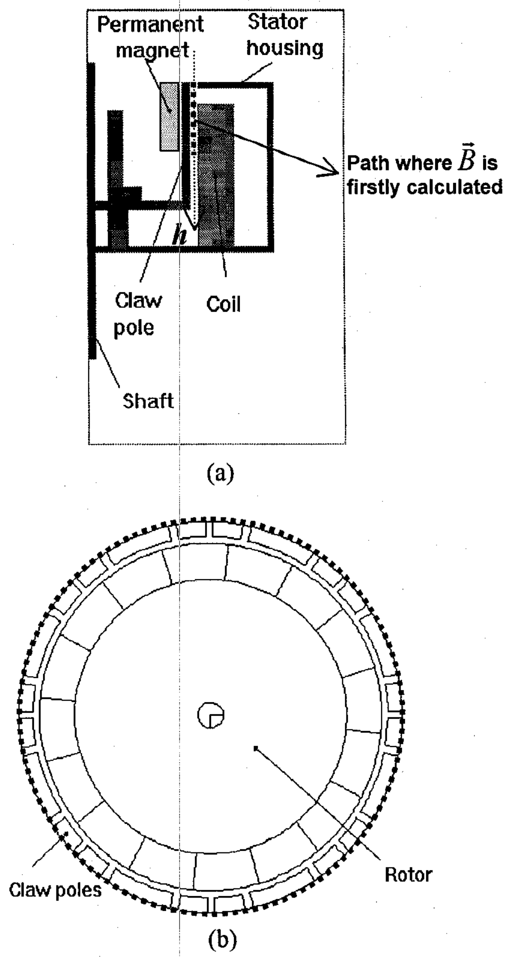

Fig. 3. Geometrical representations of the motor for the two 2D simulations: (a) axisymmetric geometry showing the path (dotted line) where the flux density was plotted; (b) cross-section geometry used in the calculation of torque. The dotted line is the one where a non-homogeneous Dirichlet boundary condition was imposed, whose value was determined in the previous axisymmetric simulation.

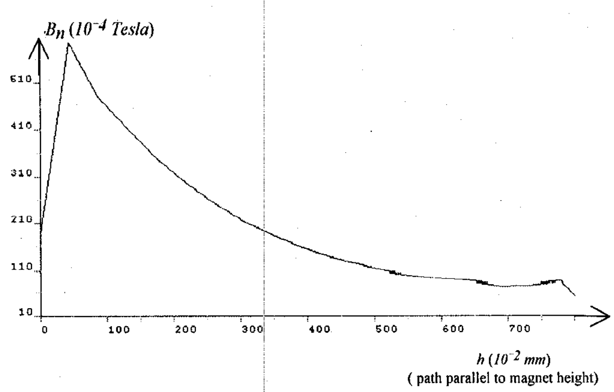

Fig. 4. Normal flux density plotted along the bold dashed line shown in Fig. 2.

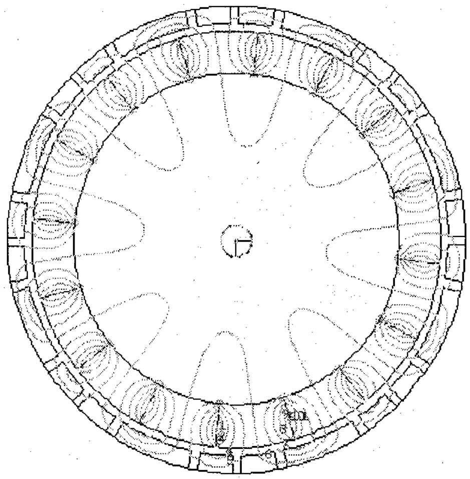

Fig. 5. Flux lines resulting from the second (planar) 2D simulation.

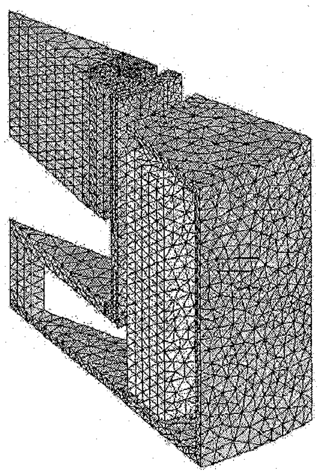

Fig. 6. Showing one pole pitch of the prototype machine with the 3D FE mesh.

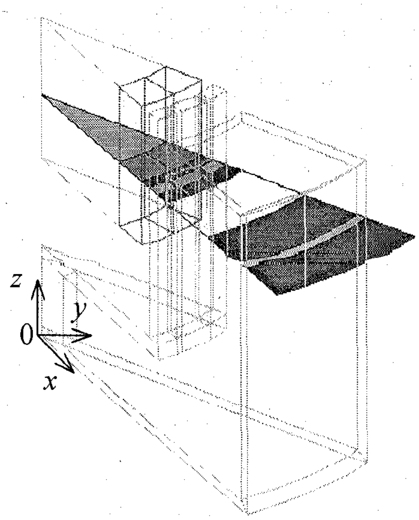

Fig. 7. A cut plane (parallel to $x0y$ plane of global co-ordinate system) in the 3D motor geometry.

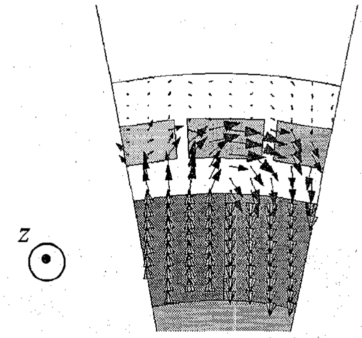

Fig. 8. Distribution of the flux density vectors in the cut plane shown in Fig. 7.

