Analysis of Induction and Permanent Magnet Motors for Aerospace Applications Using Multiple Slices FE Technique and Pseudo-cooling Thermal Boundary Conditions

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Two original numerical techniques are developed for the finite element (FE) transient analysis of induction and permanent magnet motors operating in demanding aerospace applications. The first technique is the electromagnetic and thermal analysis weak coupling using a multiple slices 2D FE model. The advantage of the specific technique is the representation of complex actuator geometries including skewed magnets and winding ends, by using a low computational cost 2D model while taking into consideration temperature dependent material attributes. The second technique consists in the development of properly defined boundary conditions for the emulation of the cooling housing of actuators. Those boundary conditions are applied at the outer surface of the actuators in contact with the housing and eliminate the need of modeling complex 3D geometries of highly integrated actuator housings.

***Index Terms*—Aerospace industry, finite element methods, induction motors, permanent magnet motors.**

I. Introduction

POLITICAL, economical and environmental trends lead to the all electric aircraft concept and the corresponding elimination of high-pressure hydraulic lines [1]. As a result, electric actuators used in aerospace applications, work in excessive environmental conditions due to reduced thermal dissipation and extreme changes of loading conditions [2], [3]. The numerical analysis of such devices requires an elaborate coupled electromagnetic and thermal, 3D finite element (FE) transient analysis, due to the extreme loading conditions and the high integration of the actuators [4], [5].

This paper develops two original numerical techniques in order to reduce the complexity of the aforementioned problem and consequently reduce the computational cost. They were incorporated into a FE package developed by the authors and used for the coupled electromagnetic and thermal analysis of two actuators, a permanent magnet synchronous motor (PMSM) and an induction motor (IM), designed for demanding environmental conditions encountered in an aerospace application [2], [3].

II. Development of Numerical Techniques

A. Electromagnetic and thermal analysis weak coupling

The 3D FE transient thermal analysis is weakly coupled with a multiple slices 2D FE code for the evaluation of the thermal sources. In fact, the important difference of time constants between thermal and electromagnetic phenomena has been exploited in order to ensure updating of both copper conductivity and permanent magnet magnetization variation with temperature.

This is achieved by implementing an appropriate steady state 2D FE electromagnetic analysis for several actuator cross sections at every time step of the transient 3D FE thermal simulation. Moreover, the temperature variation of the thermal conductivity, and the temperature dependent characteristics of materials and losses were taken into consideration [6], [7].

B. Thermal boundary conditions application

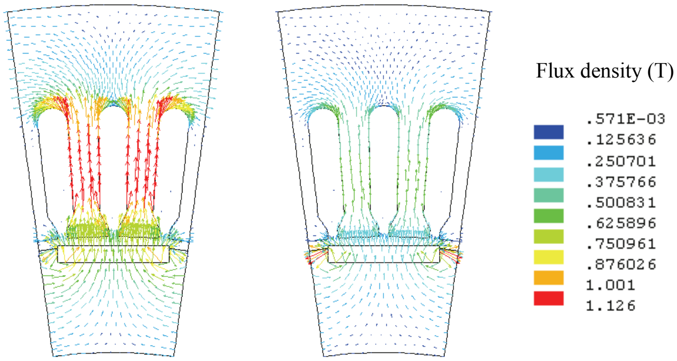
Due to the high integration of the actuator, the housing of the PMSM and IM has a complex and unsymmetrical geometry with no 2D or 3D symmetry. In order to emulate this housing a novel numerical method is developed [5]. The proposed method consists in the application of properly defined boundary conditions at the outer surface of the actuators in contact with the housing. The surface is partitioned into m areas each representing a different component of the actual housing e.g., a fin, or the area between two fins. At each area a different boundary condition is applied so that (1) is satisfied, where $q_i^{"}$ is the heat flux transfer per unit area of the i-th area, h_i is the convection coefficient of the i-th area, and $\overline{T}_{si}$ is the mean surface temperature of the i-th area. The first term of (1) must satisfy (2), where q is the heat transfer rate i.e., the sum of the actuators heat sources, and A is the sum of the m areas.

