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INTEGRATING MANUFACTURERS OF MAGNETIC MATERIALS INTO THE DESIGN PROCESS OF ELECTRO-MAGNETIC MECHANICAL ACTUATORS

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ABSTRACT

A great number of actuators applied in industry act as electro-magnetic mechanical energy converters. Developed for special applications, they are designed according to different criteria in order to fulfill the required functions. One design criterion is the choice of magnetic material for the actuator. Due to the growing demands with regard to electro-mechanical energy conversion, it is necessary to consult manufacturers of magnetic materials when designing electro-magnetic mechanical actuators. An objective of this integration is to inform the manufacturer about desirable calculated parameters of materials. An evaluation of the field diffusion process as observed in the magnetic material cores is a possibility to retrieve a set of parameters for the development of materials.

Index Terms— electromagnetic field diffusion

1. INTRODUCTION

Today a lot of products which use some sort of electro-magnetic actuators are designed. The design process of these products does not normally include interactions and the exchange of knowledge between the designers of the actuators and the suppliers of the materials the magnetic circuits are made of.
A numerical criterion to evaluate the effect the field diffusion has inside the magnetic materials described in this paper. With this number designers of magnetic circuits and manufacturers of electro-magnetic material are able to optimize their design and the electro-magnetic material for a given purpose. The described criterion is one of many criteria that can be used to optimize the design process. We suggest that the developers of magnetic circuits and the manufacturers of electro-magnetic material work closely together with each other to enable us to create better magnetic systems than today.
At first the theoretical background is presented in this paper. After that the used simulation setup is shown and a numerical criterion to compare electro-magnetic material regarding the diffusion process is described. Finally the effects which varying the shape of the permeability and the conductivity has on this criterion are described.

2. LITERATURE RESEARCH

Some research regarding the efforts that have been made to analyze the diffusion process inside electro-magnetic material was carried out. There were only two relevant sources. The first one [1] is an abstract published 1968 and the second one [2] is a patent from 1998 which is based on [1].
The content of this paper is based on a master's thesis [3] by Philipp Zipf.

3. FIELD DIFFUSION EQUATION

The equation for the diffusion process in electromagnetic material can be derived from Maxwell's equations of the quasistatic condition according to [4] and [5].

$$
\begin{aligned}
rot\ \vec{E} &= -\frac{d}{dt}\ \vec{B} \\
rot\ \vec{H} &= \vec{S} \\
div\ \vec{B} &= 0 \\
div\ \vec{D} &= \rho
\end{aligned}
\tag{1}
$$

The following material properties are valid

$$
\begin{aligned}
\vec{D} &= \epsilon\ \vec{E} \\
\vec{B} &= \mu\ \vec{H} \\
\vec{S} &= \kappa\ \vec{E}
\end{aligned}
$$

By rotating formula 1 one gets

$$\begin{aligned} rot\,rot\,\vec{H} &= rot\,\vec{S} \\ &= \kappa\,rot\,\vec{E} \\ &= -\kappa\frac{d\,\vec{B}}{dt} \end{aligned}$$

By substitution of $\vec{H}$ with $\vec{B}\,/\mu$ one gets

$$\frac{1}{\mu}rot\,rot\,\vec{B} = -\kappa\frac{d}{dt}\,\vec{B}$$

The permeability μ is constant and can be set before the operator.

$$rot\,rot\,\vec{B} = -\mu\,\kappa\frac{d}{dt}\,\vec{B}$$

By using vector analysis one gets

$$rot\,rot\,\vec{B} = grad\,div\,\vec{B} - \Delta\,\vec{B}$$

As the magnetic flux density $\vec{B}$ is free of divergence

$$rot\,rot\,\vec{B} = -\Delta\,\vec{B}$$

One can now rewrite the formula

$$\begin{aligned} -\Delta\,\vec{B} &= -\mu\,\kappa\frac{d}{dt}\,\vec{B} \\ \Delta\,\vec{B} &= \mu\,\kappa\frac{d}{dt}\,\vec{B} \end{aligned}$$

The Delta Operator can now be expressed as a partial derivation

$$\frac{d^2}{dx^2}\,\vec{B} = \mu\,\kappa\frac{d}{t}\,\vec{B} \qquad (2)$$

Equation 2 is called field diffusion equation of the magnetic field.

4. SIMULATION OF THE DIFFUSION PROCESS

Some research on the diffusion process in electromagnetic materials was carried out and two sources were found. The first one is a publication by B. Aldefeld [1] from 1968 and the second one is a patent of Daimler Chrysler [2].
Both publications analyze the diffusion process with the help of numerical computing.

4.1. Test Object

The field diffusion equation is evaluated with the Finite Element Method and a test object that is limited in space is needed. The aim is to get a numerical criterion to compare the diffusion process in different materials. The geometrical shape of the test object should not influence the results.
A cube has been chosen as test object. A picture of this test object can be seen in fig.1.

4.2. Software used for simulation

The software which has been used for solving the equations is Comsol Multiphysics [6].

