Comparison of induction machine stator vibration spectra induced by reluctance forces and magnetostriction

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Abstract — **For electric rotating machines, the reluctance forces (Maxwell stresses) acting on the stator teeth are a major cause of noise emission. Next to the reluctance forces, magnetostriction is a potential cause of additional noise from electric machinery. This paper presents the computation and comparison of the stator vibration spectra caused by these two effects separately, by example of an induction machine. Moreover, two kinds of material magnetostriction are compared: a quadratic λ(*B*) curve and a λ(*B*) curve with zero-crossing around 1.5 Tesla.**

INTRODUCTION

Noise and vibration research has been focussing on reluctance forces (Maxwell stresses) as the major cause of noise and vibrations in rotating electric machinery. While for non-rotating machinery (transformers, inductors), magnetostriction is the major cause of noise, even for induction machines, magnetostriction can be responsible for a considerable part of the machine's noise [1]. The simulation of vibration spectra induced by reluctance forces has been investigated extensively using finite element models, e.g. [2][3], while the simulation of magnetostriction effects has been left aside since it is difficult to embed this material behaviour in finite element software. However, finite element methods to capture the magnetostrictive deformation have been presented earlier and are used in this paper to estimate, for a 45 kW induction machine:

1. the relative importance of reluctance forces and magnetostriction with respect to stator deformation,
2. the impact of using materials with different magnetostrictive behaviour.

The isotropic magnetostriction curve

$$\lambda = 10^{-6}\ B^2 , \tag{1}$$

will be referred to as *magnetostriction type 1* and the isotropic curve with zero-crossing around 1.5 Tesla

$$\lambda = 10^{-6}\ (B^2 - 2(\frac{B}{1.5})^4) , \tag{2}$$

will be referred to as *magnetostriction type 2*.

RELUCTANCE FORCES

The total energy E of a magnetomechanical system is the sum of the elastic energy U and the magnetic energy W:

$$E = U + W = \frac{1}{2} a^{\mathrm{T}} K a + \frac{1}{2} A^{\mathrm{T}} M A , \tag{3}$$

where K is the mechanical stiffness matrix, M is the magnetic 'stiffness' matrix, $a=[u\ v]^{\mathrm{T}}$ is mechanical 2D displacement and A is the z-component of magnetic vector potential. The reluctance force is given by

$$F_{mag} = -\frac{\partial W(A,a)}{\partial a} = -\int_0^A A^{\mathrm{T}} \frac{\partial M(A,a)}{\partial a} dA , \tag{4}$$

for nonlinear magnetic systems [4]. Applying (2) to every node of the magnetic mesh results in the reluctance force distribution F_{rel}.

MAGNETOSTRICTION FORCES

The deformation caused by magnetostriction can be represented by a set of magnetostriction forces F_{ms}. By *magnetostriction forces* we indicate the set of forces that induces the same strain in the material as magnetostriction does. This approach is similar to how thermal stresses are usually taken into account. To evaluate thermal stresses, the thermal expansion of the free body (no boundary conditions) is calculated based upon the temperature distribution, and then the thermal stresses are found by deforming the expanded body back into its original shape (back inside the original boundary conditions). To calculate magnetostriction forces, the expansion of the free body due to magnetostriction is found based upon the magnetic flux density and the material's λ(*B*) curve, and the magnetostriction forces are found as the reaction to the forces needed to deform the expanded body back into the original boundary conditions. For finite element models, this is performed element by element. The magnetostrictive deformation a^e_{ms} of the element is found using the element's flux density B^e and the λ(*B*) characteristic of the material, as is explained in detail in [5]. The element's mechanical stiffness matrix K^e allows us to convert the magnetostrictive displacements a^e_{ms} into a set of forces using $F^e_{ms} = K^e a^e_{ms}$. This procedure is performed for every element and as a result, the distribution of magnetostriction forces F_{ms} is obtained.

MODAL DECOMPOSITION

Using the 2D mechanical stiffness matrix K and mass matrix M_m, the undamped 2D stator mode shapes are found. The modes are calculated taking mass and stiffness of both the yoke iron and the stator coil copper into account. For a given force pattern f^{α} (in this case F_{rel} or F_{ms}) occurring for

