Less Losses in Active Magnetic Bearings

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Abstract

An optimization method and a design for a reduction of eddy current losses in an active magnetic bearing (AMB) are presented. Since eddy current losses are a major source of energy dissipation in an AMB, their reduction may increase efficiency and operating range of the AMB, reduce cooling efforts and hence lower manufacturing and operational costs. With the proposed optimization, a reduction of eddy current losses of about 30 per cent is achievable.

Keywords: *Active Magnetic Bearings, Losses, Eddy Current, Optimization, Stator Design*

1. Introduction

In this paper, a method and a design example are presented that aim to reduce losses in an active magnetic bearing (AMB). Emphasis is put on demonstrating how the geometry of an AMB stator can be optimized in order to minimize the generation of eddy currents which are a major source of heat in the rotor part of the AMB. Reducing eddy currents and related losses may increase efficiency and operating range of the AMB and reduce cooling efforts as well as manufacturing and operational costs.

A typical heteropolar AMB design comprises a stator configured to provide a magnetic flux density and a rotor part configured to be magnetically attracted by the stator via the magnetic flux density. Stator and rotor are separated by an air gap. Based on Faraday's law of induction, the generation of eddy currents depends on the time derivative of the magnetic flux density acting upon the rotor, which usually consists of an electrically conductive material. In a heteropolar magnetic bearing, the magnetic flux density, as provided by the stator, generally includes a number of opposite polarization zones along an inner circumference of the stator. Therefore, during rotation, a point on the rotor usually passes a number of different polarization zones causing a number of more or less abrupt changes of the magnetic flux density in the point of the rotor and hence an induction of eddy currents. Details about AMB hardware and the generation of eddy current losses can be found in [1] and [2].

To reduce eddy current losses, it is commonly practiced to laminate the rotor portion of the AMB [2]. In addition to laminating the rotor (or at least a portion of the rotor), the method proposed in this paper aims at optimizing the AMB stator geometry with respect to eddy current losses in the rotor while maintaining, as an optimization constraint, a required minimum AMB load capacity. As it is shown in the sequel, a reduction of eddy current losses of about 30 per cent is achievable at a typical operating speed of a large machine.

2. Methods

2.1 Outline of the optimization procedure

The objective of the proposed optimization is to find a stator geometry that reduces the generation of eddy currents in a rotating rotor to a minimum.

The optimization procedure comprises the steps

a) defining the stator geometry as a function of stator geometry parameters and generation of a finite element model (FEM);
b) computing the value of a cost function for a given set of stator geometry parameters, wherein the cost function maps estimated eddy current losses to a scalar value;
c) varying the stator geometry parameters and repeating step (b) until a minimum of the cost function is reached.

The variation of the stator geometry parameters, can be performed with standard optimization methods, for example, sequential quadratic programming (SQP) and/or evolutional/genetic algorithms. Steps (a) and (b) are explained in the sequel. Optimization methods are available in numerical software packages, for example MATLAB [8].

2.2 Defining the stator geometry with geometry parameters and FEM modeling

For optimizing the AMB stator geometry it is, in a first step, required to establish a model of the AMB's magnetic circuit including a parametric model of the AMB stator. Model parameters determine at least a part of the geometric shape and material of a stator portion to be optimized and need to be accessible by an optimization routine.

In Figure 1a, an example of a part of an AMB's magnetic circuit is depicted, that is, a cross-sectional view of a quadrant of an AMB's rotor (1) and stator (2). The AMB stator (2) in Figure 1a comprises a nose (5) which is present in some AMB designs and which may be optimized to achieve a minimum of eddy current losses in the rotor.

The shape of the nose (5) may, for example, be modeled with a mathematical function such as a polynomial or a segment wise linear function or in some other parametrizable way. Parameters of the mathematical function serve as optimization parameters. Figure 1b shows an example for a polynomial and for a segment wise linear function.