4.3. Simulation setup

When starting the simulation a magnetic field with the strength B_{BC} is switched on parallely to one surface of the cube. The BC stands for boundary condition. A transient simulation is performed to analyse the diffusion process inside the cube.

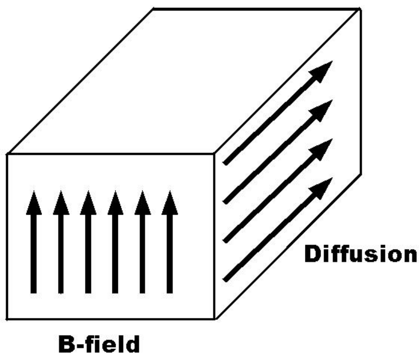

Fig. 1. Test Object

Fig. 1 shows the test object with the B-field applied at one surface while the B-field is diffusing inside the test object.

5. SIMULATION RESULT

In several simulations the conductivity and the relative permeability were varied. The typical forms of the curves are shown below in pictures fig.2 and fig.3.

5.1. Linear diffusion

By linear diffusion means that:

- The relative permeability is constant
- The conductivity is constant

Fig. 2 shows the typical form of the diffusion process that takes place in linear materials e.g. copper.

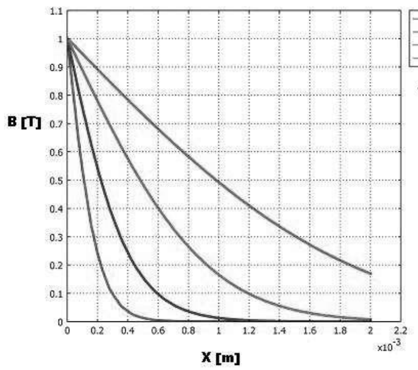

Fig. 2. Linear Diffusion

The value of the magnetic flux density decreases with an increasing penetration depth. This distance is shown on the x-axis of the graph. The flux density decreases assuming the shape of an e-function.

5.2. Nonlinear diffusion

Nonlinear diffusion means that:

- The relative permeability is dependent on the value of the flux density
- The conductivity is constant

Fig. 3 shows the typical form of the diffusion process at it takes place in nonlinear materials.

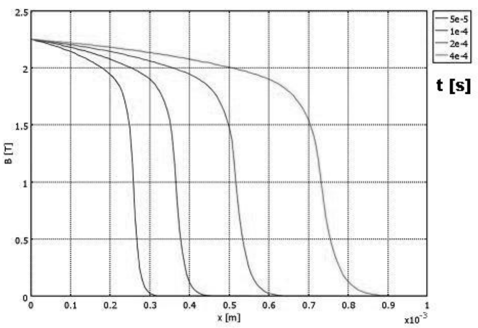

Fig. 3. Nonlinear diffusion

The graph of a nonlinear diffusion process reveals the following: With an increasing penetration depth, flux density decreases, slightly at first, then falling steeply, until finally lewelling off and converging towards 0. This development is shown.

6. DEFINITION OF A NUMERICAL CRITERION

The aim was to find a suitable criterion to differentiate various magnetic materials with each other regarding the diffusion process.
The following formula is used to describe the diffusion process inside a material.

$$PC_B = \frac{\int_0^{X_0} Bdx}{B_{BC} X_1} \tag{3}$$

This number is called Penetration Coefficient. The Index is B is used, because the formula is based on the diffusion of the B-field. Fig. 4 shows the definition of PC_B in a graphical form.

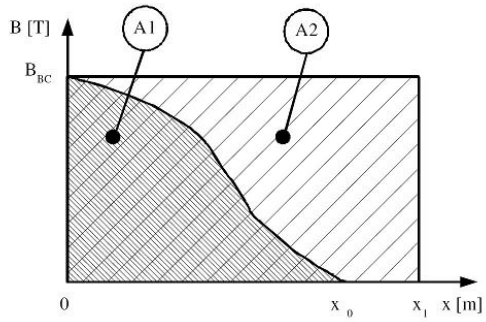

Fig. 4. Penetration Coefficient

Area A1 is bounded by the x-axis and the boundary condition B_{BC} on the y-axis. Area A2 can only theoretically be reached by the field diffusion process. This area is bounded by the path X1. PC is calculated by the division of those two areas ($PC_B \in$ [0;1]).

The value of the PC_B represents the amount of the material that is filled with the magnetic flux density. The greater the number the more the flux density has diffused inside the material. The value of PC_B is the area ratio of A1 to A2. The simulation time is fixed to 1ms and PC_B is evaluated for various materials for different boundary conditions B_{BC}.

7. EXAMINED MATERIALS

PC_B is evaluated for three different materials that are described below

Materials	Chemical composition
Material 1	49%Co,49 % Fe,2 % V
Material 2	Iron, 2.4 % Si, 0.35 % Al
Material 3	18 % CoFe alloy mit Cr, Mn und Si

Table 1. Examined materials, chemical composition

The data sheets and the numerical data for the B-H-Curve were aquired from the manufacturers of the materials.