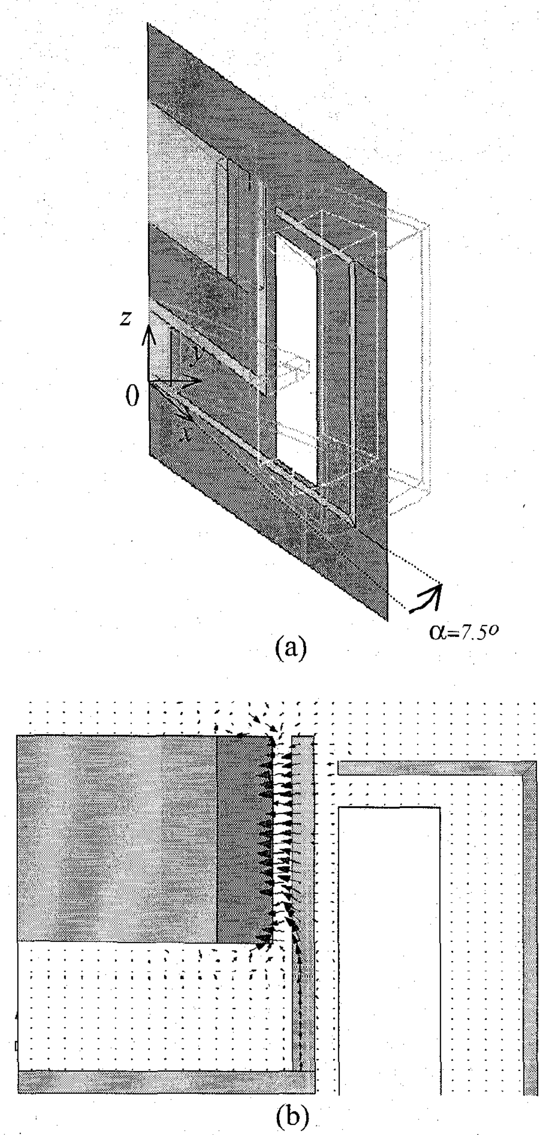

Fig. 9. (a) A radial cut plane (normal to $x0y$ plane of global co-ordinate system) in the 3D motor geometry; (b) distribution of the flux density vectors in this cut plane.

III. RESULTS

A curve of the reduction in torque when varying the air gap in the range 0.2 - 0.8 mm is plotted in Fig. 10, which exhibits a comparison between the values issued from the second 2D simulation and from experimental measurements.

The 3D simulation for an air-gap of 0.8 mm yielded a torque of 0.01277 kg.cm. The error is less than 8 % in comparison with 2D simulation and the tests in the prototype machine.

Table I shows the mesh data and CPU times. The great difference of total CPU time between the 2D and 3D simulations for nearly the same number of nodes can be noticed. This is because the 3D model leads to 3 times as many unknowns as the 2D model for the same number of nodes (3 components of magnetic vector potential in 3D versus 1 component in 2D).

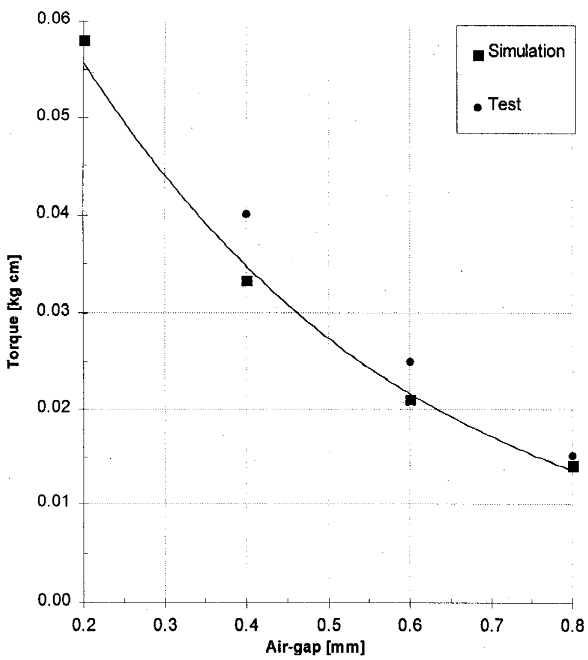

Fig. 10. Torque variation with air-gap length: 2D FE analysis and experimental results.

TABLE I
MESH DATA AND CPU TIME FOR THE 2D AND 3D FE SIMULATIONS

	2D (planar)	3D
Number of nodes	10.097	10.498
Number of elements	53.089	55.198
Number of non-linear iterations	5	10
Total CPU time [a]	15	140

[a] Computer used: IBM PC compatible Pentium 166 MHz - 64 MB RAM

IV. CONCLUSIONS

The study of a typical 3D problem, namely the determination of magnetic field distribution in SPMM exhibiting complex geometry, through two simplified 2D FE analyses has been proposed and reported. The design of the magnetic circuit and determination of synchronous torque was carried out with the aid of a 2D FE computer package and validated by 3D FE package. The accuracy of the results issued from the 2D approach has been verified by measurements in a prototype and proved to be sufficient, thereby avoiding the need of the costly 3D FE analysis.

APPENDIX

SPMM DIMENSIONAL DATA

Rated power	2.75 W
Rated voltage	220 V
Current	15 mA
Frequency	50 Hz
Based speed	375 rpm
Number of phases	1
STATOR	
Outer diameter	43 mm
Winding type	multi-layer
Number of coils	1
Phase resistance	7200 Ω
Self inductance	4.2 H
ROTOR	
Number of poles	16
Magnet outer diameter	21.5 mm
Magnet inner diameter	16.8 mm
Magnet height	8.6 mm
Magnet material	Sintered *Ba* ferrite
Air-gap length	0.2-0.8 mm

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