The modeled AMB's magnetic circuit including stator and rotor geometry is subsequently used to establish a FEM model being used to calculate the magnetic flux density in the air gap (3). Based on the calculated magnetic flux density, the estimation of eddy currents (step b of the optimization procedure) is performed. The actual computation of the magnetic flux density can be performed with FEM software. In our investigation we used FEMM4.2 [7].

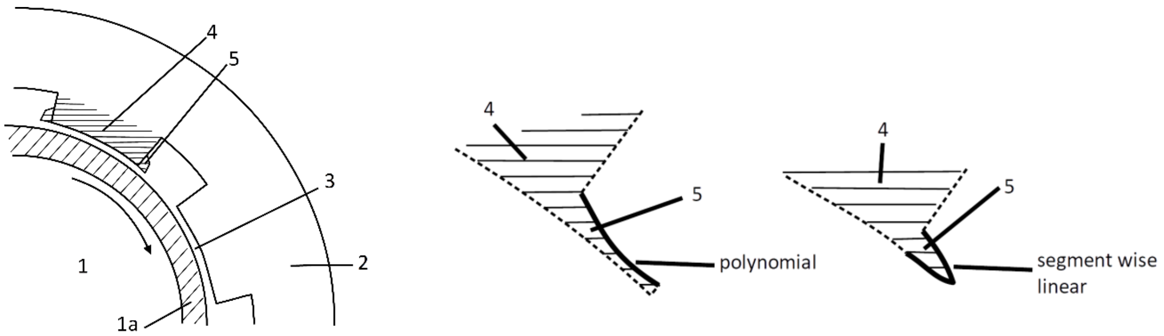


Figure 1a (left): Cross section of a non-optimized AMB: 1: rotor, 1a: rotor lamination; 2: stator, 3: air gap, 4: pole tooth; 5: nose;
Figure 1b (right): parametrizations of the nose (5) - with a polynomial function or segment wise linear

2.3 Estimation of eddy current losses

The estimaton of eddy current losses has been investigated by several authors, for example [3,4,5,6]. Therein, it has been shown that eddy current losses depend on the time derivative of the magnetic flux density. Applied to the AMB setup as shown in Figure 1a, it is sufficient to consider only the normal component of the magnetic flux density. The term 'normal component of the magnetic flux density' refers to the magnetic flux density in the air gap in a direction orthogonal to the rotor surface which is often denoted as radial direction.

Great values of the time derivative of the normal component of the magnetic flux density may be experienced by a point on the rotor, when, during rotor rotation, the point on the rotor passes zones of different absolute values and/or polarizations of the magnetic flux density, wherein the local absolute value of the magnetic flux density depends on the local geometry of the magnetic circuit at the inner circumference of the AMB stator. In general, during rotor rotation, a change of the magnetic flux density as experienced by a point on the rotor may be rather abrupt.

When the circumferential course of the radial component of the magnetic flux density is transformed into Fourier domain, such abrupt changes, i.e. high values of the time derivative, correspond to large high frequency Fourier coefficients $F(jk)$. Hence, the generation of eddy current losses largely corresponds to these high frequency Fourier coefficients of the circumferential course of the radial component of the magnetic flux density.

In our approach we use an estimation formula for eddy current losses based on a method discussed in [4] where the Discrete Fourier Transform (DFT) of the circumferential course of the radial component of the magnetic flux density is applied as

$$Loss = \sum_{k=1}^{K} m_a \left| \frac{2 \cdot F(jk)}{1.5\,T} \right|^2 \cdot \left[\left(\frac{f_k}{50\,Hz} \right)^2 \cdot \sigma_{w,50} + \left(\frac{f_k}{50\,Hz} \right) \cdot \sigma_{h,50} \right], \qquad (1)$$

wherein m_a is the mass of the relevant rotor portion, $f_k = k \cdot N/60$ (in Hz) with N as the rotational speed (in rpm), the frequency component $F(jk)$ is the k^{th} Fourier coefficient (frequency component) of the circumferential course of the radial component of the magnetic flux density in the air gap, K is the total number of Fourier coefficients considered (with $\max\{K\} = \mathrm{floor}(N_s/2)$ and N_s as the number of samples of the circumferential course of the magnetic flux density used for the Fourier transform), σ_w is the eddy current loss coefficient and σ_h is the hysteresis coefficient - both deducible from manufacturer's data sheets. The latter coefficients are material properties often determined for an excitation frequency of 50 Hz.

