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The Magneto-Elastic Effect in High-Speed Rotors of Electrical Machines

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Abstract

Due to the increasing amount of high power density high-speed electrical machines, a detailed understanding of the relationship between higher mechanical stress distribution inside the rotor and magnetic properties of the electrical steel is necessary. Magnetic materials are prone to mechanical stress. Therefore, the relation between the local mechanical stress distribution and magnetic properties such as magnetic flux density and iron losses has to be studied and its consequences on the machine behavior such as iron losses or magnetic flux path has to be analyzed. In this paper, different approaches for equivalent mechanical stress criteria are analyzed. Resulting machine characteristics such as magnetic flux density distribution or iron are compared. The study shows a strong influence on the magnetic flux density distribution when considering the magneto-elastic effect for all analyzed models.

1 Introduction

Increased power density of electric drives for automotive applications can be achieved by increasing the rotor speed. As a consequence, high mechanical stress occurs within the rotor lamination. The magnetic properties of the soft magnetic material such as magnetic flux density or iron loss are influenced by these mechanical stress (magneto-elastic effect). Several publications present models for magnetic flux density [1] or iron loss [2]. The most of these presented models relate to magnetic measurements, where electrical steel sheet is subject to mechanical stress. Usually, uniaxial measurements are performed, which means that the applied mechanical stress is collinear to the magnetic field [3]. In electrical machines, the local mechanical stress distribution does not represent simple one-dimensional cases and can be very complicated. The link between a complicated mechanical stress distribution and its consequences for the magnetic properties is essential for electrical machines which have an improved design resulting in less iron losses.

This paper focusses on the detailed study of the mechanical stress distribution in high-speed rotors of electrical machines. Different approaches for equivalent stresses are compared and their appropriate use in electrical machines is discussed. Therefore, a detailed methodology is presented. This study compares the influence of the different models on machine quantity such as magnetic flux density distribution or iron loss.

2 Model

The magneto-elastic effect can be measured by using uniaxial single sheet tester attached to a hydraulic cylinder such as described in [3]. The results can be used to determine mechanical stress-dependent material parameters such as permeability or iron loss dependency. Due to the test setup, measurements are restricted to collinear measurement of magnetic field and mechanical stress direction. A stress criterion is necessary to compare an arbitrary stress condition in the electric machine with measured magnetic properties.

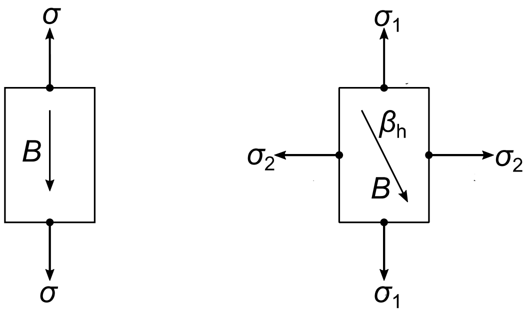

Fig. 1: Mechanical load cases

In Fig. 1, the mechanical load conditions of the uniaxial and biaxial case are illustrated. In the uniaxial case as applied in the test setup, the directions of the magnetic field density B and the principal stress do match. In the biaxial case as found in a real application, the principal stress in the second dimension σ_2 is not zero. Further, the direction of the magnetic field B is not correlated to the direction of one of the principal stress components σ_1 and σ_2. The direction of the magnetic flux density B and the principal stress σ_1 deviates by the magnetisation angle β_h.

In order to determine compressive or tensile load condition, the sign of the larger principal stress is evaluated. This model was introduced in [4] and is called Model 0 in the following discussions:

$$\sigma_{eq,VM} = \begin{cases} sgn(\sigma_1)\sigma_{VM}, if \ |\sigma_1| > |\sigma_2| \\ sgn(\sigma_2)\sigma_{VM}, if \ |\sigma_2| > |\sigma_1| \end{cases}.$$

Model 1 is introduced by Daniel and Hubert [5]. The model is based on magneto-elastic energy conservation and includes the directions of principal stresses σ_1, σ_2 and the magnetic flux density B (Fig. 2). The equivalent stress $\sigma_{eq,dir}$ is defined as:

$$\sigma_{eq,dir} = \left(\sigma_1 - \frac{1}{2}\sigma_2\right) h_1^2 + \left(\sigma_2 - \frac{1}{2}\sigma_1\right) h_2^2$$

with the unit vector h in direction of the magnetic field density B.

