Application of the magneto-mechanical coupling to the prediction of deformation of non-oriented FeSi based transformers.

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***Abstract*— This paper deals with the prediction of deformation of the sheets of a 3 phases transformer made of non-oriented iron-silicon based alloy. Magnetic and magnetostrictive behavior of the material is first carried out thanks to a single sheet frame and strain gauges. The material exhibits an anisotropic behavior, demonstrating the necessity to use an anisotropic constitutive model for the behavior of the FeSi alloy. A Multi Scale Model (MSM) describing both magnetic and magnetostrictive anisotropies is implemented in the numerical process leading to accurate mechanical and magnetic simulations.**

***Index Terms*—Magnetostriction, transformers, predictive model, iron alloys, finite element methods.**

I. INTRODUCTION

The aeronautic world is undergoing deep changes which can be seen through the increase of electrical based equipment onboard airplanes. To power these systems, the electrical power, supplied by the generators plugged to the turbojet, has to be increased. In order to feed the on-board equipment, this power is adapted through a transformer. Therefore the increase of the electrical consumption leads to an increase of the size and mass of these devices. One way to reduce the mass is the use of materials presenting a higher power density (e.g. iron-cobalt). Such transformers generate unfortunately a loud noise in operation caused by periodic deformations of all sheet metal. This strain has two origins: - elastic deformation associated to magnetic forces appearing on the free surface and volume. Their effect is negligible considering the given geometry of transformers in the present study - spontaneous magnetostriction $\underline{\underline{\varepsilon}}^{\mu}$ depending on the local magnetic state of the material. Magnetostriction strain and magnetization can be linked by a constitutive equation. This strain is an effect of the discretization in space of the material in magnetic domains that subdivide each grain of a polycrystal, with magnetization equal to $\underline{M}_s$ (magnetization at saturation) and magnetostriction $\underline{\underline{\varepsilon}}^{\mu m}$. Magnetic domains are on the other hand separated by magnetic walls [1]-[2].When a magnetic field $\underline{H}$ is applied, the domain's walls move, increasing the volume fraction of the domains aligned with the field $\underline{H}$. Thus a deformation appears at the macroscopic scale which tends to reach the free strain $\underline{\underline{\varepsilon}}^{\mu m}$ of the considered domain [3]. The crystallographic texture defining the initial distribution of domains, has a strong impact on the magnetostrictive behavior. The purpose of the work is to obtain a complete chain from the material parameters characterization to the prediction of the transformer's deformation in the aim of the optimization of the material and the design to reduce the noise emissions.

II. STRATEGY

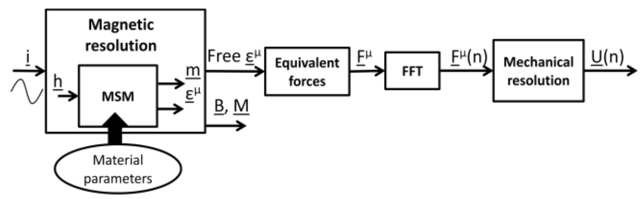

Figure 1: Diagram of the resolution's strategy

In order to model the deformation of a transformer, several steps are needed, summed up fig 1. At first we need a magnetostrictive model with a constitutive equation complex enough to take into account the anisotropies due to the crystallographic texture. These data are gathered by conducting experimentations on sheet samples. Then a numerical model of the geometry, 2D then 3D, is required to simulate one or several sheets. The resolution of the magnetic problem is done under quasi-static assumptions. Each of the 3 coils are fed by a delayed sinusoidal current loading. The magnetization field being known, the free magnetostriction strain field is calculated for each node thanks to the previously mentioned constitutive equation, leading to an « equivalent stress field ». The resolution is done for each time step for a whole period of excitation. A discrete Fourier transformation of the forces at each node is performed, providing, for each node of the mesh, the module and the phase for each harmonic. This way the study of the deformation of the transformer for each harmonic is possible, especially the one corresponding to the resonance of the structure.

III. MATERIAL CHARACTERIZATION

The studied material is a 0.2mm thick non-oriented (NO) FeSi. 3 samples are cut following the Rolling Direction (RD-0 deg), the Transverse Direction (TD – 90 deg) and a direction at 45° from RD (45 deg). Each sample is equipped with a secondary coiling (B-coil) and bidirectional strain gauges (longitudinal and transverse deformation) glued on both faces for averaging. A primary coil is positioned around the sample that generates the magnetic field. Two U-shaped yokes are added to close the magnetic track. Anhysteretic experiments are conducted by performing a demagnetization around a given magnetic H and measuring the associated magnetization and deformation of a single sheet of material.