Equation (1) provides a quantitative expression of how the circumferential course of the radial component of the magnetic flux density is transformed into eddy current losses during rotation of the rotor. Since the circumferential course of the magnetic flux density depends on the AMB geometry, equation (1) can be used as a cost function in the optimization of the AMB's geometry.

As an optimization result, abrupt changes of the radial component of the magnetic flux density, and correspondingly high frequency Fourier coefficients $F(jk)$, are expected to be attenuated.

3. Verification Setup

The effectiveness of the proposed method is computationally verified for an AMB of a large machine with a nominal power of about 5 MW. The considered AMB has a load capacity of about 9 kN. Its stator has a cross-sectional diameter of about 400 mm. The finite element modeling is performed in two dimensions (2D) using [7].

The stator and rotor geometry are generated using the MATLAB interface of [7], wherein the nose of the stator is parametrized as a segment wise linear function. With [7], the circumferential course of the radial component of the magnetic flux density in the air gap, in total $N_S = 1500$ samples, is calculated in every iteration of the optimization and, based thereon, the eddy current losses are calculated using equation (1).

The actual optimization – step (c) of the optimization procedure – is performed using SQP-optimization of MATLAB's Optimization Toolbox [8] under the constraint of a minimum load capacity of 9 kN. The optimization is performed for a rotor speed of 6000 rpm.

4. Verification Results

Optimization result are shown in Figures 2a and 2b. Figure 2a shows the optimization result for the shape of the nose (5) modeled as a segment wise linear function. For the given setup, the shape of the nose (5) produces minimum eddy current losses in the rotor. With respect to the nature of the optimization algorithm, the identified minimum cannot be guaranteed to be a global minimum.

In Figure 2b, the curves of the radial component of the magnetic flux density along the rotor circumference are depicted for the optimized and the non-optimized case (in the non-optimized case the nose (5) is entirely omitted). The optimized curve (solid line) has a much smoother course compared to the course (dotted line) of the non-optimized nose indicating that, in the Fourier domain, the amplitudes of the high frequency Fourier coefficients of the optimized nose are attenuated. The load capacity of the optimized case is 96.4 per cent of the non-optimized one.

