Analysis and Tests of Electromagnetic Vibration of a Motor Core Including Magnetostriction under Different Rotation Speed

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This paper presents a generalized magneto-elastic 3D finite element model, which can be used to numerical calculate the magnetic field and structural vibration of laminated cores including magnetostrictive effect. Magnetostriction is a property of electrical steel and an important cause next to electromagnetism forces of the electromagnetic vibration for motor cores. The rotating speed of motor also has an influence on the vibration. Considering the magnetostriction and rotation effects, the vibration of a permanent magnetic synchronous motor core is analyzed by the proposed model and measured under different rotation speed. The analysis results show that the vibration due to magnetostriction is significant and the magnitude of vibration is related with the operating speed, which is agreement with the measurement results.

***Index Terms*—Electromagnetic coupling, magnetostriction, numerical model, rotation speed, Electromagnetic fields**

I. Introduction

THE reduction of vibration and noise from motor cores is increasing crucial for its prosperous application, especially in home applications and navy vessels. Magnetostriction (MS) is a property of electrical steel in which the material will exhibit strain in the presence of magnetic field and previous researches [1,2] shown MS is another cause next to reluctance forces of the vibration and noise for motor laminated cores.

This paper presents a 3D numerical model including MS effects to analyze the deformation of motor core. Then the deformation of motor core is analyzed by finite element method under different rotation speed, which performed by adjusting supply frequency. To be consistent with the analysis model, a motor contains only fixed and rotor which is designed and processed. The deformations of different core positions are measured by acceleration instruments to verify the model, while a rotation speed tester is used at the same time. The numerical model and the analysis are useful to study the vibration of motor cores in the design stage.

II. Numerical Model

Magnetostriction is the intrinsic characteristics of laminated core and is dependent on the magnetic induction. To analyze the vibration of the motor including MS effects, the MS strains are obtained by MS measurements on the no orientation (N.O.) silicon sheet sample of the core steel material in a test set up, and the MS curves can be seen in [2].

Experimental measurement results showed that the MS behavior of silicon steel materials is non-linear, considering only the variations around the initial bias state, the material behaves in a quasi-linear manner and follows piezomagnetic laws, rewritten as:

$$\begin{cases} \varepsilon_i = s_{ij}^H \sigma_j + d_{ni} H_n & i, j = 1,\dots 6 \\ B_m = d_{mj}\sigma_j + \mu_{mn}^{\sigma} H_n & m, n = 1,\dots 3 \end{cases} \tag{1}$$

where s^H ,$\boldsymbol{d}$, μ^σ are the tensors matrix of constant-H compliance, MS coefficients and constant-σ permeabilities, ε and σ, the tensors of strain and stress, $\boldsymbol{B}$ and $\boldsymbol{H}$, the vectors of magnetic flux density and magnetic field, respectively.

Based on finite element method, the total energy functional of the motor cores can be expressed as follows:

$$\begin{aligned} I = &\int_{\Omega_2}\left(\frac{1}{2}\boldsymbol{\sigma}^T \boldsymbol{s}^H \boldsymbol{\sigma}\right)dV + \int_{\Omega_2}\left(\boldsymbol{\sigma}^T \boldsymbol{dH}\right)dV + \int_{\Omega_1}\left(\frac{1}{2}\boldsymbol{H}^T \boldsymbol{\mu}^\sigma \boldsymbol{H}\right)dV \\ &-\int_{\Omega_1}\boldsymbol{J}\cdot \boldsymbol{A}dV - \int_{\Gamma_1}\boldsymbol{f}_\Gamma \cdot \boldsymbol{u}dV - \int_{\Omega_2}\boldsymbol{f}_V\cdot \boldsymbol{u}dV \end{aligned} \tag{2}$$

where $\boldsymbol{A}$ is the magnetic vector potential, and $\boldsymbol{B} = \nabla \times \boldsymbol{A}$, $\boldsymbol{u}$, the mechanical displacement, $\boldsymbol{\varepsilon}$ and $\boldsymbol{\sigma}$, the vector of strain and stress, and $\boldsymbol{d}$, the MS coefficient matrix.