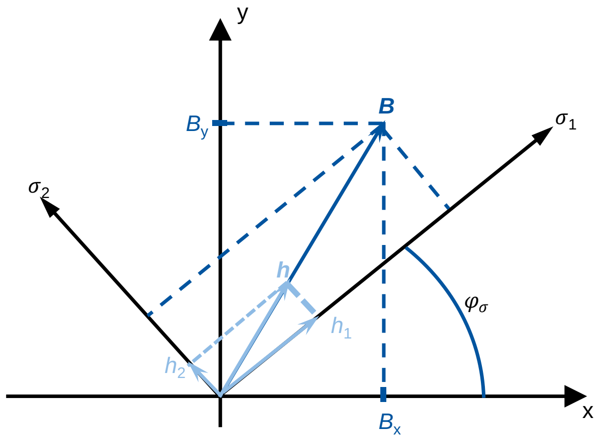

Fig. 2: Visualization of direction-dependent equivalent stress

h_1 and h_2 are the components of h in the direction of the principal stress components σ_1 and σ_2. The vector components h_1 and h_2 are used as weighting factors for the calculation of the equivalent stress $\sigma_{eq,dir}$. The angle φ_σ is used to determine the position of the principal mechanical stress relative to the global x-y coordinate system. The unit vector h is aligned to the magnetic flux density B. The consideration of the directions of principal stresses and magnetic field vector is an advantage of the methodology used.

3 Consideration in Electrical Machines: Example Interference Fit

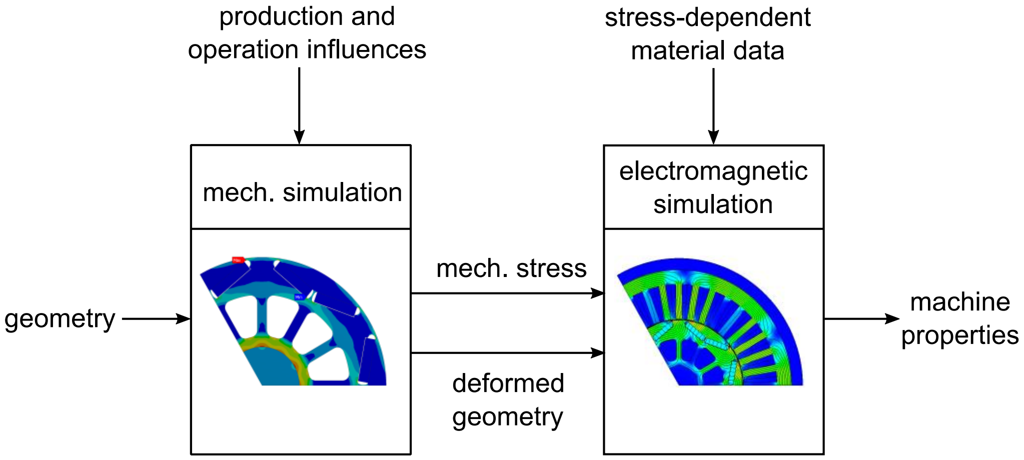

Fig. 3: Simulation Chain

The most significant mechanical load caused by machine operation at high speed application is the centrifugal mechanical load [6]. In the mechanical simulation tool, the local deformation and the principal stresses are simulated (Fig. 3). For the electromagnetic simulation, the deformed rotor geometry must be simulated together with the stator geometry. Then, the electromagnetic simulation is performed. The mechanical stress distribution is transferred to the electromagnetic machine model. With the knowledge of the mechanical stress distribution inside the machine, the magneto-elastic effect can be considered. In the simulation, the relative magnetic permeability is locally provided as a function of the mechanical equivalent stress and the magnetic flux density by stress-dependent material data. In this work, a permanent magnet synchronous machine (PMSM) is studied. The operating point is chosen at the speed of $n = 10{,}000\,rpm$ where high centrifugal forces occur. The centrifugal forces are superposed with the mechanical stress coming from the interference fit of shaft and rotor lamination stack.

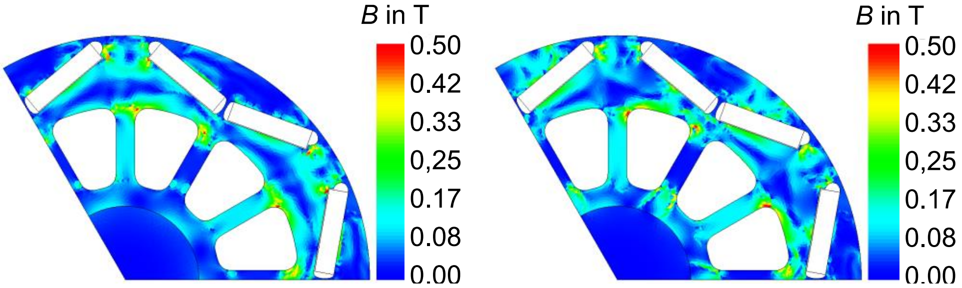

Fig. 4: Differences in magnetic flux density distributions of Model 0 (left) and Model 1 (right) referred to distribution without consideration of mechanical stress

The differences in the equivalent stress models lead to different distribution of the magnetic flux density inside the rotor. Fig. 4 shows the difference between the magnetic flux densities without and with consideration of the magneto-elastic effect. For compressive stress, a significantly reduced relative magnetic permeability was measured [4]. According to this, areas with negative stress values lead to significant differences of the magnetic flux density. This effect can be seen for Model 1 between the magnet fillets and the outer edge of the rotor. Due to the high magnetic flux densities at the minimum distances between the magnet fillets and the outer diameter of the rotor, the high mechanical stress has no effect on the magnetic flux density. In conclusion, the magnetic flux densities are significantly altered when considering the magnetic-mechanical effect.