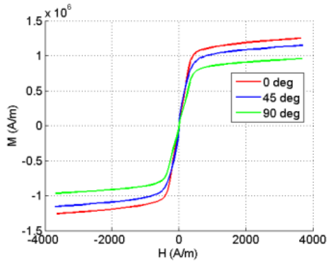

Figure 2: Anisotropy of the magnetic behavior

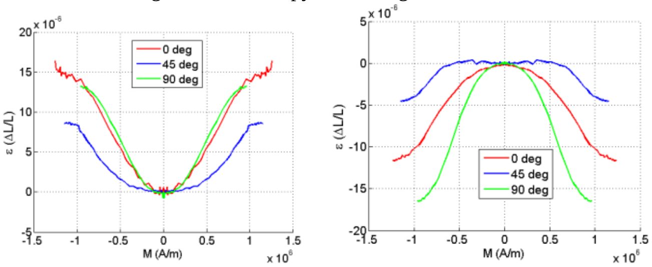

Figure 3: Magnetostrictive anhysteretic behavior parallel to $\underline{H}$ (a) and perpendicular to $\underline{H}$ (b)

Results obtained are plotted in fig 2 & 3. They reveal a strong anisotropy of the FeSi. ΔM/M is about 20% after the magnetization knee. The strongest anisotropy is observed for magnetostriction: Δε/ε reaches 50% for measurements carried out in the direction of the applied field and more than 400% along the direction perpendicular to the applied field. This behavior can be explained by the huge grain size of the material (150µm) comparing to the thickness (200µm) leading to crystallographic texture and surface effect [3]. This point will be detailed in the full paper. Results confirm the need to use an anisotropic model to be implemented in numerical model.

IV. Transformer Geometry and Coupling Model

The geometry used is a simplification of the design of an industrial FeSi-based transformer fig 4(a). At each step, an homogeneous current of $I_{max} \times \sin\left(\frac{2\pi t}{T} + \psi\right)(A)$ where T is the period of the current, t the time of the considered step and ψ is the phase shift (equal to 0, $\frac{2\pi}{3}$ or $\frac{4\pi}{3}$, depending on the coil). Current density and magnetic field are linked by eq. (1).

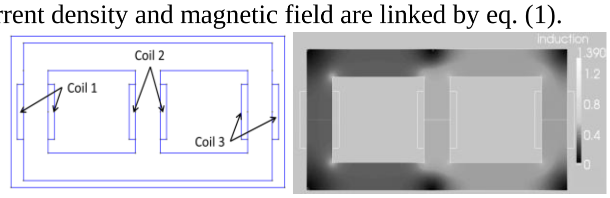

Figure 4: (a) geometrical model of the transformer; (b) norm of magnetic induction

The coupling between mechanical and magnetic problems is considered through the magnetostriction which is considered as a loading of the mechanical problem. Resolution is consequently sequential: magnetic resolution followed by mechanical resolution.

$$\underline{rot}(\underline{H}) = \underline{J} \qquad (1)$$

The magnetic problem is solved with the magnetic vector potential $\underline{A}$, defined by $\underline{B} = \underline{\mathrm{rot}}(\underline{A})$. An iterative resolution process (fixed point method [4]) is required, due to the non-linearity of the magnetic behavior. The constitutive equation is given thanks to a Multi-Scale Model (MSM) [5], where domain scale is considered. The local potential energy of domains is calculated regarding the applied field and magnetocrystalline constants to obtain a probability of existence of a domain. The macroscopic magnetization $\underline{M}$ and the free magnetostriction strain $\underline{\underline{\varepsilon}}^{\mu}$ are obtained through an averaging operation over all the directions [6]. Details about this modeling will be given in the full paper.

Next, a field of equivalent forces $\vec{f_v}$ (2) is calculate to obtain, at each node of a finite element problem, a force profile over the time as illustrated in fig 5:

$$\underline{f_v}^{\mu}{}_{v} = -\underline{div}\left(\boldsymbol{C}.\underline{\underline{\varepsilon}}^{\mu}\right) \qquad (2)$$

where $\boldsymbol{C}$ is the stiffness tensor of the material

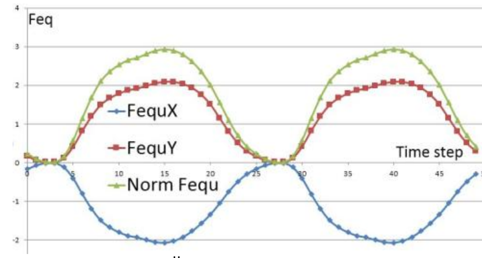

Figure 5: History of F^{μ}_{equ} at one node over one period of current

Once the mechanical problem is solved a FFT of volumetric forces is performed on the whole mesh. That allows calculation of the module and phase of the forces, for each harmonic, at each node. The volumetric force $\vec{f_v}$ leads to an admissible displacement field $\underline{u}$ when the mechanical problem (3) is solved (ρ_m: material density).

$$\underline{\mathrm{div}}\left(\underline{\underline{\sigma}}\right) = \rho_m \frac{\partial^2 \underline{u}}{\partial t^2} \qquad (3)$$

The mechanical behavior is considered elastic, isotropic and homogeneous. Extension to anisotropy is in progress. Fig. 6 gives an example of deformation field at a chosen time in the period of the 2nd harmonic (100Hz).

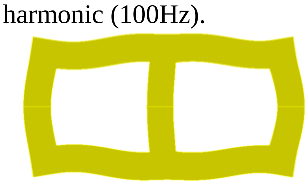
Figure 6: Deformation of the transformer at a chosen time in the period, 2nd harmonic (100Hz).

V. Conclusion

This model, taking into account the anisotropy of the material, allows the calculation of the 2D deformation field of an electrical transformer. Such study shows a feasibility of the optimization of the transformer design in order to reduce the strain level and consequently noise level. A final coupling between strain field and acoustic noise is still missing at this step.

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