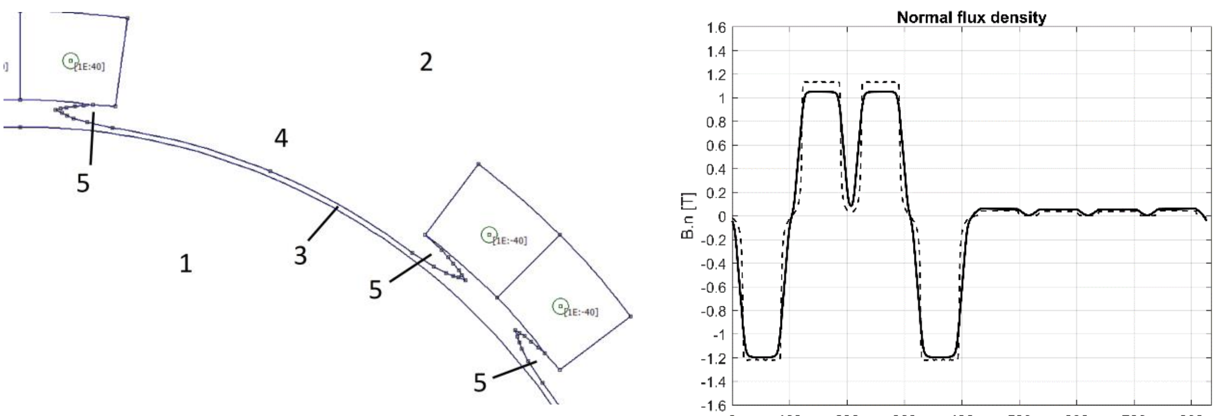
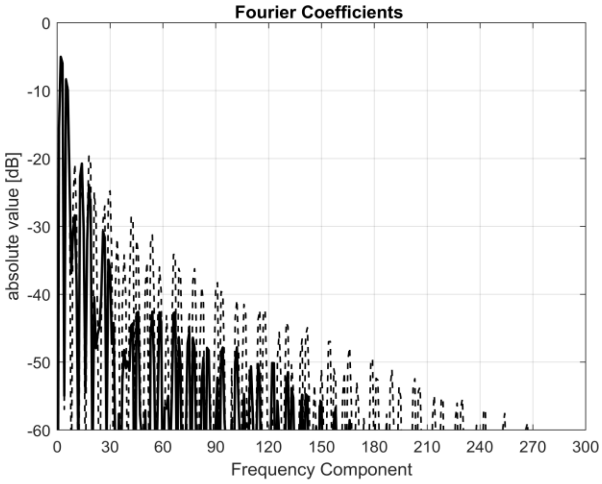


Figure 2a (left): Cross section of an AMB with an optimized stator (FEMM4.2 screenshot with additional denotations 1: rotor, 2: stator, 3: air gap, 4: pole tooth 5: nose); Figure 2b (right): circumferential course of normal component of the magnetic flux density in the air gap (3) for the optimized stator (solid line) and for the non-optimized stator (dotted line);

Figure 3a depicts the results of the verification in the Fourier domain. The dotted curve shows the absolute values of the Fourier coefficients up to frequency component $k = 300$ for the non-optimized case, the solid curve shows the corresponding values for the optimized case. The high frequency Fourier coefficients are clearly less for the optimized stator than for the non-optimized stator. The low frequency Fourier coefficients are in about the same range.

Figure 3b depicts the corresponding cumulated loss curves as a function of the frequency component and based on equation (1). Whereas the non-optimized Fourier coefficients contribute to the losses until approximately frequency component $k = 150$, in the optimized case there is no significant contribution above frequency component $k = 40$. For the assumed rotor speed of 6000 rpm, the eddy current losses are reduced by about 27 per cent. This value even increases for higher speeds: for example, the loss reduction for 12000 rpm (not depicted) is about 32 per cent.



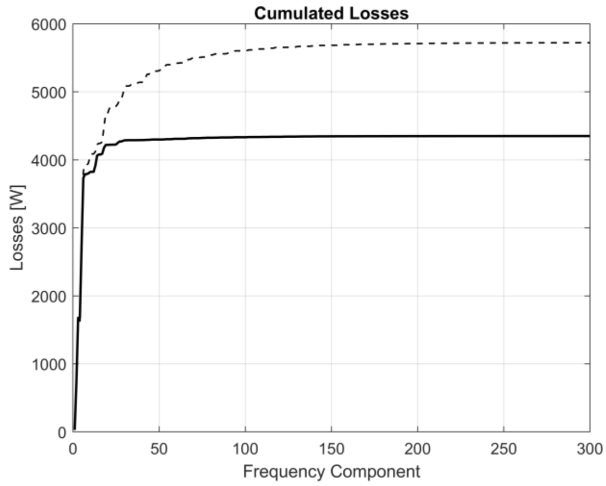


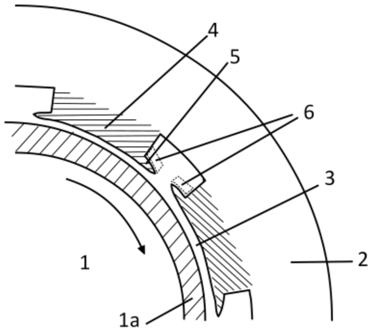
Figure 3a (left): Normal component of the static magnetic flux density along the rotor circumference optimized (solid line) and non-optimized (dotted line); Figure 3b (right): estimates of cumulated losses vs. frequency component optimized (solid line) and non-optimized (dotted line) – estimates for rotor speed 6000rpm using equation (1)

