Calculating Magnetostriction Forces in Induction Machines using Finite Elements

Koen Delaere, Ward Heylen*, Kay Hameyer and Ronnie Belmans
Katholieke Universiteit Leuven
Electrical Engineering Dept. ESAT-ELEN, Kardinaal Mercierlaan 94, B-3000 Leuven, Belgium
*Mechanics Dept. PMA, Celestijnenlaan 200C, B-3000 Leuven, Belgium

Résumé - Magnétostriction dans le fer magnétique des machines électriques cause une déformation du stateur et une radiation de bruit. Si on connaît le caractéristique du matériel λ(B) (élongation magnétostrictive en fonction de densité de flux), la distribution de la contrainte peut être représentée par une distribution équivalente de forces, en employant la matrice de rigidité du stateur. Ainsi les forces magnétostrictives, les forces de réluctance et d'autres forces externes peuvent être sommées pour obtenir la déformation totale du stateur. Cette méthode est démontrée en calculant les forces magnétostrictives dans le stateur d'un moteur d'induction de 45 kW.

Abstract - Magnetostriction of the stator iron yoke causes stator deformation leading to vibrations and noise. When the material behaviour λ(B) is known (magnetostrictive strain as a function of flux density), the strain distribution can be represented by an equivalent force distribution using the mechanical stiffness matrix of the stator. This way, magnetostriction, reluctance and other external forces can be summed to obtain the total stator deformation. As an example, the magnetostriction forces in the stator of a 45kW induction machine are computed.

I. Introduction: Magnetostriction

The deformation caused by magnetostriction (MS) can contribute significantly to the vibrations and noise of electric machinery. The incorporation of the magnetostrictive effect in the (numerical) design process is usually impaired because detailed data on the material behaviour are hard to obtain. Versatile experimental methods to obtain all needed technical data on MS effects, permeability, losses, etc. are reviewed in [1]. Once the MS behaviour of the material has been determined, it has to be incorporated in the magnetic and mechanical finite element analysis. Here it is illustrated how to take the magnetostrictive strain into account using a simple cascade procedure. The $\lambda(B)$ characteristic is assumed to be known, i.e. magnetostrictive strain λ as a function of magnetic flux density B.

II. Coupled Magneto-Mechanical Analysis

The coupling between the magnetic finite element (FE) model and the mechanical FE model is usually effected using a weak coupling, because the stator deformation occurring is very small (about 10 micron). In a cascade approach, first the magnetic problem is solved. The reluctance forces and magnetostrictive strain acting on the stator are found by post-processing the magnetic solution. By *magnetisation forces* we indicate the set of forces that induces the same strain in the material as the magnetostriction effect does. This approach is similar to the use of "thermal stresses" due to heating [2].

When all relevant forces have been determined, the mechanical problem is solved, giving the static stator deformation, a time-harmonic vibration [3] or the full vibration spectrum [4].

III. Magnetostriction Forces

The finite element method is used to solve for the magnetic field inside the induction machine (Fig.1), giving the flux density vector **B** for every element. Then, element by element, the following steps are taken to obtain MS forces:

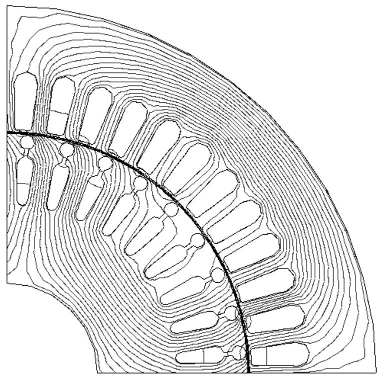

Fig.1: Quarter model of induction machine: flux pattern at time t=0s for rotor position α=0°.

1. The strain λ^e in the element is determined using the flux density B in the element. Fig.2 shows a typical magnetostrictive strain versus flux density material characteristic $\lambda(B)$ for yoke material for a tensile stress of 1 N/mm^2.

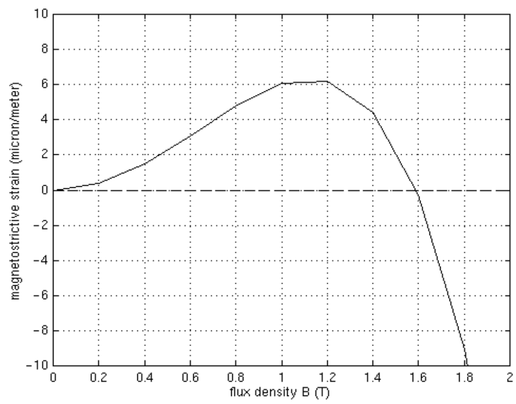

Fig.2: Typical magnetostrictive material characteristic: strain versus flux density $\lambda(B)$ for 3% Si Fe, non-oriented (tensile stress 1 N/mm^2).

The strain λ given in Fig.2 is the strain in the direction of the flux density vector **B**. The strain in the perpendicular direction is $\lambda_t = -\lambda/2$ [5]. This is equivalent to a magnetostrictive 'Poisson modulus' of 0.5, which is bigger than the mechanical Poisson modulus of 0.3. Therefore, when the MS deformation is represented by a set of mechanical forces in the direction of the vector **B**, there always is a set of forces *perpendicular* to **B** to correct this difference in Poisson modulus (Fig.3).

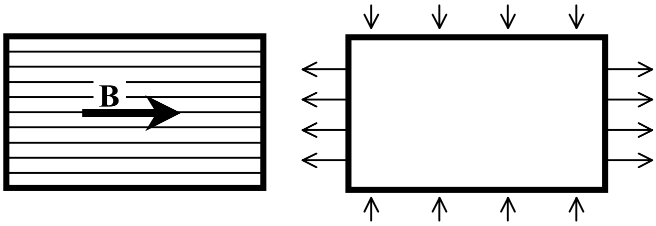

Fig.3: Set of forces (right) representing the strain caused by magnetostriction due to the magnetic field **B** (left), consists of a set parallel and a set perpendicular to the flux vector.