7.1. Conductivity

Materials	Conductivity[$\frac{S}{m}$]
Material 1	2.5E-6
Material 2	2.5E-6
Material 3	1.56E-6

Table 2. Examined materials, conductivity

7.2. Relative permeability

Fig. 5 shows the initial magnetization curve of the examined materials

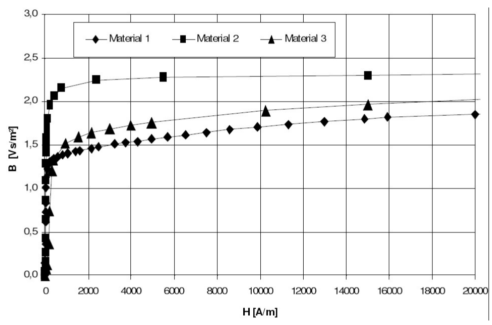

Fig. 5. Initial magnetization curve

8. SIMULATION RESULTS

Fig. 6 shows the simulation results for PC_B.The boundary condition B_{BC} was varied and PC_B was evaluated at the same time (t=1ms).

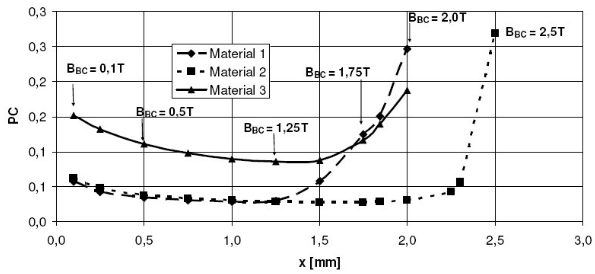

Fig. 6. Simulation results for PCB

By using flux density BBC as a parameter [eq. (2)] individual curves of the PC function can be reached (see fig. 6). Material no. 2, for example has reached the maximum of PC (3.0) by a flux density of BBC=2.5 T. In contrast to that, material no. 1 reaches the second highest PC value at a lower flux density (BBC=2.0 T).

9. INFLUENCE OF MATERIAL PROPERTIES ON OUR NUMERICAL CRITERION

9.1. Conductivity

The conductivity of the materials has been varied. The effect on PC_B can be expressed with the following formula:

$$PC_B \cong \frac{1}{\sqrt{\kappa}} \tag{4}$$

By decreasing the conductivity κ by a factor of 100 the PC_B increases by a factor of 10.

9.2. Relative Permeability

By observing the field diffusion equation 1 one can see that the relative permeability μ remains at the same position as the conductivity κ. Therefore the effect of μ should in principle be the same as the effect of changing κ on PC_B. κ is a constant and not depending on any other factor whereas μ is depending on the value of the magnetic flux density which is a nonlinear function. Because of that there is no simple formula as there is for κ but it can be stated that PC_B increases when μ decreases.

10. OPTIMIZATION OF DESIGNS BY INTEGRATING MANUFACTURERS OF MAGNETIC MATERIALS INTO THE DESIGN PROCESS OF ELECTRO-MAGNETIC MECHANICAL ACTUATORS

The relative permeability and the conductivity of magnetic materials have a great effect on the magnetic field diffusion inside the materials. Designs can be optimized by choosing the moste appropriate magnetic material that is currently available on the market.
The electro-magnetic materials can also be optimized by telling the manufacturers in question of the magnetic material what is needed for the specific design.
The previously described Penetration coefficient PC_B is one of many parameters that can be varied to optimize the material for our given purpose.
At first the manufacturer should be informed about the requirements. After that the manufacturer tells the designer of the magnetic circuit what can be done. With this information the design can be optimized by the designer of the magnetic circuit. By using simulations the designer of the magnetic circuit might again recognize that the electro-magnetic material has to be changed once more. This process of integrating

the manufacturer leads to a closed loop which is run several times until the design goal is reached.
Fig. 7 shows the proposed design process in graphical form as a flow diagramm.

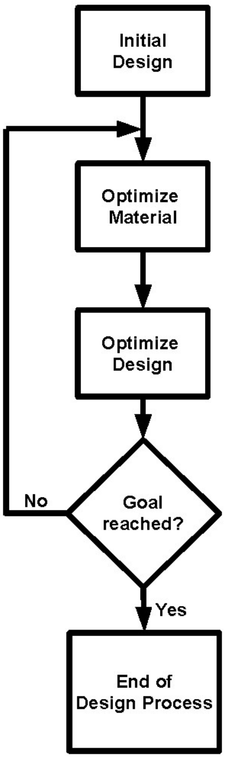

Fig. 7. Flow Diagram of the proposed design process

11. CONCLUSION

The calculated Penetration Coefficient allows for an evaluation of magnetic materials independent of geometry. Given initial magnetization curves as well as curves modified by varying the B(H) curve can be evaluated on the basis of the PC value. By feeding back the results to the manufacturers, they can be integrated into the design process of electro-magnetic mechanical actuators.

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