MS coefficient matrix d, in whic d_{11}, d_{22} can be obtained from measured MS characteristic curves $\lambda_x(B_x)$ and $\lambda_y(B_y)$[2]. If shearing strains of the steel lamination is neglected, there is d_{ij}=0 (i=4,5,6, j=1,2,3). The MS coefficient in the normal direction is assumed as $d_{33}=(d_{11}+d_{22})/2$. Using the Hooker's law, we can get $d_{21}=d_{31}=-\alpha d_{11}$, $d_{12}=d_{32}=-\alpha d_{22}$, $d_{13}=d_{23}=-\alpha d_{33}$, where α is the Poisson ratio. So the magneto-mechanical coupling energy is given by

$$\int_{\Omega_2}\boldsymbol{\sigma}^{\mathrm{T}}\boldsymbol{dH}\mathrm{d}V =$$

$$E^\alpha \int_{\Omega_2} \begin{pmatrix} (1-\alpha)\varepsilon_x + \alpha\varepsilon_y + \alpha\varepsilon_z \\ \alpha\varepsilon_x + (1-\alpha)\varepsilon_y + \alpha\varepsilon_z \\ \alpha\varepsilon_x + \alpha\varepsilon_y + (1-\alpha)\varepsilon_z \\ (1-2\alpha)\gamma_{xy}/2 \\ (1-2\alpha)\gamma_{yz}/2 \\ (1-2\alpha)\gamma_{zx}/2 \end{pmatrix}^{\mathrm{T}} \begin{pmatrix} 1 & -\alpha & -\alpha \\ -\alpha & 1 & -\alpha \\ -\alpha & -\alpha & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} d_{11}H_x \\ d_{22}H_y \\ d_{33}H_z \end{pmatrix}^{\mathrm{T}} \mathrm{d}V \tag{3}$$

$$= E\int_{\Omega_2}\left(d_{11}\upsilon_x B_x \varepsilon_x + d_{22}\upsilon_y B_y \varepsilon + d_{33}\upsilon_z B_z \varepsilon_z\right)\mathrm{d}x\mathrm{d}y\mathrm{d}z$$

where, $E^\alpha = \dfrac{E(1-\alpha)}{(1+\alpha)(1-2\alpha)}$, and E is the Young's modulus of the cores.

Permeability is anisotropic due to **B** and **H** is no longer consistent for the rotation of the motor, and the reluctivity tensor are given in as[1,2]:

$$\left.\begin{aligned} \nu_x &= \nu_{xx}\cos\theta_{ph}\cos\theta_B - \nu_{yy}\sin\theta_{ph}\sin\theta_B \\ \nu_y &= -\nu_{xx}\sin\theta_{ph}\sin\theta_B + \nu_{yy}\cos\theta_{ph}\cos\theta_B \end{aligned}\right\} \tag{4}$$

where θ_{ph} is the angle between **B** and **H**, θ_B is the angle between **B** and the rolling direction. And υ_{xx}, υ_{yy}, the reluctivity, can be obtain from measured magnetization curves $B_x(H_x)$ and $B_y(H_y)$ by interpolation. And $\upsilon_z = 1$, because the core is laminated by sheets which coated by insulating layer.

Then we can get the matrix equation of the magneto-mechanical system, as in (5), in which the magnetic field including MS and mechanical coupled strongly.

$$\begin{pmatrix} \boldsymbol{M} & \boldsymbol{D} \\ \boldsymbol{C} & \boldsymbol{K} \end{pmatrix}\begin{pmatrix} \boldsymbol{A} \\ \boldsymbol{u} \end{pmatrix} = \begin{pmatrix} \boldsymbol{J} \\ 0 \end{pmatrix} \tag{5}$$

where M is the electromagnetic matrix, K, the mechanical stiffness matrix, C, D, the coupling interactions between the magnetic field and mechanical deformation, and C=D^T.

III. NUMERICAL CALCULATION AND TESTS

The numerical model and vibration tests were implemented on a three-phase, 6-pole, 36 stator slots and 33 rotor slots, 1.5KW surface mounted PMSM core with 155mm stator outer diameter and 0.45mm air gap.