Another important quantity of the electric machine is the iron loss. The iron loss can be distinguished into hysteresis, eddy current, excess and non-linear loss component. The iron losses for the reference machine without magneto-elastic effects shown in Fig. 5 (left).

The eddy current losses represent the largest contribution to the total iron losses. Hysteresis and excess losses in the rotor are lower. In the next step, the stress-dependent change in magnetic flux density is considered for the calculation of the iron loss. The magneto-elastic effect in use of the different equivalent stress models shows slight deviations in the eddy current losses when compared to neglected effect. The other loss components show small deviation. According to this, the total iron loss increases. When using Model 1, the deviations are highest with $p_{cl} = 2.3$ %.

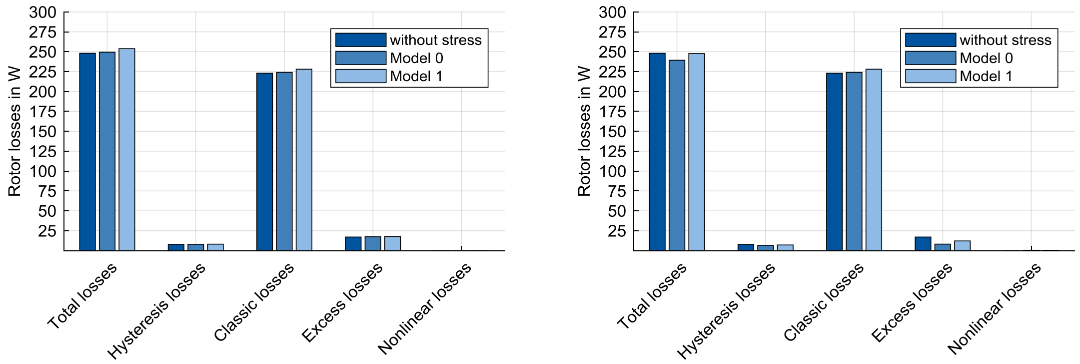

Fig. 5: Rotor losses without (left) and with (right) stress-dependent loss parameters

Another aspect is to study in which way the magneto-elastic effect influences the iron losses when using the stress-dependent iron loss parameters. The non-linear iron loss in the rotor of the reference machine is negligible. However, there is a deviation in the hysteresis and excess losses. The hysteresis and excess losses without consideration of the magneto-elastic effect ($P_{hys} = 7.94\,W,\ P_{exc} = 17.09\,W$) are significantly higher than taking this effect into account. The hysteresis losses decrease when the effect is considered because the stress-dependent iron loss parameters for positive mechanical stresses is decreasing [3]. Because the stress-dependent parameters of the hysteresis losses for negative stress values increase, the hysteresis losses for Model 1 are also increased when compared to the other equivalent stress models. The hysteresis losses for Model 1 deviate by $10.6\,\%$. when compared to the losses without neglecting of the magneto-elastic effect. Similar correlations are observed for the excess losses. When using Model 0, the excess losses are $6.83\,W$ and thus deviate by $60\,\%$. from the excess losses without consideration of the magneto-elastic effect. However, if Model 1 is used, the excess losses only deviate by $28.7\,\%$. from the excess losses without consideration of the effect.

Due to the high differences in the use of the equivalent stress models, the most appropriate choice of the equivalent stress model is important. Model 1 is best suited here due to the consideration of the directions of magnetic field and mechanical principal stress axis.

4 Conclusions

In contrast to the other presented equivalent stress model, the direction-based equivalent stress model is the best suited model for the application in electrical machines. This model considers the biaxial mechanical stress and direction of the magnetic flux density distribution which allows an exact mapping of the real conditions in lamination stacks.

Both presented models show a high influence on the magnetic flux density distribution when considering the magneto-elastic effect. In particular, regions with magnetic flux densities between $0.5\,T$ and $1.5\,T$, the models show a difference.

The consideration of the magneto-elastic effect leads to a significant change in the properties of the magnetic circuit as it can be seen in the magnetic flux density or iron loss. Therefore, considering the effect of mechanical stress on magnetic properties can be crucial for the design, simulation and analysis of rotating electrical machines.

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