$$\sum_{i=1}^{m} q_i^{"} = \sum_{i=1}^{m} h_i \cdot \overline{T}_{si} \tag{1}$$

$$\sum_{i=1}^{m} q_i^{"} = q / A \tag{2}$$

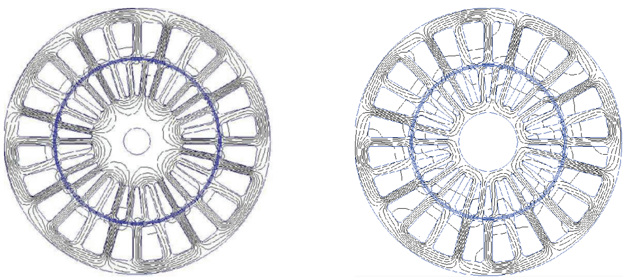
C. Short description of the FE package

The aforementioned techniques were integrated into a FE package assembled by the authors. For the storage of the FE matrices a modified Morse technique was used. The solution of the FE linear system is carried out by combining the specific assembly scheme and the conjugate gradient method with Van der Vorst preconditioning. A considerable reduction in mesh size of the actuators FE models was achieved by considering the copper wire, the air-varnish-epoxy composite, and the iron-laminated materials as homogeneous and anisotropic media at the level of finite elements [8].



(a) (b)

Fig. 1. Flux density distribution of the PMSM for different ambient temperatures. (a) 20 °C. (b) 140 °C.



(a) (b)

Fig. 2. Magnetic flux of the IM for different slipping frequencies and loading conditions. (a) $s \cdot f = 3$ Hz and 1.2 $N \cdot m$. (b) $s \cdot f = 15$ Hz and 6 $N \cdot m$.

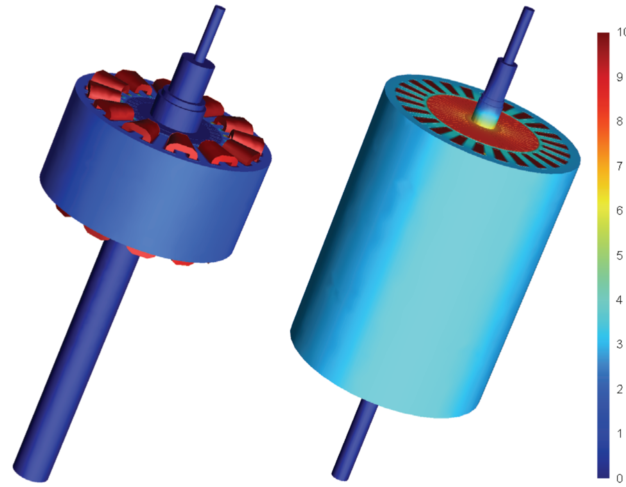
III. Results and Discussion

A. Prototype IM and PMSM actuators

An IM and a surface mounted PMSM were designed and optimized for two different modes of operation encountered in a demanding aerospace application [2]. Under normal mode of operation the torque and rotating speed are equal to 1.2 $N \cdot m$ and 180 rpm respectively. Under the extreme mode of operation, torque and rotating speed are equal to 6.0 $N \cdot m$ and 6,000 rpm respectively. High temperature, samarium cobalt permanent magnets were used for the PMSM. For the rotor bars of the IM the NEMA design class A was adopted.

B. 2D FE electromagnetic analysis

The steady state 2D FE electromagnetic analysis is employed in every step of the 3D FE transient thermal analysis in order to determine the thermal sources of the PMSM and IM models i.e., winding losses and iron losses. The temperature dependent demagnetization characteristics of the samarium cobalt permanent magnets of the PMSM were taken into consideration by using a set of demagnetization curves for various ambient temperatures and an appropriate interpolation scheme. Fig. 1 shows the flux density distribution of the PMSM for two different ambient temperatures. Fig. 2 shows the magnetic flux distribution of the IM for two different slip frequencies $s \cdot f$, and for the normal and extreme mode of operation encountered in the aerospace application under consideration.



(a) (b)

Fig. 3. Temperature distribution at 82.7 s. (a) PMSM. (b) IM.

C. 3D FE thermal analysis

A number of transient and steady state 3D FE thermal analyses for different material attributes and load characteristics of the PMSM and IM, were carried out using the FE package integrating the methodologies of Section II. Mesh sizes of $1.0 \cdot 10^6$ to $2.0 \cdot 10^7$ elements and a typical desktop PC were used for the analyses. Fig. 3 shows the temperature distribution of the PMSM and IM under the extreme mode of operation for an intermediate step of the transient analysis.

IV. Acknowledgment

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