2. The strains λ^e and λ^e_t are converted into three nodal displacements $(a_{x,i}, a_{y,i})$, i=1,2,3, while considering the element midpoint (x^e_m, y^e_m) as fixed:

$$\begin{bmatrix} a_{x,i} \\ a_{y,i} \end{bmatrix} = \begin{bmatrix} x_i - x^e_m \\ y_i - y^e_m \end{bmatrix} \begin{bmatrix} \lambda^e \\ \lambda^e_t \end{bmatrix}, \; i=1,2,3 \qquad (1)$$

with (x_i, y_i) the co-ordinate of node i. The strains λ^e and λ^e_t have to be applied in a local set of axis, so that the vector **B** coincides with the local x-axis. The three sets of $(a_{x,i}, a_{y,i})$ are then transformed back into the element's MS displacement a^e_{ms} in the global xy-axis.

3. For static problems, the mechanical element stiffness matrix K^e is constructed and multiplied with the MS displacement a^e_{ms}, yielding the *magnetostriction forces* $F^e_{ms} = K^e a^e_{ms}$ on the three element nodes. For vibration problems with fixed angular frequency ω (time-harmonic), also the mass matrix M^e is constructed and the equivalent MS forces are found using $F^e_{ms}=(-\omega^2 M^e+K^e)a^e_{ms}$ (damping is neglected).

This three-step procedure is performed element by element; it cannot be done for the whole mesh at once, because the displacements a^e_{ms} due to the different elements surrounding a node, *cannot* be summed. The resulting nodal forces F^e_{ms} however, *can* be added. As a result, the distribution of magnetostriction forces F_{ms} is obtained.

Fig.4 shows the (static) F_{ms} distribution in the yoke of the induction motor, for the magnetic field shown in Fig.1. The yoke wants to increase its circumference. The perpendicular forces on the outer stator surface are pointing inwards and the perpendicular forces at the slot ends are pointing outwards in order to help the circumference increase. The forces at the tip of the teeth are inaccurate due to the large local field values (discretization error).

The MS forces can now be added to any external or reluctance forces to give the total force distribution acting on the stator, which can be readily used for deformation or vibration calculation.

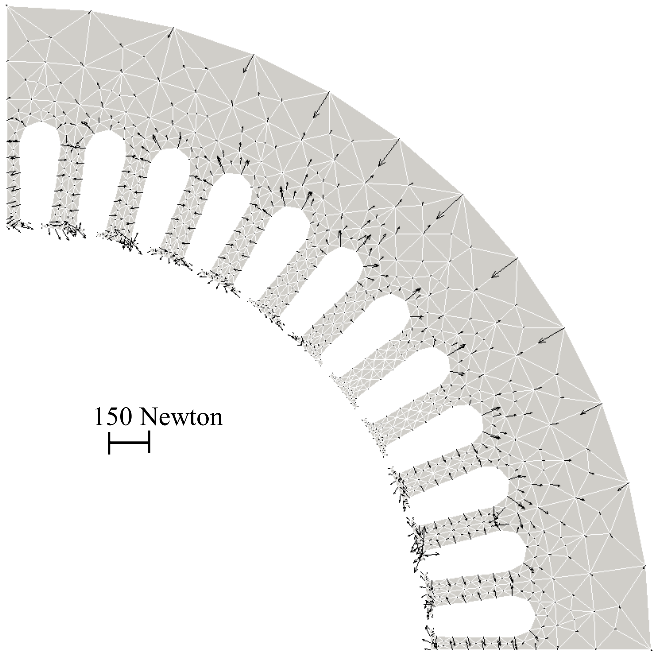

Fig.4: Nodal force distribution caused by magnetostriction in the 3% Si Fe iron yoke of the induction machine stator.

IV. Conclusion

The magnetostrictive strains are represented by a set of forces that induce mechanical strains and deformation of the same size as those caused by magnetostriction. Using the finite element method, the magnetostriction forces are obtained as a nodal force distribution on the finite element mesh. These forces can be used for further deformation or vibration analysis.

Acknowledgement

The authors are grateful to the Belgian "Fonds voor Wetenschappelijk Onderzoek Vlaanderen" and the "Vlaamse Wetenschappelijke Stichting" for their financial support; Koen Delaere has a FWO-V scholarship. The authors thank the Belgian Ministry of Scientific Research for granting the IUAP No.P4/20 on Coupled Problems in Electromagnetic Systems. The research Council of the K.U.Leuven supports the basic numerical research. Special thanks to R.Mertens for his valuable help in preparing the FE models.

References

[1] Pfützner H., "Rotational magnetization - an effective source of numerical data on multidirectional permeability, losses and magneto–striction of soft magnetic materials," Xth Int. Symposium on Theoretical Electrical Eng., Magdeburg, Germany, Sept. 1999, pp.377-383.

[2] B.D.Cullity, *Introduction to Magnetic Materials*, Addison-Wesley (Series in Metallurgy and Materials) Philippines 1972.

[3] L.Meirovich, *Computational Methods in Structural Dynamics*, Sijthoff & Noordhoff, Alphen aan den Rijn 1980.

[4] K.Delaere, A.Tenhunen, W.Heylen, R.Belmans, K.Hameyer, "Predicting the stator vibration spectrum of induction machines under normal operation," International Congress and Exposition on Noise Control Engineering INTERNOISE'99, Fort Lauderdale, Florida, USA, 6-8 December 1999.

[5] D.Jiles, *Introduction to Magnetism and Magnetic Materials*, Chapman & Hall 1991.