5. Discussion

The verification results clearly show that a reduction of eddy current losses is possible with an optimized stator design. For a typical rotational speed of a high-speed machine, the reduction of losses can reach values of about 30 per cent. The reduction of losses is due to a, compared to the non-optimized stator, smoother circumferential course of the radial magnetic flux density. The smooth circumferential course corresponds to a reduction of high frequency Fourier coefficients. Low frequency Fourier coefficients have values similar to the non-optimized case. This can be explained by the constraint with respect to a required minimum load capacity.

Looking at the proposed solution for the shape of the nose of the pole tooth there may be concerns regarding the mechanical stability of the optimized design. A possible solution for an improved mechanical stability may include a further, non-magnetic mechanical support in order to take up mechanical forces as depicted in Figure 4a (reference sign (6)).

Regarding the actual objective of the method, i.e. to make the circumferential course of the radial component of the magnetic flux density smoother, further optimization strategies targeting the same objective can be found. For example, a smoothing effect may also be achieved by implementing a permeability profile within the pole tooth. This might be implementable, for example, by means of 3D printing. An example for 3 permeability zones in a pole tooth is depicted in Figure 4b. In general, there could be more than 3 permeability zones and even a continuous transition or a continuous permeability gradient are conceivable.



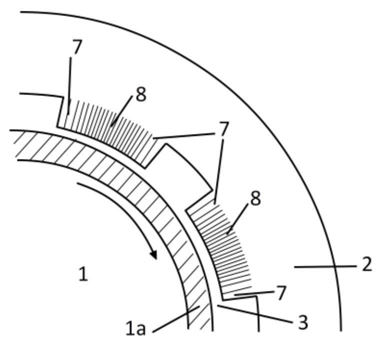


Figure 4a (left): Optimized AMB stator similar to Fig. 1b with additional mechanical support (6); Figure 4b (right): example for pole teeth with zones of different permeability – low permeability (7) and high permeability (8).

Another point to discuss is the estimation of the eddy current losses. Although there seems to be a general consent about impact factors, physics and methodology how eddy currents are to be estimated, there is currently, at least to the knowledge of the authors, no unique and commonly agreed estimation formula. So, even though the general trend should be independent from the actual formula being used, there may be differences with respect to the concrete results. In this sense, the proposed method for optimizing the magnetic bearing stator should be seen as a tool that needs to be adopted to the actual situation and design.

Furthermore, two examples of how a stator parametrization can be carried out are given in this paper. Other mathematical parametrizations may be available and may lead to different results.

6. Conclusion

The objective of the method proposed in this paper is to reduce eddy current losses in an AMB rotor. The applied strategy is to optimize the AMB stator geometry in order to make the circumferential course of the radial component of the magnetic flux density in the air gap smoother and to avoid, or at least to attenuate, abrupt changes of the radial component of the magnetic flux density for a point on the rotor moving in circumferential direction. The verification results have shown that the objective can be achieved by optimizing the shape of an AMB's pole tooth.

Depending on rotor speed, a significant reduction of eddy current related losses is possible. For a typical rotor speed of a large high-speed machine, a reduction by about 30 per cent is achievable.

The presented method may be generalized to the question about how an optimal AMB structure and/or what an optimal material (parameter) distribution within the AMB could look like. That is, which material with which property, for example permeability, must be placed where within the AMB. In this sense, the proposed method shows a path for further AMB optimization.

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