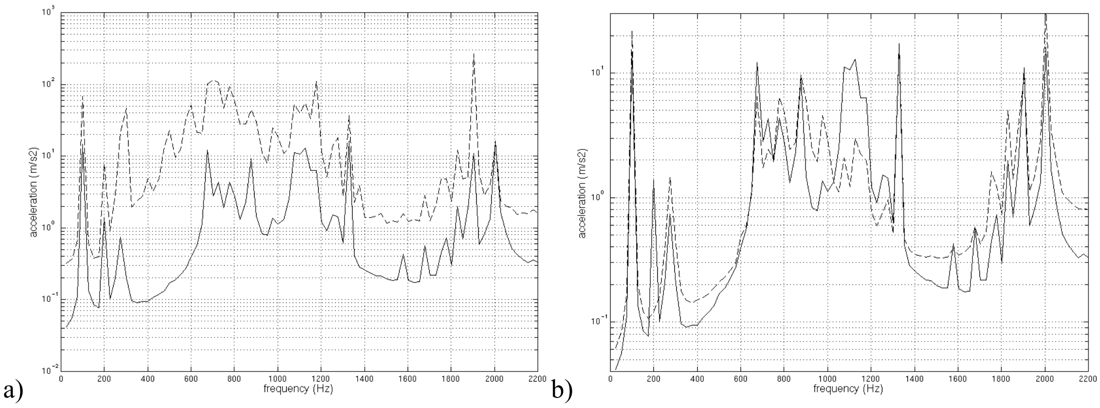

Fig.1 Stator acceleration spectra induced by a) reluctance forces (dotted line) and magnetostriction type 2 (solid line), and b) magnetostriction type 1 (dotted line) and magnetostriction type 2 (solid line).

rotor position α, and a given mode shape ϕ_i, the mode participation factor (MPF) Γ_i^{α} is defined as

$$\Gamma_i^{\alpha} = \frac{\phi_i^T f^{\alpha}}{\phi_i^T M_m \phi_i} . \qquad (5)$$

For a slip s, the period of the MPF can be approximated by 90º/(1–s)=88.66º or a multiple of this [3]. Here, the period of the MPF is approximated by 360º/(1–s)=354.6º and the MPF are sampled using 180 rotor positions at 2° intervals.

The vibration of the stator is governed by

$$M_m \ddot{u} + C_m \dot{u} + Ku = f(t) , \qquad (6)$$

where $u(t)$ is the nodal displacement and $f(t)$ is the force distribution acting on the stator, $f(t)= f^{\alpha}$. M_m, C_m and K are the mechanical mass, damping and stiffness matrices. Neglecting damping and using the modal decomposition $u = Pq$ with P the modal matrix containing a selected set of N=30 stator mode shapes and q the vector of generalised modal co-ordinates, (6) is transformed into

$$\ddot{q}_i + \omega_i^2 q_i = \Gamma_i(t) , \; i = 1..N, \qquad (7)$$

where ω_i is the mode's eigenfrequency. Note that the modal decomposition indeed transforms the force $f(t)$ into the MPF Γ_i(t), i = 1..30, as prescribed by (5). From (5), the MPF are known as a function of rotor position, and the rotor speed n allows us to find the MPF as a function of time. The individual modal equations are solved in the frequency domain by applying a discrete Fourier transformation to (7):

$$Q_i(k\Delta\omega) = \frac{\Gamma_i(k\Delta\omega)}{\omega_i^2 - (k\Delta\omega)^2} . \qquad (8)$$

The spectrum Q_i of all mode shapes of interest can be found in this way. The separate complex spectra Q_i of the N relevant modes are composed back into the actual stator displacement and acceleration spectra using the modal composition $u = Pq$.

EXAMPLE

These procedures were used to compute the reluctance and magnetostriction force distributions acting on the stator of a 45 kW induction machine. Fig.1 compares the three spectra obtained for the reluctance forces and for the two types of magnetostriction. In the full paper, results for anisotropic magnetostriction will also be presented.

CONCLUSION

Using a thermal stress analogy, a set of magnetostriction forces is computed that induces the same strain in the material as magnetostriction does. This force distribution is compared to the reluctance force distribution with respect to the resulting stator vibration spectrum. Different kinds of magnetostriction are also investigated. For this induction machine, the noise and vibration effect due to magnetostriction is considerably smaller than the effect due to the reluctance forces.

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REFERENCES

[1] L. Låftman, *The contribution to noise from magnetostriction and PWM inverter in an induction machine*, Ph.D. thesis, Dept. Industrial Electrical Eng. and Automation, Lund Inst. of Techn., KF Sigma, Sweden 1995.

[2] C.G.C.Neves, R.Carlson, N.Sadowski, J.P.A.Bastos, N.S.Soeiro, S.N.Y.Gerges, "Experimental and numerical analysis of induction motor vibrations," *CEFC 1998*, Tucson, USA.

[3] K.Delaere, A.Tenhunen, W.Heylen, K.Hameyer, R.Belmans, "Predicting the stator vibration spectrum of induction machines under normal operation," *INTERNOISE 1999*, Fort Lauderdale, Florida, USA, 1999.

[4] J.L.Coulomb, G.Meunier, "Finite element implementation of virtual work principle for magnetic or electric force or torque computation", *IEEE Transactions on Magnetics,* Vol 20 no,5, pp.1894-1896, 1984.

[5] K.Delaere, W.Heylen, R.Belmans, K.Hameyer, "Weak magnetomechanical coupling using local magnetostriction forces", 2nd International Seminar on Vibrations and Acoustic Noise of Electric Machines VANEM, Lodz, Poland, June 1-3, 2000, pp.33-38.