A. Calculation results

The analyzed model of the motor is shown in Fig.1(a). Fig. 1(b) shows the enlarged view of the 3-D finite-element mesh, which shows is 1/6 of the entire region. Tetrahedron elements are used in the magneto-elastic analysis. In order to investigate the effect of MS on the core vibration, the analysis results are compared with those without the MS under the same excitation and mesh. Fig. 2 shows the sectional view of stator deformations with physical dimension from transient solution without and with the MS effects added.

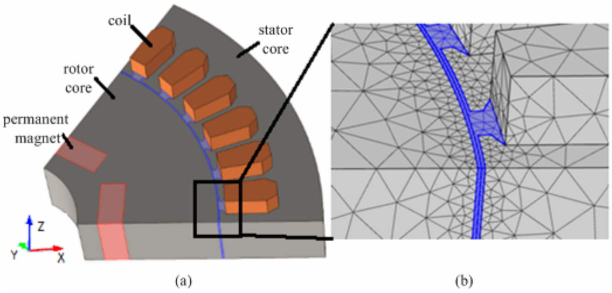

Fig. 1. Analyzed model and finite-element mesh. (a) Analyzed model. (b)Enlarged view of the finite-element mesh.

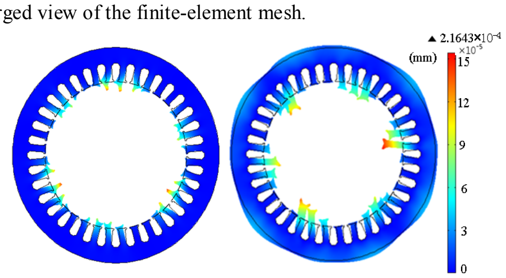

Fig. 2. Sectional view deformations without and with MS

The deformation of every node, which can express the impact of MS on the vibration more visibly, can be got from FE calculation. The acceleration of a particle on the stator shown in Fig. 3, which is calculated by a_x, a_y, and a_z, a=sqrt(a_x^2+a_y^2+a_z^2). It can be easily seen from the figure that the MS effect has significant influence on vibration and additional pulsation is added that reduce more noise.

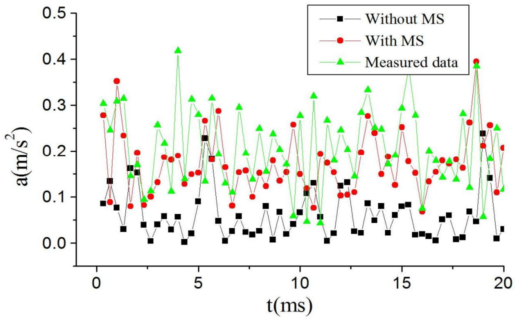

Fig. 3. Accelerations of a particle on the stator

B. Measurement results

The testing system is shown in Fig. 4. The vibration of multiple positions of the core was carried out and the analysis particle is also shown in Fig.3, which shows that the analysis with MS is more consistent with measurement results.

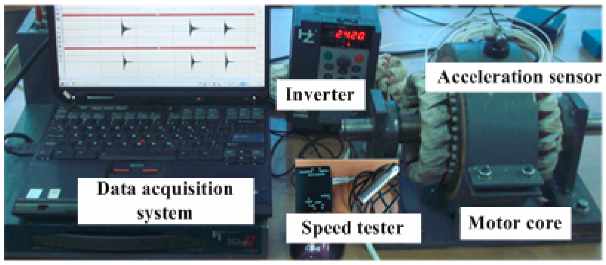

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Fig. 4. The vibration measurement of the motor core

The points acceletation both from calculation and test under speeds are shown in Fig. 5, which indicates the vibration is related to speed and the motor should avoid the sensitive frequency when adjust speed by frequency conversion.

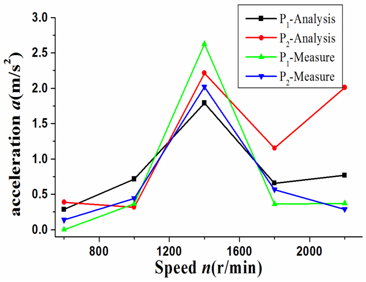

Fig. 5. Accelerations under different rotation speed

IV. REFERENCES

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